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OCEAN SCIENCES AND ETHICS

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Editorial: Ocean Sciences and Ethics

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Editorial on the Reseach Topic

Ocean Sciences and Ethics

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"The Anthropocene is changing our relationship with the planet, and we must determine how to assume this responsibility" (Nobel Laureate Elinor Ostrom, 1933-2012). Humanity must be the steward of the planet's natural resources and all stakeholders must participate to reduce anthropogenic damage to the environment. In this context, ethical behavior is necessary to ensure the sustainable use of our planet and our oceans. Consequently, it is our responsibility to apply core ethical values, identify and promote sustainable ocean principles, especially in line with the United Nations (UN) Sustainable Development Goals (SDGs) (United Nations, 2016). For the marine environment, this is particularly evident in the UN Decade of Ocean Science for Sustainable Development (Ryabinin, 2020).

Responsibility is one of the core values that humans accept as universally representative of individual and social good in terms of honesty, justice and respect for life and the environment (Chan et al., 2016). The responsibility of scientists and industry is to take necessary actions to secure a healthy and productive ocean. Industries and researchers must ensure that the effects of their actions do not destroy the autonomy, dignity, integrity of future humanity, especially under human induced climate change challenges, or increasing blue economy (Bennett et al., 2021).

The term "Ocean Ethics" emphasizes reflection and reasoned actions based on scientific advances to develop the exploration and exploitation of the oceans. It involves social, scientific, environmental, legal, political, industrial and associative actors to adopt commendable and responsible behavior that will support the sustainability and stability of the ocean and support the resilience of the Earth system (Auster et al., 2009).

A bibliometric search in Scopus, in the title, abstract and key words, using the terms "marine" OR "ocean" AND "ethic*" AND NOT "health*", was made on 4th February 2022. "Health" was removed, because in a first search medicine studies in small islands were very abundant, biasing the topic studied here. A total of 840 references was found, for the period 1977-2022, and exported to EndNote. A keyword co-occurrence analysis was undertaken, using VOSviewer software, version

1.6.16 (Van Eck and Waltman, 2010; Van Eck and Waltman, 2020), in order to determine the main research topics under these terms. For details on this kind of analyses, Borja and Elliott (2021) can be consulted.

For those keywords with more than 10 co-occurrences, 5 clusters with 118 items have been identified (**Figure 1**). Cluster 1 (in red) includes 46 items, and is built around ethics in conservation, sustainability, environmental impact and protection, governance and management of the marine and coastal systems, especially in Europe, North America and Asia. Cluster 2 (in green) includes 26 items and relates ethics with the research in Oceania about the aborigine culture and their multiple relationships with the ocean, including the use of traditional knowledge. Cluster 3 (in blue) includes 24 items, with links between ethics and the use of animals in controlled experiments, bioassays and toxicity studies. Cluster 4 (in yellow) includes 12 items and is an emerging field of research on the ethics and climate change effects, sustainable development, education and awareness (Allison and Bassett, 2015). Finally, Cluster 5 (in magenta) includes 10 items, is closely related to Clusters 1-3, and relates research on ethics and some economic uses of the sea, such as fishery and aquaculture, but also the conservation of natural resources and the animal welfare (Hobday et al., 2019).

This means that the ocean ethics topic covers currently diverse approaches and fields of research, which maintain some interaction among them and the number of papers around this topic is growing progressively: before 2002, less than 10 papers were published by year; between 2003 and 2009, the papers published ranged from 15 to 40 per year; between 2010 and 2017, they ranged from 40 to 50; and after 2018, >50 papers are published per year.

In this context, this Research Topic (RT) on Ocean Sciences and Ethics intends to provide a platform to publish research, recommendations and guiding principles on the many ethical challenges and issues that scientists and industries may face when conducting research activities or develop innovation at sea. This includes protecting and respecting natural processes and phenomena when planning and implementing environmental interventions; sustainability of economic and social activities linked to energy and other natural resources; advance ocean education and awareness to promote sustainable economic development, prevent and mitigate environmental risks, environmental protection, and improve the resilience and well-being of societies; respect different cultural interest in the oceans; prevent unfair advantages or benefits for one or more parties over others; developing clear, transparent and traceable procedures regarding the exploitation of natural resources; ensure the effectiveness of decision making to prevent duplication of effort, minimizes investments and environmental impact, and ultimately reduces service and maintenance costs.

Within this Research Topic, eight manuscripts have been published, covering an ample selection of topics. Hence, Miller et al. focus on a current increasing debate about the effects on the extraction of minerals from the seabed of the deep ocean (Levin et al., 2016). Miller et al. provide a perspective on: (1) arguments that deep seabed mining is needed to supply minerals for the green energy revolution, using the electric vehicle battery industry as an illustration; (2) risks to biodiversity, ecosystem function and related ecosystem services; and (3) the lack of equitable benefit sharing to the global community now and for future generations. These authors explore the justification for a global moratorium on deep seabed mining to ensure protection of marine ecosystems, the need to focus on baseline research, and how improved governance of targeted marine regions could be key to the preservation and conservation of the ocean biome.

The second paper focuses on the current most growing Research Topic, which is the plastic pollution in the ocean (Borja and Elliott, 2021). Here, Owens and Conlon consider that plastic waste is currently understood by industry as an externality that demands a technological solution. However, when the problem of plastic waste is ignored, the costs are pushed to marginalized communities around the world, to future

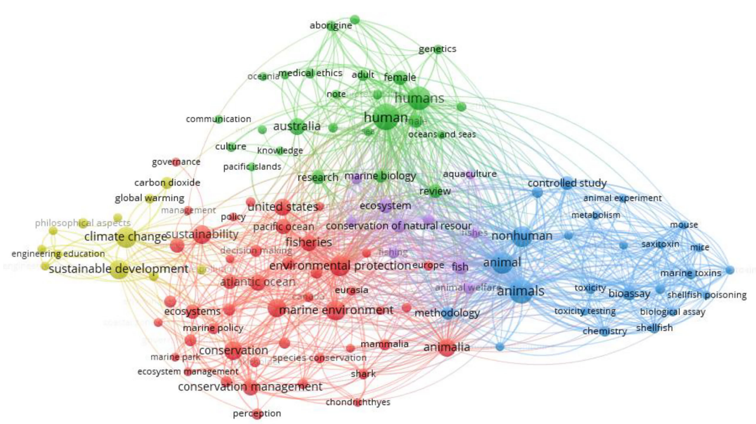

FIGURE 1 | Clusters (bubbles in same color) of keywords co-occurring at least 10 times in the 840 references identified for the topic ocean ethics, together with the links among them (lines in same color).

generations, citizens, governments, and taxpayers, producing multiple ethical problems. These authors consider that, rather than leave the problem-solving to the problem-creators, scientists, policymakers, and governments are advised to frame plastic waste narratives like that of Common Seas: with an emphasis on reduction, redesign, re-use, and collaborative decision-making for plastic reduction rather than downstream management.

Sánchez-Arcilla et al. say that met-ocean factors (waves, currents, etc.) are normally selected from a probability distribution, where only the central trend is considered, and then the analysis of hydro-morphodynamic processes is carried out within a deterministic framework. This analysis is often based on a non-updated topo-bathymetry, with implicit error intervals for many variables, which results in uncertainties that, unless presented from an ethical perspective, tend to hinder proactive decision making and thus result in growing coastal degradation. To address this challenge, the article develops an approach for field and lab data, to estimate key variables in coastal sustainability and engineering decisions. The article addresses the implications that the uncertainties associated to those variables may have for coastal risk assessments and proactive decision making, discussing how large error levels without a suitable ethical assessment may result in socio-economic mistrust, which will limit the necessary optimism to address future coastal sustainability.

Cappelletto et al. focus on "ambassadorship" programmes in marine science. These programs are conceived to address the future generations of scientists, entrepreneurs, policymakers, and citizens, and to promote the awareness and shared responsibility on the sustainable use of marine resources in an authentic and credible way, through the empowerment of young researchers and professionals, communicators, or activists. Such ambassadors are well-positioned to act as agents of change, improving the dimension of Ocean Ethics related to inclusive governance, especially necessary for an equal, just, and sustainable management of multi-actor and transboundary socio-environmental contexts. Pivoting on the Young Ambassadors' Program developed in the framework of the BlueMed Research and Innovation (R&I) Initiative for "blue jobs" and growth in the Mediterranean area as case practice, the article aims to propose some reflections about the long-term perspective of such experiences. Outlining an emerging physiognomy of the "One Ocean Ambassadors," it discusses their potential to build the next generation of responsible scientists, citizens, and decision-makers and to embed ethical principles in research-based marine governance.

Giuffredi et al. quantify the effects of the unprecedented experimental conditions induced by the reduction of many anthropogenic pressures during COVID-19 lockdown. This was undertaken in a project conceived with a holistic, interdisciplinary approach, geared to combine scientific, economic and cultural observations to promote collective actions suitable to the governance of socio-ecological systems, reconciling respect for the environment with human activities and wellbeing, and thus grounding an ethical approach to marine resources. The authors comment the process- and community-related features, explore limits and opportunities, and propose a set of recommendations, based on a preliminary review of their experience and oriented to promote the development of a shared Ocean ethics.

Nauen and Arraes Treffner work on the Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication (SSF Guidelines) (FAO, 2015). The authors investigated with self-selected men and women in small-scale fisheries in Senegal, a country with a large and dynamic SSF, which suffers, however, from diminishing profitability as a result of multiple pressures. The authors report ongoing work on the principles and approaches of the Small-Scale Fisheries Academy as a way to support the implementation of these Guidelines. The first phase of developing the SSF Academy focuses on testing learning methods aimed at developing critical thinking, planning and action. Respectful dialogue in the secure space of the Academy made academy learners, particularly women and younger participants, gradually more confident, articulate, and active. They started harvesting the results of enacted planning. The authors argue that it would be useful to expand these tests combining dialogue, the art of hosting communication and visual thinking to different places in Senegal and elsewhere. They provide an opportunity to address sensitive social issues like gender equity and intra-household violence and open perspectives on other societal challenges that hamper the implementation of the SSF Guidelines.

Whoriskey et al. commented that globally huge investments are made annually in establishing infrastructure for shorter-term ocean observing systems, with punctual studies that address targeted as opposed to broad science needs. Given punctual infrastructure's small and frequently transient nature, these authors consider that connections to enable sharing will probably be done locally, and both potential additional users and owners of the infrastructure will need to be energetic, receptive and flexible. The accommodation of new uses will have to be balanced against any costs of these additional activities, which could pose an ethical dilemma in themselves if they compromise the infrastructure's ability to meet its original intent. However, such adaptive infrastructures may be the most efficient way to provide the resources needed to identify and monitor emerging or new ocean stressors.

Xiao et al. studied the transformation of the reclaimed land in Quanzhou Bay (China), dividing it into four stages, which are closely linked to the economic development in the region. In the early industrialization period, reclaimed land in the region was used for agricultural production, whereas in the mid-industrialization period, it was gradually transformed into a combination of industrial and agricultural lands. In the later period of industrialization, the reclaimed land was gradually converted into urban industrial and port lands. Finally, with further refinement and upgrading of economic and industrial structures, the socio-economic and environmental benefits from coastal reclamation projects have been increasing, whereas the proportion of economic benefits (in the total benefits) has been decreasing, posing ethical questions.

The variety of topics submitted to this Research Topic shows that this field of knowledge is growing progressively, incorporating new areas linking ethics and the use of marine resources (e.g. deep-sea mining, use of space, fisheries), the legacy of pollutants (including plastics), the observation of the ocean and the use of such data in an equitable way, or the awareness of young people and young scientists about the ocean problems. We hope that this Research Topic can contribute to increase our responsibility to apply ethical fundamental core values, identifying and promoting sustainable ocean principles.

AUTHOR CONTRIBUTIONS

MB developed the idea of the RT. AB wrote the first draft of the article and all authors contributed equally to the discussion-conclusions and in writing the final manuscript.

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Challenging the Need for Deep Seabed Mining From the Perspective of Metal Demand, Biodiversity, Ecosystems Services, and Benefit Sharing

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The extraction of minerals from the seabed of the deep oceans is of increasing interest to investors, mining companies and some coastal states. To date, no commercial-scale deep seabed mining has taken place but there is considerable pressure for minerals mining to become an economic reality, including to supply the projected demand for metals to support a global transition to renewable energy. At the same time, the full environmental impacts of deep seabed mining are difficult to predict but are expected to be highly damaging, both within, and perhaps well beyond, the areas mined. Here, we reflect on the considerable uncertainties that exist in relation to deep seabed mining. In particular, we provide a perspective on: (1) arguments that deep seabed mining is needed to supply minerals for the green energy revolution, using the electric vehicle battery industry as an illustration; (2) risks to biodiversity, ecosystem function and related ecosystem services; and (3) the lack of equitable benefit sharing to the global community now and for future generations. We explore the justification for a global moratorium on deep seabed mining to ensure protection of marine ecosystems, the need to focus on baseline research, and how improved governance of targeted marine regions could be key to the preservation and conservation of the ocean biome.

Keywords: marine minerals, deep sea, biodiversity, battery technology, ocean governance, critical metals

INTRODUCTION

Interest in mining deep-sea minerals is growing because of a perceived or predicted need to meet increased demand for minerals, including in support of a “green transition,” and the financial rewards that could flow from exploitation of metal-rich deposits. The International Seabed Authority (ISA), has, as of May 2021, issued 31 exploration contracts, many of which are with private companies headquartered in the global north. Exploitation regulations are being drafted by the ISA. To date, no exploitation contracts have been awarded by the ISA for mining in the area beyond national jurisdiction (ABNJ), and no commercial deep-sea mining has taken place on continental shelves.

In spite of the irreversibility of environmental impacts, and huge uncertainties over their scale and severity, the deep-sea mining industry is gaining prominence, supported by carefully crafted narratives that aim to position proposed operations as a viable option to supply virgin mineral resources (Childs, 2019). In some cases, seabed mining is presented as an unavoidable consequence of ever-growing demand, in others as the "lesser of two evils" in comparison to land-based mining. Reasons cited by deep-sea mining proponents to exploit ocean mineral reserves include a decline in terrestrial ore quantity and quality (Ali et al., 2017; Hein et al., 2020), the potential for social conflict in regions from where natural resources are extracted (Ali et al., 2017) and the potential impact from terrestrial mining, including on the climate (Paulikas et al., 2020a). Civil society groups are becoming increasingly vocal in their opposition to deep sea mining, and there are calls for industry to take into account the profound cultural and spiritual ties that many remote island nations have with the sea.

Mining the deep sea will cause extensive damage to, and will have long-lasting impacts on, the ocean biome (Miller et al., 2018; Vonnahme et al., 2020). Marine ecosystems are already experiencing an unprecedented combination of pressures, including climate change, acidification, deoxygenation, pollution and the over-exploitation of living marine resources (Danovaro et al., 2020). Targets have been set for global ocean protection, mechanisms implemented and conservation programmes initiated, but these are overshadowed by the overarching lack of a coherent strategy. For example, UN Sustainable Development Goal 14 ("to protect the health of the ocean") is not fully on track to achieve all ten targets by 2030 (Johansen and Vestvik, 2020) and none of the Aichi targets have been achieved within the past UN Decade on Biodiversity (Secretariat of the Convention on Biological Diversity, 2020). Progress continues this year (2021) to develop a legally binding instrument for conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction. Opening the deep seabed to mining on an industrial scale would be fundamentally at odds with such commitments.

THE PERCEIVED BENEFITS AND RISKS OF DEEP-SEA MINING

The Argued Need for Deep Seabed Mining to Supply Minerals for the Green Revolution

The move towards a low-carbon economy is projected to lead to increased demand for minerals including cobalt, lithium, nickel, copper, vanadium and indium for use in electric vehicles (EVs), green energy technologies and storage batteries, with large increases in demand predicted for cobalt, nickel and lithium (Teske, 2019; World Economic Forum, 2019; Hund et al., 2020). Interest in mining virgin resources from the deep sea has, in part, been driven by such projections, alongside desires to maintain a diversity of supply and concerns about environmental and human rights impacts associated with terrestrial mining (Church and Crawford, 2020; Lèbre et al., 2020; Paulikas et al., 2020b).

Despite detailed estimates for the quantities of minerals and metals needed to realise the transition to green technologies, the extent of future demand remains highly uncertain. Assumptions on which projections are based are subject to considerable uncertainties and are likely to evolve substantially over the coming decades. Two key factors that influence modelled demand are the future availability of energy-related technologies (especially for batteries) and what those imply in terms of metal demand and the rate and scale of manufacturing of those technologies. Månberger and Stenqvist (2018) report that terrestrial mineral reserves are sufficient to support a transition to renewable technologies given potential future innovations, with the possible exception of lithium-containing batteries (planned exploitation of deep-sea reserves generally does not target lithium).

Batteries have been highlighted as posing a dominant future demand for certain metals that are also associated with deep seabed resources and provide a useful example (**Figure 1**). Many projections assume ongoing use of current lithium-ion battery technology (incorporating cobalt and nickel) for both EV and stationary storage uses (Hund et al., 2020), despite available and in-development alternatives such as the cobalt-free lithium-ion car battery from Svolt (2019), and Tesla's use of lithium-ion phosphate batteries in certain vehicles, which require neither cobalt nor nickel (Tesla, 2020). Projected future demand for EV batteries depends on the assumed transport model and the relative scale of different transport modes. Projections are based on models that range from a business-as-usual approach to sustainable transport models that are less dependent on personal vehicles. More integrated transport systems could enable even fewer vehicles and batteries. Improved technological design, such as elimination of built-in obsolescence, could also have a major influence on future demands for raw materials and finished goods (Thompson et al., 2018).

The European Commission (EC) proposal concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020 (EC, 2020), includes measures to ensure large increases in recycling rates and greater use of recycled content, as well as ensuring due diligence in sourcing raw materials for batteries. The EC proposal does not make direct reference to seabed mining but emphasises the need for the development of sustainable battery technology and carbon-neutral energy storage. It will be vital that, alongside pursuit of a circular economy-based approach, the sustainability and ethical issues arising from existing and future terrestrial mining are also addressed.

Paulikas et al. (2020b, p.8) argue that deep seabed mining is necessary because "Economic impact outcomes are expected to be overall better when producing metals from nodules." The impact of lower prices on those currently reliant on terrestrial mining aside, in reality, it is unlikely that terrestrial mining would be displaced significantly if deep-sea mining were to commence; the sectors would become competitors in a larger minerals market without a transformational economy that reduces demand. Paulikas et al. (2020b) express some confidence in the financial

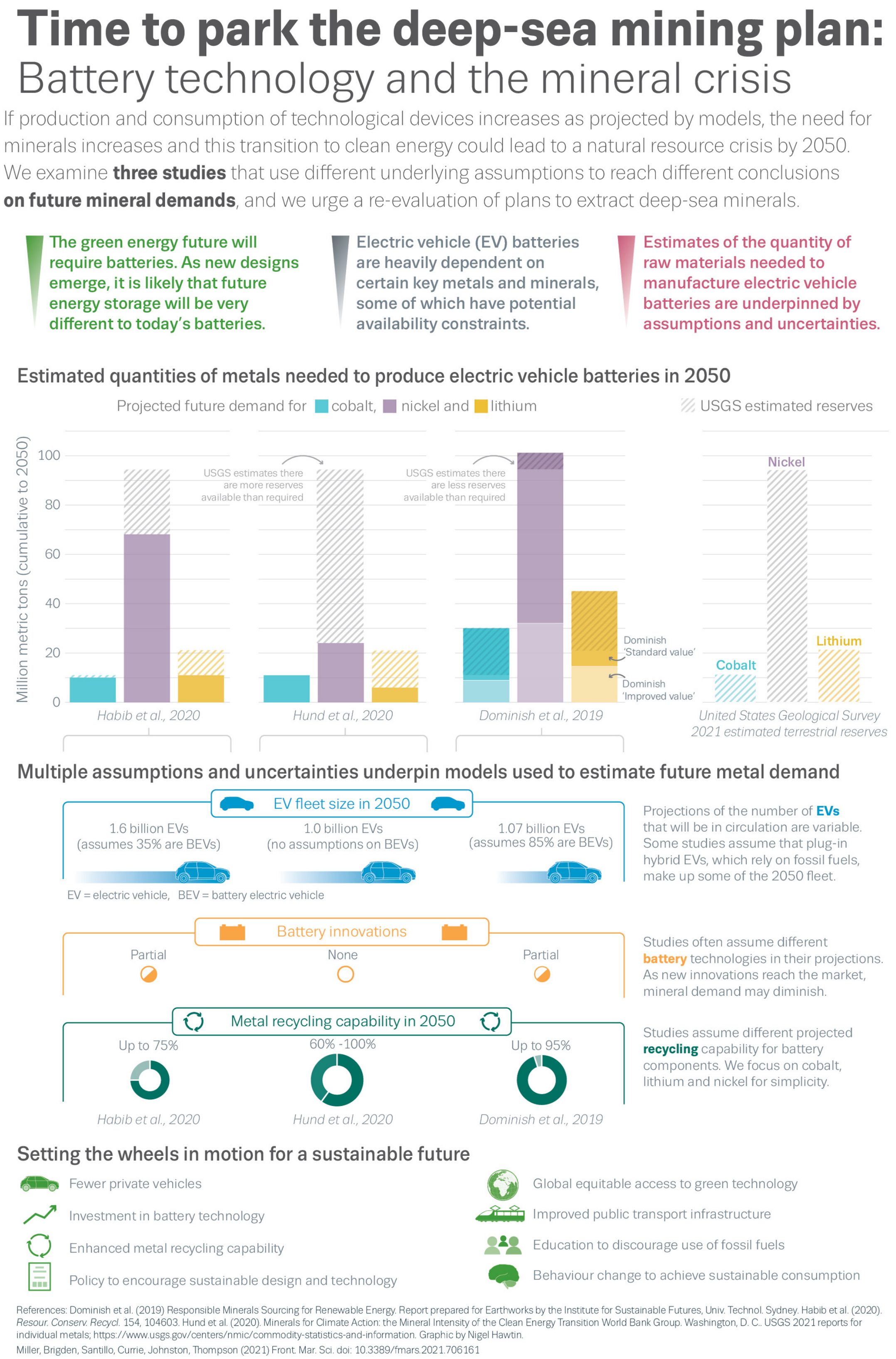

FIGURE 1 | Electric vehicle (EV) battery technology provides a useful case study to illustrate the uncertainties in projected demand and need for deep sea minerals. Our focused analysis suggests that demand for the minerals used to manufacture EV batteries could vary significantly – complex underlying reasons involve an interplay of factors such as human behaviour, investment in public transport infrastructure and technological advances.

outcome of their proposed nodule collection, but their analysis fails to take proper account of the risks for current and future generations of ignoring or undervaluing the functional ecology of the oceans and the ecosystem services they provide.

The Risks to Biodiversity and Ecosystem Services Should Deep Seabed Mining Proceed

Seabed mining will cause unavoidable, irreversible harm to deep-sea ecosystems and puts the health of the wider ocean at risk, adding to other stressors including various forms of pollution (litter, noise, and chemical), poor fisheries management and climate change. Mining impacts include light and noise pollution, sediment plumes and biodiversity loss resulting from widespread habitat fragmentation (Van Dover et al., 2017; Miller et al., 2018; Jones et al., 2020; Duarte et al., 2021). Deep-sea mining poses significant risks to midwater ecosystems, which represent more than 90% of the biosphere, contain fish biomass 100 times greater than the global annual fish catch, connect shallow and deep-sea ecosystems, and play key roles in carbon export and nutrient regeneration. Deep and midwater ecosystem services could be negatively affected by the return sediment plume, projected to be discharged at around 1,200 m, which may persist for hundreds of kilometres and, among other effects, clog respiratory and olfactory surfaces (Drazen, 2020).

Mitigating the impacts of deep-sea mining – or restoring ecosystems in a post-mining scenario – will be extremely difficult and can never be fully achieved (Niner et al., 2018). Even gaining an understanding of the potential biodiversity loss that could be caused by deep-sea mining will require far greater baseline knowledge than exists at present as well as knowledge of the technology that would be used and its direct and indirect effects (Clark et al., 2020; Levin et al., 2020a). Fundamental knowledge gaps remain in our understanding of the oceans, particularly of vulnerable deep-sea species such as cold water corals, crabs and shrimps (Van Dover, 2014; Thompson et al., 2018; Wagner et al., 2020). Connectivity between deep seabed habitats and broader ecosystem functioning are poorly understood. Research suggests that polymetallic nodules play an important part in food-web integrity in benthic ecosystems (Stratmann et al., 2021), and that *in situ* carbon fixation on abyssal plains and hydrothermal vents and their contribution to surface productivity is greater than previously expected (Levin et al., 2020b). Climate change is already having a profound impact on ocean chemistry and temperature, even in the deepest parts of our oceans, and may be contributing to changes to the distribution or migration of species, loss of habitat and food availability (Levin et al., 2020b). There remains a vital need for further primary research to inform decisions and programmes aimed at ensuring protection of the marine environment in the face of multiple existing stressors (Levin et al., 2020b) rather than a focus on “proof of concept” testing of exploitation techniques that will increase those pressures.

Predicting the scale of impacts of deep seabed mining is made more difficult by governance and regulatory uncertainties. For areas of the Pacific earmarked for mining (such as the Clarion-Clipperton Zone), there is no clear vision of how many commercial operations might proceed in parallel within an area, to what extent mining will impact biodiversity cumulatively over broader spatial scales, or how regulations might be enforced and by whom. Ecosystem services framework approaches are increasingly being used to evaluate situations where terrestrial or shallow-water ecosystems – for example forests or wetlands – could be impacted by human activities. It is hard to see how such approaches could be applied within the deep sea given the extent of uncertainties regarding ecosystem processes and their interconnectivities across space and depth. Some have argued that there is an opportunity for the ISA to take on such a framework, given that no commercial-scale mining has yet taken place (Le et al., 2017; Levin et al., 2020b).

Ecosystems services – which can be subdivided into provisioning, regulating and cultural services (Millennium Ecosystem Assessment, 2005) – have direct relevance to the habitats that fall under proposed deep seabed mining areas. Le et al. (2017) provide examples of provisioning services, such as spawning and nursery habitats supported by seamount ecosystems. Potentially vast provisioning resources are provided by deep sea habitats in relation to marine genetic resources and biomaterials, many of which have important applications in human health (Ehrlich et al., 2006; Arrieta et al., 2010; Blasiak et al., 2020). Regulating services include long-term methane and carbon sequestration, both of which are highly important for climate change mitigation. Microbial communities of vent and nodule systems are diverse and, in many cases, still poorly described, but may play an important regulatory part in the global cycling of carbon, sulphur and heavy metals (Meyer-Lombard et al., 2013; German et al., 2015; Sweetman et al., 2019). Experiments indicate that the regulatory function is significantly affected by physical disturbance, with changes persisting over long timescales, such that deep seabed mining may be directly at odds with current climate goals if such regulatory services are degraded (Nath et al., 2012).

The cultural services provided by undisturbed ecosystems are diverse and may pose still greater challenges for inclusive and quantitative assessment. Many societies hold the oceans and marine life as sacred within their traditions and histories. Such services include those that relate to educational and aesthetic resources provided by the deep sea. Local community organisations and Indigenous groups such as The Alliance of Solwara Warriors are, alongside civil society organisations such as the Deep Sea Conservation Coalition, questioning the need for, and implications of, deep-sea mining. These groups are challenging the lack of transparency within the processes under the ISA by which applications are considered and exploration contracts issued with little public scrutiny and with no clear regard for cultural values (Levin et al., 2020a).

The Lack of Equitable Benefit Sharing With the Global Community

To date, considerations of equitability in relation to deep-sea mining have focused largely on the proposed mechanisms for financial benefit sharing. Article 140 of the United Nations Convention on the Law of the Sea (UNCLOS), under which mandate the ISA operates, requires that revenue generated from seabed mining needs to be equitably shared between nations, with a particular consideration taken of developing States. The ISA is in the process of negotiating benefit sharing, with some suggestions that initial royalties to be shared among nations will total 2%, rising to 6% at a future date (Levin et al., 2020a). This model would mean that mining companies would benefit from around 70% of the total project profits, the ISA around 6%, including the amounts to be distributed, with the remainder to go to the sponsoring state (The African Group, 2018). Negotiations of such a benefit system had already been opposed by 47 African member states, who calculated a potential financial return of less than US$100,000 per annum per country (The African Group, 2019).

Beyond the detail of financial benefit sharing, however, an emerging approach that seeks to grant locations, habitats and ecosystems "Rights of Nature" could bring a fundamentally different perspective to debates on deep-sea mining by enabling re-evaluation of the relationship between humanity and the natural world. Although the concept of giving rights to nature might seem new to many in the industrialised West, the concept is not unusual to some Indigenous communities. In 2008, Ecuador became the first nation to include Rights of Nature in its constitution (Republic of Ecuador, 2008). Other examples of such an approach are few but are gradually increasing in number. In New Zealand, for example, the Te Urewera Forest and the Whanganui River or Te Awa Tupua are defined as legal entities with "all the rights, powers, duties, and liabilities of a legal person" (Te Urewera Act, 2014; Te Awa Tupua, 2017). A Rights of Nature approach could be applied to the oceans (David, 2017; Harden-Davies et al., 2020) alongside the precautionary principle and sustainable development concepts. A legal instrument that grants rights to an ocean is years away from being formulated and implemented, but the concept behind it is one of holistic and coherent rather than fragmented protection. If applied to the deep sea in the ABNJ, a Rights of Nature framework would recognise the ocean as a rights-bearing subject, rather than an object to be owned, controlled and exploited (Borras, 2016).

DISCUSSION

The multifarious issues surrounding deep seabed mining have no doubt contributed to the many different opinions between – and within – groups of stakeholders that include scientists, industry contractors, civil society, governments, investors and regulators. Reconciling the perspectives of such diverse groups will be extremely challenging and some may be unhappy with the outcome. What is certain, however, is that to prevent biodiversity loss and minimise stressors that impede marine ecosystem functioning and the ecosystem services that benefit humanity, ocean protection must be prioritised. Doubts that UN SDG14 may not be met fully by 2030 are of great concern – one estimate is that US$174.52 billion per year will be needed to be spent on, for example, conservation and research to achieve this one goal (Johansen and Vestvik, 2020).

But the future contains hope. Proposals from within the academic community to enhance regulations and protection measures are encouraging and include: establishing a coherent deep ocean observation system (Levin et al., 2019, 2020a; Jones et al., 2020); evaluating the part played by the ISA in regulatory actions and enforcing EIAs (Clark et al., 2020; Jones et al., 2020; Levin et al., 2020a); establishing legally binding MPA networks in the ABNJ (O'Leary et al., 2020); and questioning whether corporations are meeting human rights obligations under UNCLOS (Bernaz and Pietropaoli, 2020). A United Nations Intergovernmental Conference is negotiating an international legally binding instrument under UNCLOS on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (United Nations, 2017) which is expected to provide *inter alia* a mechanism for establishing a representative network of MPAs in the ABNJ.

In its Pathways to the 2050 Vision for Biodiversity, The Convention of Biological Diversity sets out Eight Transitions to Living in Harmony with Nature, including the target that, "by 2050, biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people" (Secretariat of the Convention on Biological Diversity, 2020).

We have an opportunity to refocus our approach towards nature. A true transition from ownership to guardianship of the natural world could include a Rights of Nature approach to the ocean, rather than only considering the benefits that it may deliver to a small percentage of the global population. As currently projected, any profits from deep-sea mining will predominantly benefit a handful of corporations in the world's richest countries, rather than less well-developed States.

SDG 12 aims to ensure sustainable consumption and production patterns, which is essential if the world is to achieve the other UN SDGs (Bengtsson, 2018). In the context of deep-sea mining, we suggest as a practical first step a conversation between all stakeholders to assess future demand for minerals required to transition to a low-carbon economy. A full appreciation of the many uncertainties and indeterminacies attached to projected demand for relevant metals could help to inform conversations between stakeholders. Realigning and refocusing research on product design to enhance the sustainability and lifespan of future technologies may enable a richer suite of options in the future. Policy mechanisms, such as those related to urban design in the sphere of public transport (including vehicle sharing), together with incentives to promote consumer awareness and behaviour change will be important to achieve a sustainable transition.

Once started, deep-sea mining is likely to be impossible to stop. Once lost, biodiversity will be impossible to restore. In writing this Perspective we have outlined the need to avoid mining the deep sea to prevent biodiversity loss and associated ecosystem services. Our case study focuses specifically on uncertainties related to future EV battery technologies and transport infrastructure and challenges the perceived demand for deep sea minerals. More broadly, however, recognising and adopting a Rights of Nature approach could help ensure a thriving natural world for generations and a more sustainable future for humanity in protecting those rights. The ongoing COVID-19 pandemic has highlighted how declining ecosystem integrity has contributed to human health and economic risk on a global scale. The pandemic may also have contributed to a reassessment of social values, promoting an awareness and willingness to fundamentally change behaviour towards the protection of natural systems. We have an opportunity to refocus our approach to managing and living sustainably within natural ecosystems and by replacing a sense of ownership and dominance to one of harmony and belonging.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

KT and KM conceived the perspective. KM, KT, KB, and DS wrote the manuscript. DS, PJ, and DC critically reviewed the manuscript. All authors contributed to the article and approved the submitted version.

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Mopping Up or Turning Off the Tap? Environmental Injustice and the Ethics of Plastic Pollution

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THE PROBLEM WITH PLASTICS

Decades of scientific research confirm that plastic pollution poses a threat to many species, to water resources, and to economies around the world (Laist, 1997; Barnes et al., 2009; Gregory, 2009; Teuten et al., 2009; Chen, 2015; Newman et al., 2015; Rochman, 2015). Experts demonstrate that oceanic plastic pollution is increasing at astounding rates (Eriksen et al., 2014; Geyer et al., 2017). Research indicates harmful levels of toxicity in everyday plastic items (SCP/RAC, 2020). Scientists find this issue so important that they have recommended plastics be classified as a pollutant on par with hazardous waste (Mouat et al., 2010; Rochman et al., 2013) or that single use plastics should be banned (Telesetsky, 2019). For many years, experts have noted that increasing plastic manufacturing and use will worsen the condition in the marine environment (Carpenter and Smith, 1972; Azzarello and Van Vleet, 1987; Gregory, 2009) and yet the global plastic industry continues to increase production, cumulatively producing 368 million tons in 2019 (PlasticsEurope, 2020). If current growth trajectories continue, by 2050 plastic could account for 20% of global oil production (Giacovelli, 2018) and the world could have four times the amount of plastic waste that we generate today (Geyer et al., 2017). Plastic debris contributes to a comprehensive global environmental problem that –if current trends continue— will worsen significantly (Borrelle et al., 2020; Silva et al., 2020). The COVID-19 crisis only exacerbates the problem, as it has led to an increase in the use of single use plastics in the form of personal protection equipment, which researchers have already begun to see in the environment at high levels (Ammendolia et al., 2021; Mejjad et al., 2021).

The majority of the plastic pollution problem falls disproportionately on the global south, especially in south and southeast Asia (Jambeck et al., 2015; Lebreton et al., 2017), creating an issue of slow violence (Homer-Dixon, 2000) and environmental injustice. While plastic pollution is universal, some consequences such as clogged drainage systems, increases in vector-borne diseases, and reduction in tourism are particularly felt in poorer communities, where solid waste management systems are not in place (Barnett, 1997; Coe and Rogers, 1997; Liffmann and Boogaerts, 1997; Jambeck et al., 2015; The Ocean Conservancy, 2015; Lebreton et al., 2017; Giacovelli, 2018; Godfrey, 2019). Plastics may be exported from the developed world to the developing world for legal or illegal disposal (Blettler and Wantzen, 2019; McCormick et al., 2019). In poorer communities, plastics may be burned as fuel (heat or cooking) or in disposal (Giacovelli, 2018). Poorer communities may also be selected as sites for plastic manufacturing (Ramirez, 2021).

Responsibility for managing plastic waste often falls on the people and places least responsible for producing said waste (Conlon, 2020).

"MISMANAGED WASTE" IN THE GLOBAL SOUTH

Critically, the way we frame the story of plastic pollution has consequences for the proposed solutions. The framing of the plastic problem typically focuses on a handful of south and southeast Asian countries where the problems of waste are most visible (Lebreton et al., 2012, 2017; Jambeck et al., 2015; Schmidt et al., 2017). This is not surprising, as these countries often represent the nexus of high population, communities clustered near river and coastal areas, extreme poverty, and a lack of waste infrastructure. Such framing fails to recognize the way issues of privilege and justice influence the distribution of debris around the world. This framing ignores the complex relationships between the industries that sell plastics, the people who use them, and how waste is handled and exported globally (Heinrich Böll Foundation., 2019). Such framing does not hold manufacturers in the developed world accountable for marketing materials in the developing world that they know will be "mismanaged." It does not account for the economic factors that drive individuals to purchase goods, often wrapped in plastic, in small quantities. It also clouds the reality that people in all countries use single-use plastics and few are immune from contributing to this global problem.

It is true that waste infrastructure is limited or non-existent in many countries and that a lack of waste infrastructure contributes to debris accumulation (Kaza et al., 2018). Yet, when researchers frame the problem of plastic pollution as "mismanaged waste" it gives the impression that if developing countries can simply "manage" their waste, then the problem will be solved. In this way, plastic pollution may be less visible but is no less pervasive in western communities with adequate solid waste management. Most developed countries serve as models of waste infrastructure, and yet still suffer from, and are a source of, marine litter (Law et al., 2020). In these more affluent communities, plastics are collected and then incinerated or buried, dispersing their chemical loads into the air and soil (Yang et al., 2015; Aryan et al., 2019; Blettler and Wantzen, 2019). In fact, a great deal of debris accumulates in freshwater and ocean and coastal systems in developed countries each year (Moore et al., 2005; Williams et al., 2011; Rosevelt et al., 2013; Lee and Sanders, 2015; Baldwin et al., 2016; Cable et al., 2017; Hardesty et al., 2017; Castro-Jiménez et al., 2019). In this way, framing the problem as mismanaged waste leads to a "solution" of more waste management. While increasing waste management may lessen the impacts of the problem, it cannot solve it.

What does "management" of plastic waste look like? Current packaging material flows indicate linear paths wherein about 14% of plastic is incinerated; 40% is landfilled; and 32% leaks out into the environment as litter or debris (World Economic Forum, 2016). Of the 14% of plastic collected for recycling, only 2% has been recycled in a closed loop (a 1:1 ratio); 8% is down-cycled; and 4% is lost in the recycling process (World Economic Forum, 2016). After decades of recycling narratives, the dysfunction of recycling systems reveal plastic recycling was not *designed* to solve the plastic waste problem, but to be a distraction to continue production (Sullivan and Gonzales, 2020). The issue of design should not be underestimated. Without conscientious design, communities will necessarily continue to grapple with voluminous waste. In other management scenarios, when plastic waste is landfilled as a part of municipal solid waste, local government and taxpayers pay for the land on which waste will be placed and the long-term health costs as this waste slowly degrades over decades and centuries releasing ethylene and methane (Royer et al., 2018), as well as poisoning soils and groundwater. When burned, municipal solid waste yields "emissions to air and chemical waste residuals" (Dijkgraaf and Vollebergh, 2003:2), which are also costs borne by the local community. Some researchers believe waste to energy incineration models have low externality costs, when they include "state-of-the-art air pollution control technology" and when "pre-sorting minimizes the potential for air toxics release" (Miranda and Hale, 1997:599). Yet, a study by Dijkgraaf and Vollebergh (2003) found "much higher gross environmental cost for a [waste to energy] plant than for a modern landfill" even when considering the constraints of available land for this purpose. According to the World Economic Forum (2016), incineration infrastructure may lock out "higher-value mechanisms" like recycling, carry a risk of "negative health effects," and yield by-products that also must be "disposed of" (26). This report names three primary externalities associated with plastics and plastic packaging: "leakage, especially in the ocean; the greenhouse gas emissions … from production and after-use incineration; and health and environmental impacts from substances of concern" (World Economic Forum, 2016:28). As a long-term solution for the problem of plastic waste, managing the increasing waste through infrastructure is limited, and too often a case of distancing waste to areas and populations with less power to regulate it (Clapp, 2002). To illustrate how different approaches can emphasize up-stream or down-stream solutions, we share examples of two organizations seeking to address plastic pollution: the Alliance to End Plastic Waste and Common Seas.

THE ALLIANCE TO END PLASTIC WASTE

The Alliance to End Plastic Waste (AEPW) is a group of multi-national and international companies "working to make the dream of a world without plastic waste a reality" [(AEPW, 2019):1]. The organization's mission is to: "develop, accelerate, and deploy solutions; engage communities; catalyze investments" (AEPW, 2020:5). Their proposed outcomes are: "demonstrated and scaled plastic waste-free cities in priority regions; enabled local ownership of waste management; demonstrated investable models, and partnerships that unlock even more capital to end plastic waste" (AEPW, 2020: 5). Initially in 2019, the AEPW membership pledged 1.5 billion dollars over 5 years in an "effort to end plastic waste in the environment" (AEPW, 2019:1). A contribution of 1.5 billion dollars represents <2% of their annual net profits (Owens, 2019). Moreover, the 28 founding members of the AEPW are a part of plastics and related industries, including plastics packaging, petrochemicals, chemicals, fossil fuels (oil and gas), personal health/care products, and water- and waste-management. The *Plastic Waste Makers Index* (Charles et al., 2021) reveals that eight of the AEPW members fall within the top 100 plastics producers that account for 90% of plastic globally, including the top two producers[1]. While it is admirable that these industries recognize the problem their products cause, their stated goal to "make the dream of a world without plastic waste a reality" in some ways conflicts with their role in producing this waste.

The AEPW writes in their 2020 progress report, they will address plastic waste by:

- Developing and accelerating technologies;
- Partnering with the extended global community; and
- Catalyzing capital.

To guide their work, they propose to "think globally and act locally; to collaborate; to change behavior; to recover and extract value from waste plastic; and to shift from short-term actions to long-lasting waste management solutions that help communities and society achieve circular economies" (AEPW, 2020: 4). Finally, the report emphasizes their four strategies: "infrastructure, innovation, education and engagement, and cleanup" (AEPW, 2020: 5).

The progress report shares several case studies that on the surface sound effective. Yet, their framing of plastic waste challenges emphasizes the end user, not the producers of the plastics. Responsibility of plastics generation is deflected from the members of the AEPW and other producers. For instance, one, from "Project Stop" Jembrana in Indonesia, emphasizes "waste segregation at the household level" and recycling. The project description highlights "local responsibility" (AEPW, 2020: 10). Framing pollution as the responsibility of the end user rather than the manufacturer is not novel. This was also the case with the American "crying Indian" anti-litter campaign from the 1970s, funded by "bottled beverage and packaging industries" through the Ad Council, whose commercials "reinforce the propensity that readily exists in our society to reduce social problems to personal challenges" (Melillo, 2013). The print campaign included a charge to the public: *People start pollution. People can stop it.* while failing to recognize the interplay of design, manufacturing, use, and options for disposal. Campaigns that shift responsibility directly conflict with the concept that polluters should be responsible for the end of life of the products they manufacture and sell (i.e., a Producers Pay Principle or Polluters Pay Principle).

The report also details the Plug and Play accelerator project created "to foster start-ups that can impact the plastic value chain" (AEPW, 2020:11). Small teams work for 12 weeks to co-develop innovations with expert advice from Alliance members. The 10 solutions described in the report include using robots to more cheaply sort recycling; using biotech to "convert[] under-used carbon into high-value industrial products;" creating materials of 100% plastic waste; using crowdsourcing to enable citizens to clean the planet; envisioning "recycling the unrecyclable;" better technology to enable curbside recycling of plastic film; using AI and robotics to sort trash from recyclables in bins; "connecting recycled plastics with trusted suppliers from around the world;" creating roof "cover boards" from plastic and paper that would otherwise enter landfills; and recycling plastics into "environmentally friendly fuels" (AEPW, 2020: 13). These are overwhelmingly end-of-pipe clean-up solutions that do not address upstream production. The report shares information on two other Indonesian projects, which are briefly described as converting "plastic waste into a petrochemical feedstock" (AEPW, 2020: 15). Continuing, in collaboration with the Grameen Creative Lab, the Alliance is developing additional projects in Puducherry, India and Tan An, Vietnam that emphasize recycling (AEPW, 2020). The ASASE Foundation project in Accra Ghana trains women to collect and recycle waste (AEPW, 2020). In another collaboration, the Aviral Project seeks to engage the local community in "recovery and recycling" to protect religiously important sites along the Ganga river and to reduce waste from religious festivals (AEPW, 2020:19). AEPW describes the Renew Oceans project in Varanasi, Indian as "the engagement of the area's student population to develop waste management concepts that cover three areas: plastic waste collection, plastic waste conversion and community education" (AEPW, 2020:22). However, as of 2021 the project has been halted, as "the organization has come to the conclusion that it simply does not have the capacity to work at the scale this problem deserves" (Brock et al., 2021: 1).

Collaborating with The Incubation Network in south and southeast Asia has yielded four projects: the Ocean Plastic Prevention Accelerator (OPPA), which focuses on waste management and recycling in Surabaya, Indonesia; the Circular Innovation Jam which asks local communities to "design solutions to advance circular economies" in India, Indonesia, Thailand, the Philippines and Vietnam; the Surabaya Access Pad, which innovates, "plastic pollution prevention products" in Indonesia; and the Plastics Data Challenge which seeks to collect data on "plastic leakage" in south and southeast Asia (AEPW, 2020:23). Of the 21 projects or innovations described in the report, 16 emphasize recycling; one citizen cleanups; one data collection; and for three projects, it is unclear what mechanism they will use to reduce plastic waste (Circular Innovation Jam, Surabaya Access Pad, Kiverdi). Overall, the report mentions reducing plastic leakage, but not reducing plastic production, considering the relative value of different kinds of plastic usage, or the exploration of reasonable alternatives to single use plastics.

It should also be noted that the AEPW, 2020 report mentions "front end design" to "boost recycling rates, support[] materials innovation, and contribute[] to reduction and reuse (AEPW, 2020: 6). In addition, it states the Alliance is "working toward a circular economy, where all people thrive" (AEPW, 2020: 2) and yet most of the projects described in the report focus on end-of-pipe solutions. While their report does not provide the full context necessary to deeply evaluate the work of the Alliance, we find it important to note that on the whole, these projects

[1] AEPW members on the Plastic Wastemakers Index: Exxon (1st), Dow (2nd), Lyondell Basell (7th); Braskem (9th); Mitsubishi Chemical (31st); Sasol (38th); Mitsui Chemicals (37th) and Shell (51st) (Charles et al., 2021). The top 20 producers account for 50% of global plastic waste; and the top 100 account for 90% (ibid.).

and initiatives focus on the symptoms of plastic pollution, not the sources. These kinds of projects may be a part of a long-term comprehensive sustainable plan to reduce global plastic waste and likely provide important opportunities to local NGOs. That said, the AEPW framing ignores the resources that must be used to remake plastics in one form into another, the pollution caused by doing so, and the abysmal rate of global recycling. In summary, the AEPW envisions a future where they continue to produce plastic but address the problem by creating technology that better deals with waste, not its generation. A more comprehensive program to eliminate plastic waste would emphasize front end design rather than pay lip service to circular economy approaches.

COMMON SEAS: PLASTIC DRAWDOWN

Common Seas is a non-profit based in the UK founded by Jo Royle with some portion of major funding coming from the Lemos family's Avra foundation. In comparison to the Alliance to End Plastic Waste, we analyze the Common Seas' Plastic Drawdown toolkit which more heavily emphasizes the sources rather than the symptoms of plastic waste. Common Seas is "a social enterprise tackling the plastic pollution crisis by driving new policy, investing in the circular economy and catalyzing a cultural shift in how we make, use and dispose of plastic" (Common Seas, 2020a).

The organization promotes a country-level analysis, a sharp decline in single use plastics, and collaborative decision making by stakeholders to "turn off the tap." Their four-phase approach:

- "Models a country's plastic waste mass and composition including future projections to 2030
- Map[s] the waste pathways and leakages,
- Analyzes the impact of key policies, and
- Enable[es] governments to convene key actors and chart a policy pathway toward dramatically reduced ocean plastics" (Common Seas, 2019:3).

Drawdown uses a wedge approach akin to that described by Pacala and Socolow (2004) to combat climate change. Through this approach it seeks to address the *sources* of plastic waste and leakage. At times, it also uses technological advances, but importantly, moves beyond downstream collection and recycling, instead working collaboratively with communities to develop a pragmatic plan. The 18 potential policy interventions proposed by Common Seas include:

1. Banning some plastics,
2. Taxing to discourage use,
3. Deposit return schemes for beverage containers,
4. Improving access to clean potable water,
5. Water refill schemes,
6. Improving regulation on and handling of plastic pellets,
7. Improved standards and labeling for textiles to reduce microfiber pollution,
8. Better regulation and labeling of tires,
9. Deposit schemes and extended producer reliability concerning fishing gear,
10. Zoning controls in fishing areas
11. Developing waste management collection potentially coupled with a "bring back" scheme that holds producers responsible for the end products they manufacture and sell
12. Better standards for storing and managing waste
13. Creating street-level waste collection to prevent littering
14. Creating systems to deter or penalize littering and unlawful dumping
15. Improving wastewater treatment infrastructure to filter water of plastics
16. Developing sewage and stormwater treatment
17. Tagging fishing gear to prevent illegal abandonment, and
18. Instituting flat rates for port-based waste disposal (Common Seas, 2020b).

Rather than emphasizing downstream options, Common Seas' policy framework includes reduction (2), re-use (1), holding producers accountable (4), addressing underlying problems like clean water access, sewage and water treatment (4), better waste management (4), and measures to reduce waste in the fishing and port industries (3).

Our analysis recognizes that publicly available documents may present an incomplete picture of the work of either of these organizations. It is important to note there are some similarities in the approaches taken by the Alliance to End Plastic Waste and Common Seas. Common Seas also take part in some monitoring and measurement of the plastic problem, while the Alliance to End Plastic Waste also works with local communities and co-creates actions. This is also not meant to condemn the work of the Alliance –which can be a part of a comprehensive effort to reduce plastic pollution— but instead to inform it to better address plastic pollution at the source.

AN ISSUE OF JUSTICE

Sze and London (2008) define environmental racism as the "unequal distribution of environmental benefits and pollution burdens based on race" while they describe environmental inequality as a broader term that includes, "class, gender, immigration status," and the interactions of these factors as a source of disproportionate environmental impacts (1332-1333). Scenarios of environmental injustice often include disadvantaged—whether by class, income, status, or race—communities experiencing higher pollution levels, while not being responsible for high production of said pollution (Pearce et al., 2006). Global environmental justice is not new (Pellow and Brulle, 2005). Pellow and Brulle noted in 2005 that we can expect further environmental injustice from a North-South perspective as, "global North nations continue dumping waste in both domestic and global "pollution havens" where the cost of doing business is much cheaper, regulation is virtually non-existent, and residents do not hold much formal political power" (11).

Bullard (1996) positions environmental injustice as "(1) unequal enforcement of environmental, civil rights, and public health laws, (2) differential exposure of some populations to harmful chemicals…in the home, school, neighborhood, and workplace (3) faulty assumptions in calculating and assessing risks, (4) discriminatory zoning and land-use practices, and (5) exclusionary policies and practices that limit some individuals and groups from participation in decision making" (493). The waste burden of plastics on the global south takes on all of these characteristics. In addition, plastic pollution takes on the characteristics of "slow violence" which is the "slow erosion[] of environmental justice" (Nixon, 2011: 8), and the slow onslaught of the social and ecological impacts wrought by plastic waste and plastic pollution. Moreover, the concept of "adaptive injustice" is also applicable to the global plastic environmental justice crisis, where those who have to adapt to increasing plastic waste streams are not the ones responsible for generating the waste (Conlon, 2020).

Experts weigh in on what they believe will be the best approach to the plastic pollution problem. While the Basel Convention (which deals with hazardous and toxic waste), the Stockholm Convention (which deals with Persistent Organic Pollutants or POPs) and the Rotterdam Convention (which focuses on hazardous materials and pesticides) may provide a framework for hazardous waste imports and exports, none were created in response to global plastic pollution reduction (Basel Convention, 2021; Rotterdam Convention, 2021; Stockholm Convention, 2021). The Basel Convention on waste, which added plastic waste amendments in 2019, does not include many common plastics (e.g., polyethylene, polypropelene, and polyethelene terephthalate) if "destined for recycling in an environmentally sound manner" (Basel Convention, 2019). As the implementation of the amendments began in January of 2021, it is still unknown how enforcement might proceed or how effective the Convention may be in reducing the impact of plastic waste. The World Economic Forum (2016) recommend a "systemic approach" …that moves… "beyond incremental improvements" (3). Haward (2018) calls for an international agreement on par with the Montreal Protocol. Worm et al. (2017) propose "a Global Convention on Plastic Pollution that incentivizes collaboration between governments, producers, scientists, and citizens" (1). Dauvergne (2018) notes that plastics governance, which "reflects industry efforts to resist government regulation, deflect accountability, and thwart critics," fails to "rein in marine plastic pollution" (22). The author recommends "hard hitting domestic regulation" coupled with an international plastics treaty (Dauvergne, 2018: 22). In their 2021 report, the United Nations Environmental Program emphasizes the inherent problem of single use materials, making the distinction that the problem is more about single-use than plastic itself (United Nations Environment Programme, 2021). Their recommendation is for a "systemic transformation of the plastics economy" through a "comprehensive policy response" including designing all products for multiple use, no matter the material, taking local conditions into account, and "addressing the needs" of affected sectors (United Nations Environment Programme, 2021:4). In a collaborative report from the Ellen MacArthur Foundation and United Nations Environment Programme (2020) they strongly prioritize "elimination of problematic or unnecessary plastic packaging through redesign, innovation, and new delivery models" (19).

Watterson and Dinan (2020) in their piece describing the lag of policy behind science in regulating air pollution in England, warn that the dominance of fossil fuel industries in policymaking is detrimental to "ethical and environmental justice decision making with significant consequences for public health (1). The same could be said of plastics regulation. Examples from cigarette manufacturers and petrochemical companies indicate that rather than incorporating scientific data, businesses may take on a strategy to actively thwart accountability (Michaels, 2005; Michaels and Monforton, 2005; Cook et al., 2019).

To combat environmental injustice, Bullard (1994) shares a framework of environmental justice, which includes:

- **The right to protection** for all people from environmental degradation conceived as a civil right
- **Prevention,** or "the elimination of the threat before harm occurs" (17).
- **Shifting the burden of proof** "to the polluters who do harm, discriminate, or do not give equal protection to minorities and other overburdened classes" (39).
- **Obviating proof of intent**, allowing instead for "disparate impact and statistical weight… to infer discrimination" (40).
- **Redressing inequities** from the impacts of pollution, through "targeting action and resources… where environmental and health problems are greatest" (41-42).

Overwhelmingly, the AEPW proposals to date emphasize 'better management' through recycling, and frame responsibility around end users in the global south; while the Common Seas approach de-emphasizes recycling and encourages reduction, re-use, and better regulation that holds producers responsible on a global scale. It also addresses some of the problems that make single use plastics a necessity at times, such as lack of access to clean water. The recommendation for an environmentally just response emphasizes that it is the onus of the upstream producers to prevent harm caused by environmental pollutants, not the downstream work of the civic sector and local governments impacted by the pollution.

CONCLUSION

If you walked into your bathroom to find your tub overflowing with water, would you first begin mopping up the water on the ground, or would you turn off the tap? When manufacturers promote solutions that address the symptoms of plastic pollution but not the source, they leave the tub overflowing while ineffectively mopping up the resulting water. Plastic waste as it is currently understood by industry is an externality that demands a technological solution. Most plastics (over 90%) originate from virgin fossil fuel stock and most are not recycled (World Economic Forum, 2016). When the problem of plastic waste is ignored, the costs are pushed to marginalized communities around the world, to future generations, citizens, governments, and taxpayers. In some cases, distribution companies take the lead in reducing plastic packaging when manufacturers and governments fail, as can be seen in initiatives taken by the supermarkets Sainsbury, Aldi, Co-Op, and Trader Joe's (Chhabra, 2019; Goncalves, 2021). For decades, peer-reviewed scientific literature has decried the threats to wildlife; the degradation of ecosystems; the instances of entanglement and ingestion; the accumulation of debris in the gyres and coastal areas; the costs to industries as varied as shipping, tourism, and agriculture; as well as the immense cost to global society to clean up beaches, waterways, and the open ocean. Waste management cannot operate in a vacuum oblivious to the social and environmental harms it causes. Not all plastics are equally useful and many single-use plastics have less environmentally harmful but comparable substitutions available. Some plastics are inexpensive and useful: they can also support important goals in the global south. That said, framing the problem of plastic waste as that of end users, particularly those in developing countries, fails to recognize the complex nature of global plastic markets. Rather than leave the problem-solving to the problem-creators, scientists, policymakers, and governments are advised to frame plastic waste narratives like that of Common Seas: with an emphasis on reduction, redesign, re-use, and collaborative decision-making for plastic reduction rather than downstream management.

AUTHOR'S NOTE

Neither of the authors is affiliated with the Alliance to End Plastic Waste or Common Seas in any way.

AUTHOR CONTRIBUTIONS

KO and KC contributed equally to the conceptualization, the writing, and the editing of this manuscript. All authors contributed to the article and approved the submitted version.

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Coastal Adaptation and Uncertainties: The Need of Ethics for a Shared Coastal Future

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Coastal hydro-morphodynamics present significant uncertainties, one order of magnitude larger for sediment transport than for the driving hydrodynamics. Met-ocean factors (waves, currents, and levels essentially) are normally selected from a probability distribution, where only the central trend is considered, and then the analysis of hydro-morphodynamic processes is carried out within a deterministic framework. This analysis is often based on a non-updated topo-bathymetry, with implicit error intervals for many variables, which results in uncertainties that, unless presented from an ethical perspective, tend to hinder proactive decision making and thus result in growing coastal degradation. To address this challenge, the article starts with the uncertainty in water/sediment fluxes and resulting morphodynamic impacts under average and storm conditions, proving the need to include explicit error levels in the analysis and subsequent assessments. The article develops this approach for field and lab data, considering how they are extrapolated to estimate key variables in coastal sustainability and engineering decisions, illustrated in terms of the longshore sand transport. Such a key variable estimation presents large uncertainties and thus requires a stricter ethical approach for extreme events, which serves to illustrate the transmission of uncertainties. The article concludes with a short overview of the implications that these uncertainties may have for coastal risk assessments and proactive decision making, discussing how large error levels without a suitable ethical assessment may result in socio-economic mistrust, which will limit the necessary optimism to address future coastal sustainability.

Keywords: coastal, adaptation, uncertainty, data, morphodynamics, risk, ethics, optimism

INTRODUCTION

Coastal conflicts, aggravated by increasing anthropogenic and climate change pressures, require an ethical assessment of coastal impacts that enable a delineation of coastal pathways, including reference and target states (Davos, 1998; Knowlton, 2021). Only from such a basis, with explicit and ethically estimated uncertainties, it is possible to develop adaptation pathways (Haasnoot et al., 2013) based on consensus aims, tipping points and the means to circumvent them. Such a development must involve scientists, stakeholders and users, within a motivated engagement where ethics and optimism define a fabric that supports a shared coastal sustainability drive.

The present dystopian situation differs from such an idyllic landscape due to: (a) large and often implicit uncertainties that allow biased decisions, often against a sustainable coastal future; (b) corrupted analyses linked to limited ethics and diverging interests that lead to aggravated conflicts; (c) unmotivated stakeholder cooperation due to social inertia or contradictory expert opinions; (d) reactive compromises because of personal interests or perceived threats, which result in inefficient adaptation; and (e) lack of decision making, due to overwhelming uncertainties and pervasive pessimism that result in inactiveness.

All these hurdles, however, should not hinder the holistic transformation, including an ethical dimension, that is required for sustaining present coastal systems, hosting an inordinate proportion of population and a significant concentration of socio-economic assets (Neumann et al., 2015). The scientific world should support this transformation by: (a) bounding and making explicit the inherent uncertainties with larger data sets and improved knowledge; (b) increasing social and economic confidence on observational and numerical results, based on cross-disciplinary analysis impelled by balanced ethics; (c) proactive decisions linked to available forecast and projection products (e.g., Garcia Sotillo et al., 2020) that apply and share such anticipated information; and (d) cooperative commitment based on stakeholder optimism and trust on the co-designed interventions and criteria.

Following such rationale this article will start from an analysis of coastal adaptation pathways and the decisions required for a sustainable conservation (section "Coastal Adaptation Pathways: Decisions for a Sustainable Conservation"), followed by the probabilistic characterization of metocean drivers (section "Field Data and Statistical Processing: Uncertainty in Diagnosis") to prove the importance of making the uncertainties explicit to build trust and promote fair decisions. The inevitable error intervals in lab/field data are examined next (section "Lab Data and Error Intervals: Morphodynamic and Engineering Consequences"), showing how they may condition coastal engineering calculations and interventions, illustrating the need for ethical approaches that avoid biased expert opinions that, in turn, may lead to a loss of socio-economic confidence on coastal interventions. After considering the difficulties in valuation and how that may result in fuzziness for impact and risk assessments (section "Coastal Risk Assessments: Hazard and Vulnerability Estimations"), the article ends with some discussion and recommendations (section "Shared Coastal Futures: Ethics and Optimism") on the need for combined ethics and optimism as a basis for increasing stakeholder cooperation to sustain coastal systems.

COASTAL ADAPTATION PATHWAYS: DECISIONS FOR A SUSTAINABLE CONSERVATION

Adaptation pathways (Armitage et al., 2008; Plummer, 2009; Haasnoot et al., 2013) consist in a structured set of interventions with deadlines and tipping points that, when applied to dynamic coastal systems, should make use of the windows of opportunity offered by socio-economic crises, storm events or accelerating climatic change. Such coastal pathways must consider the possible chronicity of these factors, introducing unbiased and dynamic tipping points that are ethically defined with their uncertainties to promote a cross sectoral cooperation that covers the entire polity. This sustained cooperation, based on objective knowledge and multifarious benefits across scales and social groups, should apply the wealth of data (in situ and remote) and knowledge now available (Sánchez-Arcilla et al., 2021) as well as the recent advances in lab and numerical tools (e.g., Kim et al., 2020) to steer adaptation pathways, co-developed by all relevant stakeholders. Such cooperation should contribute to overcome the lack of connectivity in present coastal systems, with barriers to biophysical fluxes, socio-economic activities and even perception by different actors, resulting in disconnected coastal realities (Nicolodi et al., 2021) that favor inactivity and ethical conflicts.

Building consensus for coastal adaptation, supported by ethically impregnated assessments, will facilitate the combination of short term "urgencies" with long-term planning, often related to climatic/anthropic pressures. Such combination will avoid disruptions in adaptation pathways associated to volatile and ephemeral interests, compounded by limited individual and collective ethics. These disruptions preclude stability for investments that ensure a legacy of the present coastal natural capital, compounded by the mismatch between natural dynamics and cultural speed, where slower benefits such as, for instance, from ecosystem services (Giakoumi et al., 2018), tend to be disregarded or despised. The new advances in data/models, permeated by an ethical dimension, should help to reconcile short-term views and benefits with the interest of future generations, facilitating the quest of new coastal paradigms, associated to a transformation of governance, finance and techniques that contribute to knit a social-ecological fabric that supports ethical decisions and optimistic engagement. By reconciling individual and collective interests within adaptation pathways it should be feasible to co-define tipping points and alarm criteria, favoring coastal sustainability and breaking the present trend toward degradation. An aggregation of cost-benefit utilitarian criteria with longer term benefits, less prone to monetary quantification, requires an ethical-based value system that underpins a transition in policy and governance to achieve sustainability within tipping points. This aggregation will overcome the purely quantitative assessment of cost-effectiveness that may obfuscate value conflicts, particularly at longer time scales, empowering scientists, decision-making authorities, and power elites to reach cooperative agreements rather than to impose an unfair balance from contentious negotiations to reach any "best" coastal status selected by the most powerful players.

The relationship between information and decision/power should be bounded by: (a) shared ethical values; (b) explicit uncertainties and error intervals; (c) clear distinction between true and false discourses. Such an approach requires a transformation on how information is generated, disseminated and even controlled, since that information shapes perceptions and the capacity to decide by diverse socio-economic groups. The application of an ethical approach to establish uncertainty levels and apply formulations to define a knowledge-based discourse is presented in next sections, illustrating how this approach can promote a balanced perception that combines hard facts with opinions, overcoming the present trend to overweight opinion with respect to facts. For interdisciplinary systems like coastal zones, the merging of social and ecological sciences should build upon knowledge-based ethics, to enable a transition from segmented management and rigid engineering to a holistic approach that links sustainability to social responsibility, particularly for the irreplaceable natural capital. By combining the rational and intuitive dimensions in coastal analyses, merging historic criteria with present big-data analysis (e.g., applied to regional high resolution forecasts or satellite data) it should be feasible to reach an informed consensus on what is best for coastal zones, avoiding futile contentious negotiations that seldom contribute to long term sustainability. Such a consensus must acknowledge that coastal sustainability is neither cheap nor immediate and affected by significant uncertainties, associated to the multiple scales that coexist in coastal processes and the wide fan of "partial" models for these processes (Thieler et al., 2000; Cooper and Pilkey, 2004, 2007; McLaughlin and Cooper, 2010). Such uncertainties tend to hinder stakeholder engagement (Dean et al., 2018; Dawson et al., 2020), limiting the capacity to tackle sustainability challenges, which are growing steadily by increasing anthropic (e.g., coastal population density) and climatic pressures (e.g., sea level rise) together with other emergent threats, in particular, those of anthropic origin. These threats must include less conspicuous pollutants (e.g., toxins, microplastics, viruses. . .), often forgotten interactions (e.g., with submerged aquifer, seabed contaminated sediments. . .) and the synergies between anthropic and climatic pressures (e.g., sea water temperature increases that increases the impact of high nutrient levels) (De los Santos et al., 2019).

Coastal adaptation pathways under climate change, illustrated in **Figure 1** for a typical Mediterranean coastal stretch, will become more sustainable when building upon the natural capacity of coastal systems to repair themselves (Sánchez-Arcilla et al., 2016), introducing jump-start interventions to enhance recovery if getting dangerously close to tipping points. These interventions should address the problem root (e.g., sediment starvation, and coastal rigidization, etc.) to transform degraded coastal areas into high quality habitats (Possingham et al., 2015), and here ethical criteria must be applied when estimating the always hard to quantify natural resilience capacity. Ethical criteria suggest the need, as illustrated by the examples presented in following sections, of new coastal approaches that bound uncertainty in drivers/responses and that associate predictions and valuations with explicit error intervals. Only from bounded uncertainty, underpinned by an ethical assessment, it will be possible to generate proactive decisions for tough coastal challenges that affect long term values. And these proactive decisions are key to anticipate climatic impacts, but require a baseline of optimism to launch mid to long term plans and investments, especially in situations of economic crises where present needs may underestimate the importance of longer term assets. A typical example is that of coastal protected spaces, following the road of marine protected areas and national parks on land, which provide mid to long term benefits, such as biodiversity, that are not easy to monetise but which are essential to achieve healthy and resilient coasts. Such coastal protected areas will provide room for coastal dynamics and habitats for coastal ecosystems, helping to reconnect the natural coastal capital (represented by its biodiversity and ecosystem services) with littoral socio-economic assets, key for the welfare of coastal populations.

To reduce uncertainty and promote uptake, coastal adaptation pathways should build on the best available scientific knowledge (e.g., Hilborn et al., 2020), supported by data and simulations that enable applying objective metrics to assess ecosystem services and coastal risk levels. These metrics can help steering the selection and deployment of coastal interventions, combining objective measures with subjective criteria that require an ethical framework to aggregate scales (e.g., storm scale with climatic or decadal variations) and define tipping points and the consensus "target" coastal status. The sequenced set of interventions contained in adaptation pathways should be implemented in spite of underlying uncertainties, distinguishing between success and failure based on consensus, predictions, and past experience. A proactive approach, based on ethical assessments, will result in enhanced resilience when compared to do-nothing options, enabling an explicit balance between tradeoffs (e.g., benefits for some coastal areas at the expense of other more degraded stretches) and the inclusion of long term sustainability aims (e.g., coastal legacy for next generations). Such a proactive approach can only be achieved from an ethical basis and a state of "essential" optimism, which should be supported by an informed comparison of where our coast would be if nothing had been done. The balance between positive and negative messages should be, therefore, carefully considered because negative information (e.g., Ledgerwood and Boydstun, 2014), compounded by uncertainty may preclude action and lead coastal zones to a status of irreversible degradation (**Figure 2**). The trend toward degradation, simply illustrated in the figure by "available" beach width as a measure of the protection, leisure and ecological functions the beach, can be alleviated by proactive decisions that apply Nature Based Solutions (NBS). Such a negative beach trend, however, will continue under reactive decisions, at different rates depending on the type of interventions: Business as Usual (BAU) is normally associated to small scale interventions, less effective than conventional engineering. These latter interventions may produce important oscillations in the beach response due to their limited synergy with natural coastal dynamics.

Coastal systems feature a multifarious set of natural and socio-economic assets that are at risk under present meteo-oceanographic conditions and will be increasingly threatened by climate change. Coastal natural capital stock (ecosystem structure and processes) and its evolution under climatic/anthropic stressors will be modulated by initial characteristics and the level of acting pressures (Potts et al., 2014), which together determine coastal trajectories (**Figure 2**) and impacts, that should be evaluated from an ethical basis to aggregate hard to quantify assets that require specific combinations of monetary and non-monetary metrics. The ethical dimension should build upon explicit error intervals and a consensus balance among diverging interests or a complete monetization of ecosystem services, aggregating short term values (e.g., from a severe

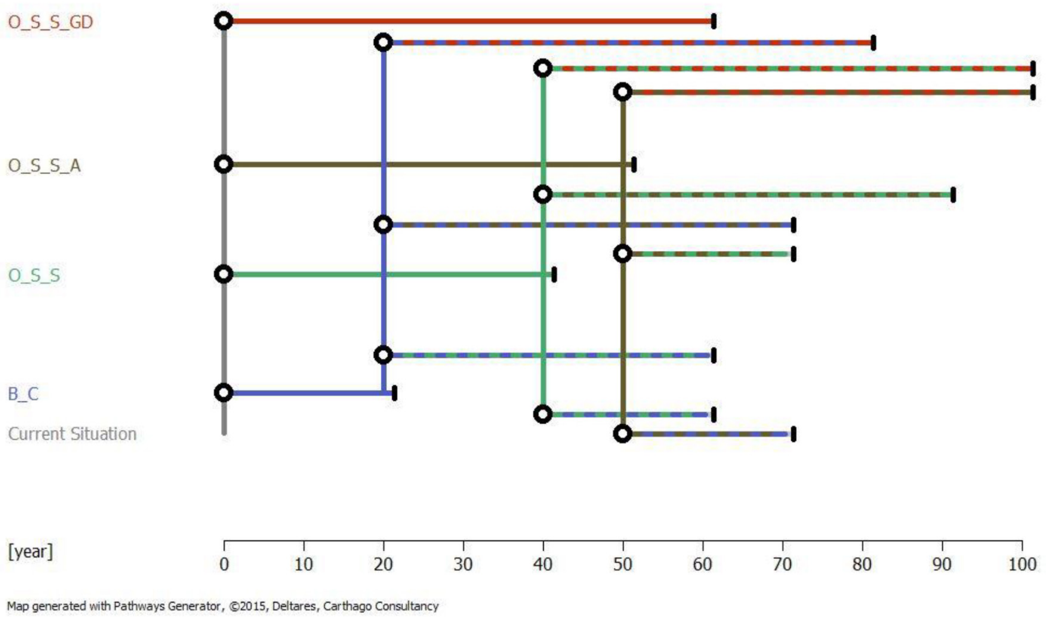

FIGURE 1 | Illustration of coastal adaptation pathways for a Mediterranean barrier beach subject to subsidence, because it is located in a deltaic system, and erosion due to longshore transport gradients in the sea (outer) side. This barrier beach has a limited natural sediment supply and experiences rotation due to frequent overwash and breaking processes, making the delineation of adaptation pathways extremely dynamic and complex. The selected pathways are: (B_C) Maintaining Breaching and Connectivity with a tipping point 20 years from now for an intermediate scenario, between RCP 2.6 and RCP 8.5; (O_S_S) Occasional Sand Supply for an intermediate scenario, with a tipping point 40 years from now; (O_S_S_A) Occasional Sand Supply and Sand Groins for the same intermediate scenario and with a tipping point 50 years from now; (O_S_S_GD) Occasional Sand Supply with Geo-Diversity for the same intermediate scenario and a tipping point 50 years from now. The circles denote change of pathway, moving to another type of approach/interventions. The vertical lines denote tipping points.

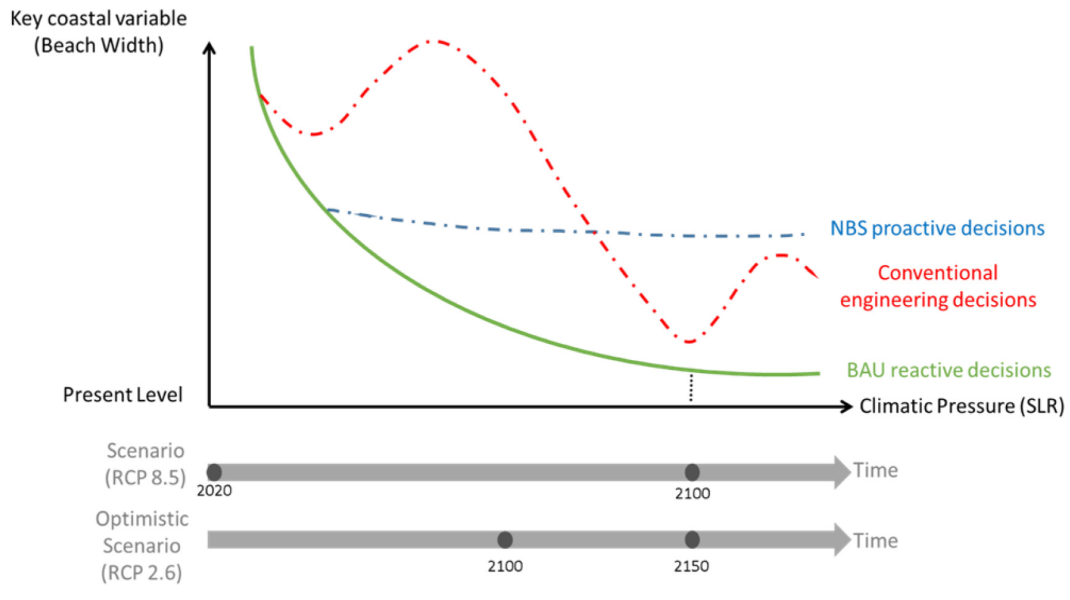

FIGURE 2 | Schematization of coastal trajectories against time and sea level rise (SLR), defined by some key variable (beach width in this case) and illustrating the effect of proactive versus reactive decisions. Beach width is a key variable to assess the three main functions of a beach: Protection, where the capacity to dissipate incoming wave energy depends critically on width; Economic support, where the emerged beach area is proportional to tourism and directly related socio-economic activities; and Ecological support, also depending on the width/height of the beach. The various types of possible interventions considered for the trajectories are: Business as usual, BAU reactive decisions (green line); Conventional engineering decisions, in a mixed reactive/proactive approach (red line); Nature Based Solutions, NBS, proactive decisions (blue line).

storm impact) with long-term criteria (e.g., maintenance of coastal defenses or biodiversity status). Only from an ethical perspective it will become credible to carry out a scale-dependent evaluation, comparing short to long term dynamics or small scale benefits versus larger scale interventions, better suited to the full development of ecosystem services. Such a balanced approach, within an ethical framework and with co-designed criteria, is the only meaningful way to assess costs/impacts for traditional versus nature-based interventions, recognizing that natural solutions may present some short term apparent losses (e.g., breaching existing defenses) but can provide mid to long term benefits impossible to achieve by conventional engineering (e.g., decarbonizing coastal protection). These multi-scale (in time and space) assessments should balance ethics with available knowledge and uncertainty levels (e.g., Helton-Fauth et al., 2003), considering their effect on engagement/perception and promoting shared benefits that are transferred to next generations. Such intergenerational and cross-sectoral transfer of benefits suppose an ethical "contract" that can be breached (Mumford et al., 2007) by excessive competition or deficiently designed coastal interventions, usually linked to an overvaluation of short term benefits or bias toward specific interests. The ethical approach will foster a transition from self-interest and company profit to common interest and social responsibility, avoiding an overconsumption of natural resources (e.g., coastal squeezing) that is likely to get aggravated under future conditions. Such aggravation will favor more frequent breaches of the ethical "contract," that should be explicitly incorporated into coastal science and technologies to reconcile natural capital with socio-economic assets and to introduce long-term values in present coastal decisions. By building an ethical contract among generations and power actors, it will be possible to jointly promote coastal sustainability and avoid the common maladaptation practices now observed, introducing uncertainty in data/models and limits of evaluations/simulations to enhance the shared responsibility for sustaining our coastal system.

FIELD DATA AND STATISTICAL PROCESSING: UNCERTAINTY IN DIAGNOSIS

Coastal analyses, necessary for adaptation decisions and for the design/selection of interventions, require field data to characterize drivers and responses. This characterization should have enough coverage in time/space to enable a robust assessment at the scales considered in the analysis, which may go from a storm event (scale of days) to climatic impacts (scale of decades). The most apparent impacts occur under impulsive storms, particularly extreme ones that find coastal systems out of equilibrium with incoming waves. Here, the scarcity of data introduces larger uncertainties which, unless handled with advanced statistical tools and an ethical basis, may lead to contradictory expert opinion on the storm features. This can be illustrated by the storm Gloria (Pérez et al., 2021) that impacted Western Mediterranean coasts in January 2020 and which some experts characterized as exceptional, while others postulated more balanced opinions, leading to contradictory interpretations, lack of socio-economic confidence on technical assessments and suggestions of poor ethics. Storm Gloria produced the highest ever recorded significant wave height in the Spanish coast, reaching 8.44 m in the deep-water Valencia buoy (Puertos del Estado network) on January 20th at 06 UTC (with an estimation of 13.5 m for the maximum wave height). The previous record for the significant wave height in the same buoy was 6.45 m and the maximum significant wave height previously recorded along Spanish coasts was 8.15 m, measured at the Mahón buoy in January 2003. Storm Gloria set a historical maximum individual wave height of 14.2 m recorded at Dragonera buoy (Balearic Islands) on January 20th at 02 UTC.

Storm Gloria can be analyzed in terms of an extreme wave height distribution, derived by best fitting of an extreme function to the XIOM (Bolaños et al., 2009) data series, providing one of the longest wave data sets along the Spanish Mediterranean coast, that cover the period 1990–2012 with 17.5 effective years of data. The extreme wave height distribution function has been obtained with a peak over threshold (e.g., Sánchez-Arcilla et al., 2008a) method (POT), where the temporal limits and adjustment parameters have been selected from a sensitivity assessment. The resulting distribution parameters, based only on "acceptable" data that comply with physical and statistical criteria as part of a strict quality control, depend on personal and technical criteria and illustrate a first decision level where ethics and knowledge are of paramount importance. **Figure 3** shows the Weibull extreme distribution (Gumbel and Frechet functions were empirically discarded) based on a least squares fit and a range of formulas to estimate relative frequencies, having selected the Goda's expression (Goda, 2010) for the plotting-position because it provided a slightly better fit. In **Figure 3** the black (solid) line represents the median value, whose 90% confidence limits are depicted by dashed black lines. Horizontal lines in this figure indicate a selection of the highest recorded significant wave height in the area during the period covered by data, where the red line shows the maximum value reached in January 2020 (storm Gloria) at the closer available wave buoy (Tarragona buoy from Puertos del Estado). From this figure it could be argued that the peak of storm Gloria is an exceptional event, higher than other recorded maxima as shown in the plot and coincident with the distribution asymptote, which may indicate storm Gloria belongs to a different population that would be related to a zonal change of wave climate (probabilistic distributions of the main wave parameters such as significant wave height, peak period and average directions), probably associated to an effective global change. Such exceptional character is underpinned by the storm energetic content, which was 417 MWh/m (Megawatts per hour per linear meter of coastline), clearly exceeding previous events, and characterized by an average (since 2004) of 35 MWh/m, which is an order of magnitude smaller.

From the adjusted extreme function and confidence limits there is a 90% probability that wave conditions reached in January 2020 in front of the Tarragona province (Tarragona buoy) correspond to a return period longer than 80 years. This return period does not mean, as indicated by some experts (e.g. Lorente et al., 2021), that another 80 years will pass until the coast receives

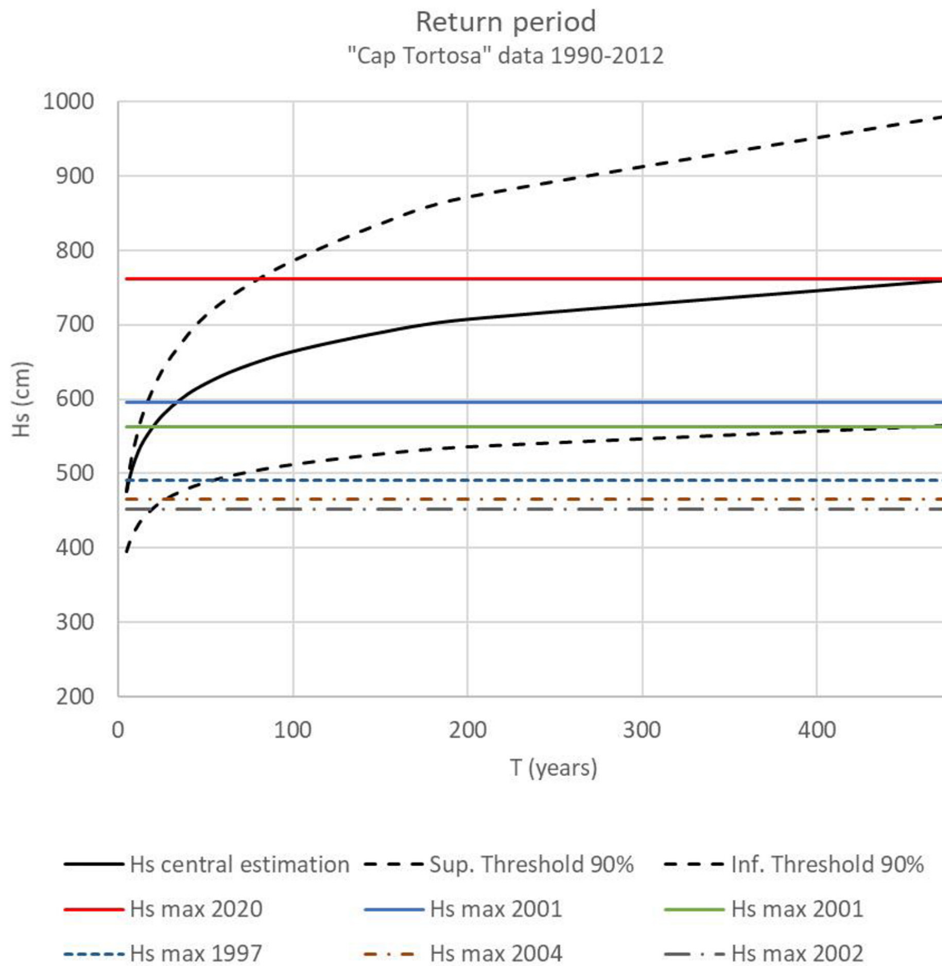

FIGURE 3 | Weibull extreme distribution function plotting significant wave height against return period. The data set corresponds to the period 1990–2012 recorded by the XIOM wave buoy station in front of the Ebro delta, at a depth of 60m and which was dismounted in 2012. Fit according to least squares and Goda's formula for the relative frequencies, applying a threshold of 2.5 m to define wave storms for the extreme sample.

a similar storm but it must be acknowledged that the return period of the Gloria event is significantly larger than that of other recent storms that produced significant damages along this coast. The central (median) estimation of the storm peak significant wave height, corresponding to the red line in **Figure 3** (significant wave height above 7.5 m in the Ebro delta coast and close to 8.5 m in the deep-water buoy off the Valencia coast), if applied for the design of coastal infrastructure, would give a return period of about 500 years, although the lower confidence interval is close to the asymptote, indicating a return period well in excess of 500 years. These results underpin the caution and ethics needed to estimate return periods from such extreme distributions, which should be preferentially used the other way round, that is introducing a return period in the horizontal axis and selecting a wave height in the vertical axis. In any case, the assessment should be carried out with indication of confidence intervals and the danger of estimates close to the asymptotes. Without these ethical constraints, the public opinion may be easily misled, as it actually happened in the aftermath of the storm. Another conclusion from the figure is the difficulty to determine the exceptionality of the event, even its return period, by applying only the central value of the extreme distribution function.

The peak Hs value during storm Gloria clearly exceeds previously recorded maxima, suggesting this storm can denote some change in climatic patterns and limitations in the available wave height time series, supported by the fact that the storm peak level is close to the asymptote of the extreme distribution function. This would mean a transition to a different storm population, resulting in underestimations when using distributions fitted to past events when applied to project future impacts. The apparent paradox, where the storm can be considered simultaneously as an event from the same population or as a representative of a new population affected by climate change, can be related to the implicit stationarity assumption associated with extreme value assessments. Ethics require making explicit the assumed stationarity or lack of, together with the various uncertainties stemming from those hypotheses, the limited size of extreme samples and the statistical techniques applied. Wave storm projections, considering these new energetic events as belonging to a different population, would lead to higher estimates, corresponding to more frequent and severe storms, as it has been observed in recent years (Lin-Ye et al., 2020; de Alfonso et al., 2021).

However, the Gloria storm is not so far away from other recent events recorded in this Western Mediterranean area and is still compatible with the assumption of a steady wave climate. An energy based analysis of all storms recorded by the Tarragona buoy, with 17.5 years of effective data, shows that Gloria represented a maximum in incoming wave energy, with 417 MWh/m, but not so different from other recent events such as the storm in January 2017 which reached 325 MWh/m, i.e., about 70% of the Gloria energetic content (**Figure 4**).

In terms of energetic contents, Gloria storm had a duration of 4.25 days, being comparable to other events in the area, where there were recorded storm durations of 4.41 days in December 2016, 5.52 days in 2017 (longest), and 4.94 days in April 2019. The duration is, thus, not exceptional and the peak intensity (**Figure 3**) has a return period between 80 years and an indefinite value that cannot be estimated due to the small size of the extreme sample available. Based on the 90% confidence band it is therefore not possible to qualify this Gloria storm as exceptional and the event duration justifies this assessment. The return period for the central distribution line is still within the range of what can be considered an extreme event but without becoming an abnormal (outlier) value. By repeating the extreme analysis, sweeping thresholds between 2.2 and 2.7 m selected to characterize storm events in the Western Mediterranean area, it was decided to compare two main thresholds (Egozcue and Ortego, 2005; Sánchez-Arcilla et al., 2008b). The comparison of 2.7 m with the previously considered threshold of 2.5 m indicates different distributions depending on the selected levels. The best fit for the 2.7 m threshold case is provided by a Gumbel function, which is shown in **Figure 5**. By increasing the wave storm threshold from 2.5 m to 2.7 m the lower bound of the 90% confidence interval asymptotically tends to the peak of the Gloria storm, indicating that this event falls within the confidence band of the Gumbel extreme event distribution. This means that this storm, analyzed with the sample of extreme events defined with respect to the 2.7 m threshold, is therefore not an exceptional storm according to this distribution function. Such result illustrates the need to combine advanced statistical knowledge and an ethical perspective to assess the exceptionality of extreme events, with direct implications for insurance and engineering decisions.

LAB DATA AND ERROR INTERVALS: MORPHODYNAMIC AND ENGINEERING CONSEQUENCES

Sediment fluxes determine transport rates and from here the sediment budget for a given coastal cell can be estimated. Longshore sand transport in particular, is one of the main drivers for morphodynamic evolution at yearly scales (Stive et al., 2002) and the error interval of sediment transport formulations will be transformed by morphodynamic and budget calculations in a non-linear manner, seldom made explicit. Even when combining field measurements, for instance to characterize topo-bathymetric evolution for a given coastal cell, with sediment transport laboratory-based formulations, the error level in data from different sources is not usually considered and this applies very clearly to mobile bed experiments where the sediment size has not been reduced properly due to scale limitations in the experimental facility (Petruzzelli et al., 2013). This section will illustrate some seldom recognized uncertainties in lab data extrapolations which then condition engineering calculations, so that without an ethical basis that acknowledges such uncertainties, coastal engineering projects will seldom perform as expected, justifying the lack of proactive action within a general coastal pessimism and a trend toward do nothing options.

Error Intervals in Lab Data

Hydraulic laboratory data need to be applied for calibrating the formulations that characterize turbulence and water-sediment interaction processes, lying at the core of coastal engineering calculations and decisions. This calibration plays a key role in reducing uncertainty for coastal impact assessments, particularly under climate change conditions where models are forced to work outside their common calibration range. However, measured data either in the field or in the lab present large error intervals, aggravated when using reduced scale models that distort hydraulic, geometric and sediment scaling laws (Hugues, 1993; Soulsby, 1997). The introduction of advanced opto-acoustic recording equipment enables much higher resolution, but the application to areas with sharp gradients, such as the air-sea or seabed boundary layers or with poorly known mechanics, such as swash zone or ripple beds (Astruc et al., 2012; Fromant et al., 2019), still present significant error intervals seldom made explicit. Such uncertainty can be illustrated by sediment fluxes in the highly turbulent wave breaker zone, where the observational gear is forced to work under highly variable conditions for which it was not initially designed.

The reliability of water and sediment flux predictions in the surf zone depends on the type of breakers, sediment granulometry and the interaction between different flow and transport modes (e.g., long-waves or suspended suspension pulses). The error level of registered data, automatically introduced into engineering formulations, determines the reliability of coastal hydro-morphodynamic calculations, especially in storm events, which is translated into uncertainty for erosion or flooding storm impact calculations. These impacts are associated to sharp gradients, such as in plunging breakers, where a large amount of incoming oscillatory wave energy is transformed into to turbulent kinetic energy and vortices that generate important sediment fluxes (e.g., Ting and Reimnitz, 2015) and therefore produce significant impacts. Violent plunging breakers trap air volumes under the overturning crest and generate abundant air bubbles within the water column, in sufficient amount to affect the measurement capacity of most of optic and acoustic equipment used in the field and hydraulic labs. Such affectation may limit data accuracy and interpretation,

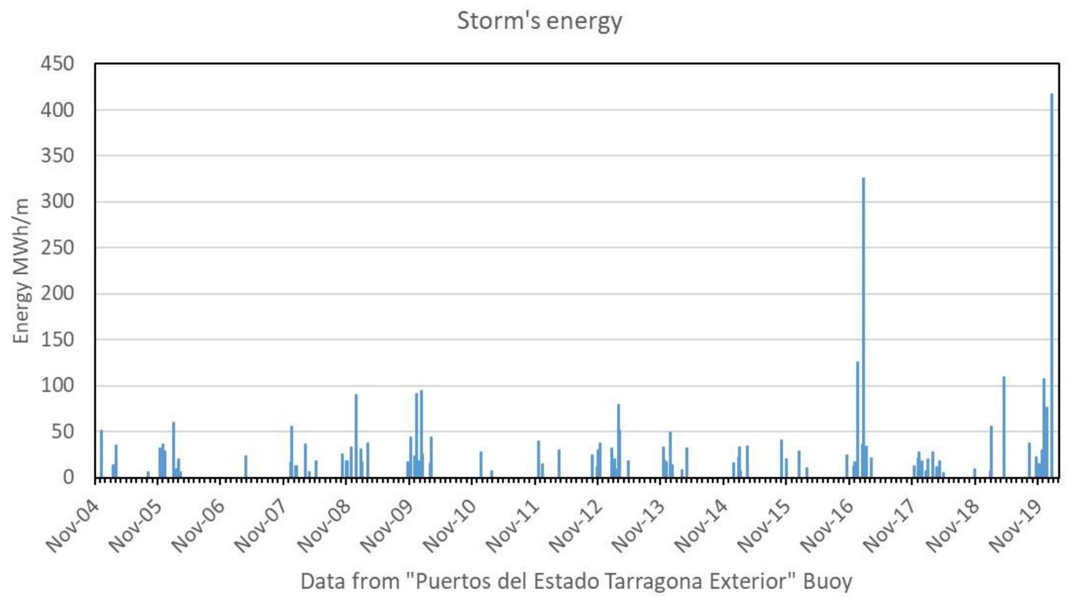

FIGURE 4 | Time series of integrated wave storm energetic contents, where storm events are defined with respect to a 2.5 m threshold for the significant wave height. The plot corresponds to wave buoy recorded data at the Tarragona deep water buoy (depth of 688 m) and it shows the Gloria peak (January 2020) and the January 2017 peak, as very energetic events in the last 3 years.

reducing the reliability of registered wave heights, induced velocities and suspended sediment concentrations.

These limitations in registered data result in uncertainties to characterize hydro-morphodynamic patterns in the surf zone, degrading the reliability of impact assessments particularly under the more energetic events, featuring a larger amount of bubble generation but also responsible for the most damaging impacts on coastal systems. Even advanced measuring equipment, like Acoustic Doppler Velocimeters, may deliver data degraded by the presence of such bubbly environments, although the recorded digital information enables an objective assessment of the error level in the data and their possible distortion by violent air entrainment (bubbles) into the water column. By jointly considering the registered amplitudes and the correlation between values (Cáceres et al., 2020), together with the delivered signal-to-noise ratio, it is possible to determine the error level and reliability of the measured signals. However, when the measurement equipment does not provide a digital signal or the data application does not consider this source of uncertainty, the error level remains implicit and the engineering calculations may lead to wrong predictions. This problem affects also Optical Backscatter Sensors (OBS), a limitation already considered (Puleo et al., 2006; Cáceres et al., 2020) in the literature, but which until now was not applied to the data derived from the commonly used Pore Pressure Transducers (PPT). Conventional applications considered that air bubbles could not affect PPT data, although available lab recordings clearly showed that PPT were affected, particularly under plunging breakers, by air bubbles that reduced data accuracy and hindered a correct physical interpretation.

Such loss of accuracy is presented in **Figure 6**, which shows the percentage of waves that produce air bubble events (P_{peaks}) for typical wave trains in a large-scale lab flume such as the CIEM flume in BarcelonaTech managed by LIM/UPC (Oliveira et al., 2012). The ensemble average free surface elevation computed from the PPT for a regular wave train with $H = 0.85$ m and $T = 4$ s and taking into account wave non-linearity, presents important differences depending on the level of bubbles present. PPT and OBS were deployed at the same vertical level in a moving carriage, providing records of bubble variation and pressures from which water free surface, an essential variable to characterize for instance the incident wave height, was determined. Panel a) in **Figure 6** shows the recorded water surface elevation under a single wave within a train, as it approaches the seabed bar and starts breaking. Such a breaking process results in wave height decay over and right after the breaker bar, as depicted by the black dots in the lower central image of **Figure 6**, where the full black dots denote wave height evolution across the beach profile. Panels B–D present a clear drop around $t/T = 0.2$ on the water surface ensemble averaged signal, produced by the air bubble cloud going through the PPT sensor. The drop on the PPT signal faithfully matches a similar drop in the ADV Signal-to-Noise Ratio and is supported by the sequence of collected images. The point where the downward plunging crest impinges the free surface in front was measured at $x = 54.9$ m, which is the position presented in panel B, corresponding to the apparent fission of the incoming wave associated to air bubble impulsive generation by wave breaking. In all panels A–D the dashed green line shows the standard deviation from the sample of incoming registered waves, with respect to the ensemble average depicted by the continuous black line.

The confidence interval of width two standard deviations, centered on the ensemble average, increases from bar crest to bar

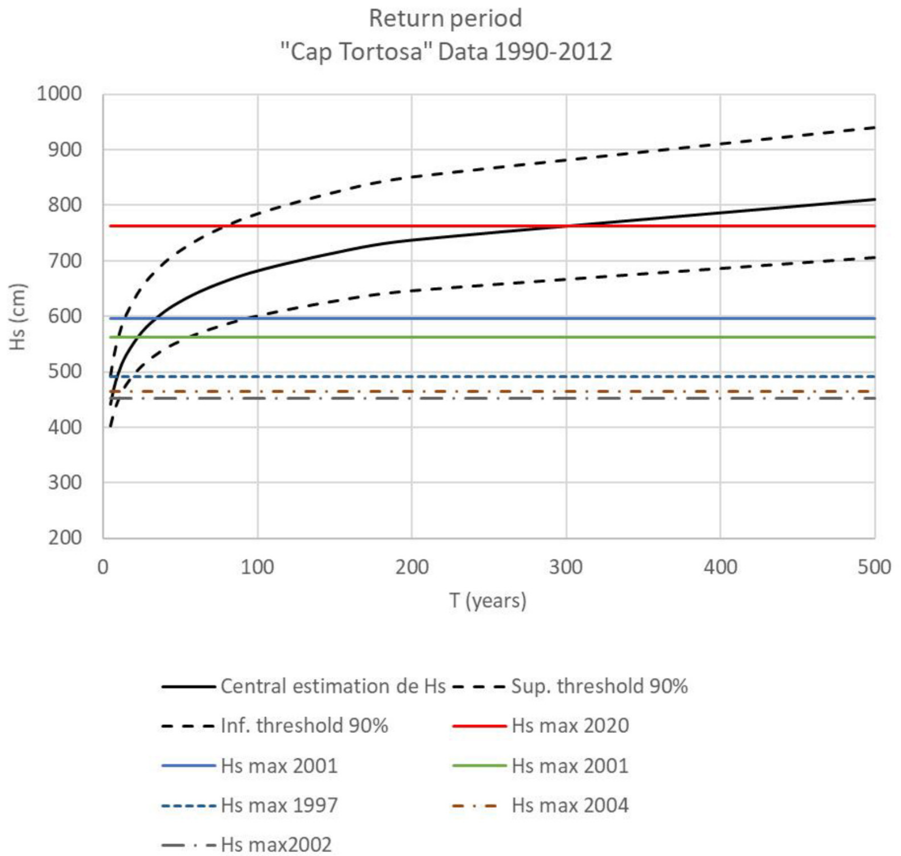

FIGURE 5 | Alternative (compare with **Figure 3**) extreme distribution function, plotting significant wave height against return period. The data set is identical to that in **Figure 3**, corresponding to the period 1990–2012 and the XIOM wave buoy station in front of the Ebro delta at a depth of 60 m (dismounted in 2012. In this case a threshold of 2.7 m has been selected to define wave storms for the extreme sample. The function providing the best fit, using least squares and Goda's formula for the plotting-position, is a Gumbel distribution function.

trough, that is as the bubble cloud and wave interactions induce non-linear transfers between frequency bands in the breaking wave spectrum. The air bubble cloud is a nearly permanent although non steady feature that distorts all PPT measurements over the bar-trough region and is maintained by the arrival of subsequent breaking waves. Such an air bubble cloud, also detected by the percentage of bubble-induced peaks in the OBS signal (P_{peaks} variable in the lower central panel), has a pervasive effect and degrades the reliability of the recorded free surface elevation, introducing error levels that may exceed, as shown in panel D, the 100% error level for wave height assessments. This uncertainty, if made explicit, should be considered in breaker zone hydro-morphodynamic analyses which, however, seldom take into account the underlying uncertainty and force conclusions that suite the research or application interests but which are not truly supported by the data. Such error intervals will grow when extrapolating to real or prototype scale and when using the wave height estimates to calculate other derived variables. For instance, sediment transport depends on wave height to a power that goes from 2.5 to 5 as described in next subsection, which would mean that for a dependency to the third power, a 50% error in wave height becomes an error interval close to 250%. These error intervals preclude deterministic assessments, particularly when used for diagnostic or prognostic applications and should be presented explicitly, based on redundant data that enable calibration followed by validation and the available knowledge on governing laws for the dominant processes. Such an explicit assessment of uncertainty, supported by an objective and ethical discussion, should facilitate the uptake of lab and field data to bound errors in engineering calculations, supporting knowledge based decisions and a stronger commitment of coastal deciders and stakeholders.

Morphodynamic and Engineering Consequences

Sediment transport formulations are calibrated with lab and field data and should, thus, include the error interval of such data. But in practice, those intervals are "lost" after the initial validation of the formulation. In addition, transport formulations represent a potential transport capacity, never verified if there is not enough sand available, which introduces an even greater uncertainty not always acknowledged in engineering applications. The key variables for sediment budget calculations (**Figure 7**), at the

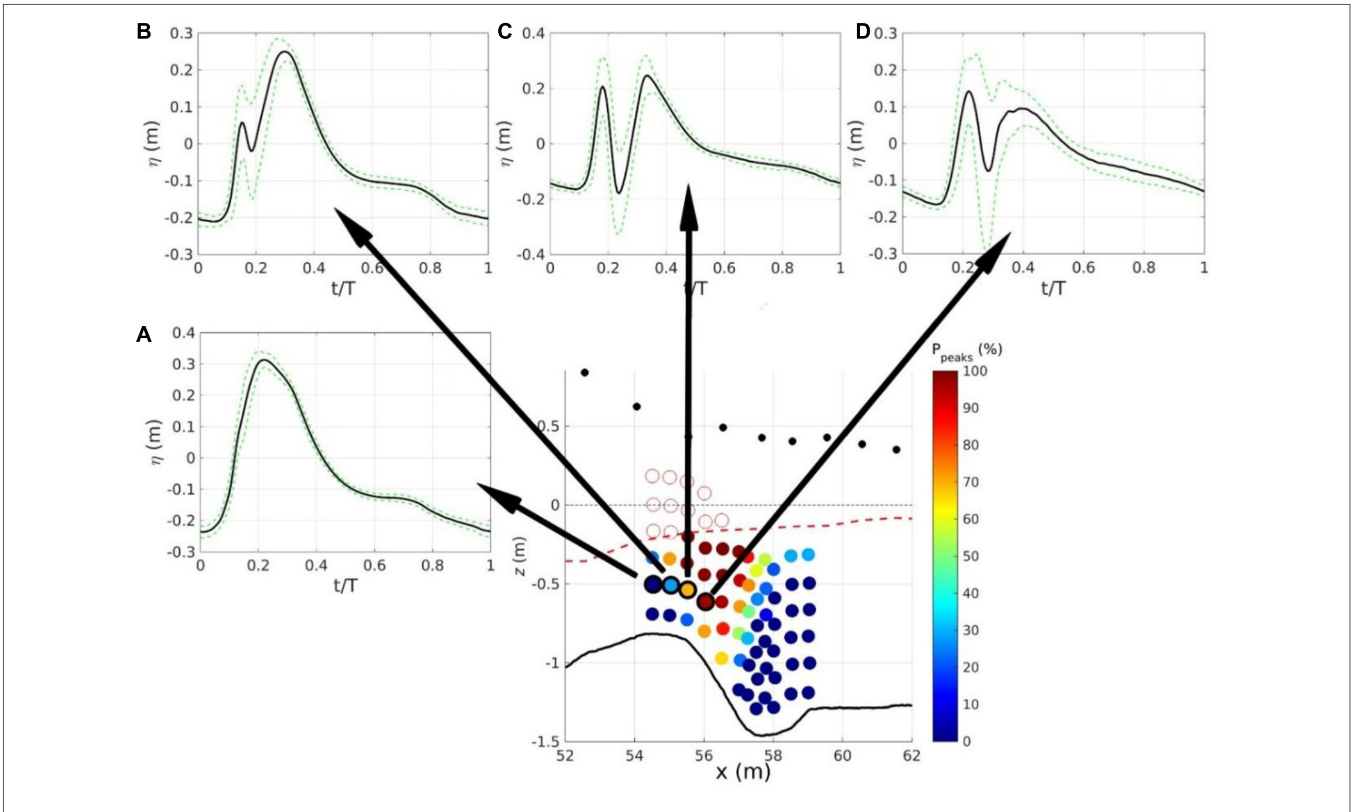

FIGURE 6 | Presence of air bubble peaks induced by wave breaking (P peaks variable), in percentage and as a function of the bar-trough geometry (lower central panel). Plots **(A–D)** depict the ensemble free water surface (black continuous line) computed from a PPT signal, progressively more affected by the bubble cloud as the wave breaks over the bar and evolves into the following seabed trough. The ensemble variation of registered free surface signals within the incoming wave train is represented by the green dashed lines, corresponding to one standard deviation above and below the ensemble average and showing how the variability and uncertainty increase with breaking and air bubble non-linear interactions, as the regular incoming waves progress from bar crest to trough.

basis of most coastal engineering assessments, are the longshore sediment transport rate, the depth of closure (DC in the figure) and the berm height (B in the figure), usually characterized in a deterministic manner.

The deterministic approach comes from the need to provide quantitative estimates for coastal decision making (e.g., artificial sand nourishment volumes) and by the cost associated with regular topo-bathymetric surveys, which limits a proper statistical characterization. Sediment budget and morphodynamic evolution are inferred from observed shoreline displacements, calculated from aerial or satellite data (e.g., ortophotos from aerial images or Sentinel 2 shoreline positions). To go from shoreline positions to sediment volumes and fluxes it is necessary to estimate the upper and lower limits of sediment transport, defined by the B and DC variables already mentioned. DC is typically obtained from a comparison of surveyed profiles (**Figure 8**) or from available formulations (e.g., Hallermeier, 1981), both approaches presenting uncertainties that may go from 3 to 15% (CIIRC, 2010). The DC formulations require the estimation of a wave height exceeded 12 hours per year, which again introduces the uncertainties from the wave height probability distribution, already discussed in section "Coastal Adaptation Pathways: Decisions for a Sustainable Conservation." For estimating the berm height B (**Figure 9**) there is no universally accepted criterion, since it depends on the time scale of the analysis and the complexity of the considered beach profiles, where the usual configurations feature more than one

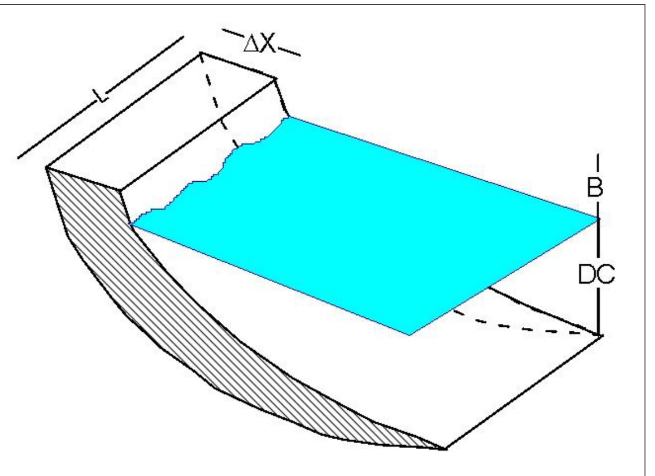

FIGURE 7 | Beach profile schematization for sediment budget calculations, indicating the berm height (B), the closure depth (DC), and characteristic distances along (L) and across (Δx) shore to define the coastal slice volume.

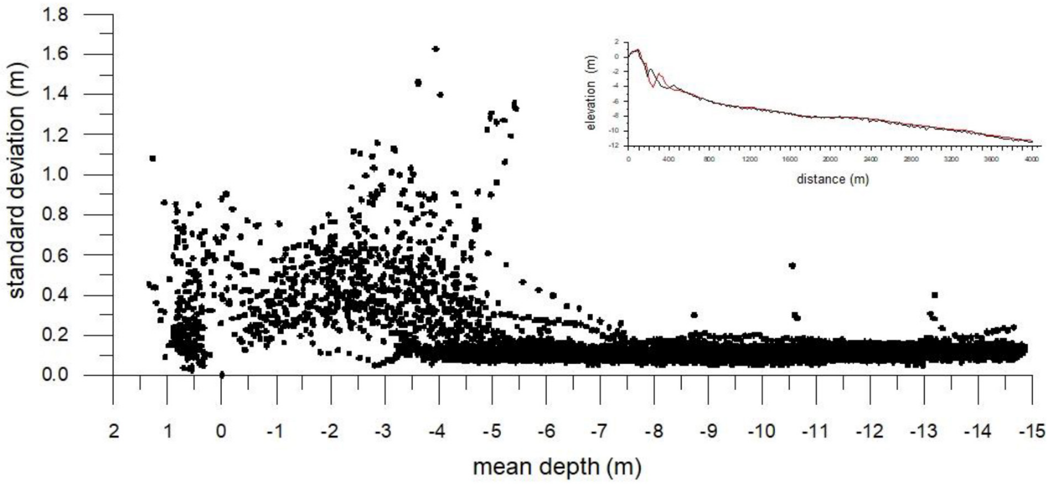

FIGURE 8 | Set of beach profiles from the Ebro delta in the Spanish Mediterranean coast, showing the standard deviation for the ensemble of surveyed profiles (vertical axis) against the profile depth (horizontal axis). The zero depth indicates the still water level shoreline, while positive depths correspond to the emerged profile and negative depths to the submerged one. The profile geometry is depicted by the inset in the upper right hand side, showing depth (vertical axis) against distance to the origin, defined from a back beach milestone.

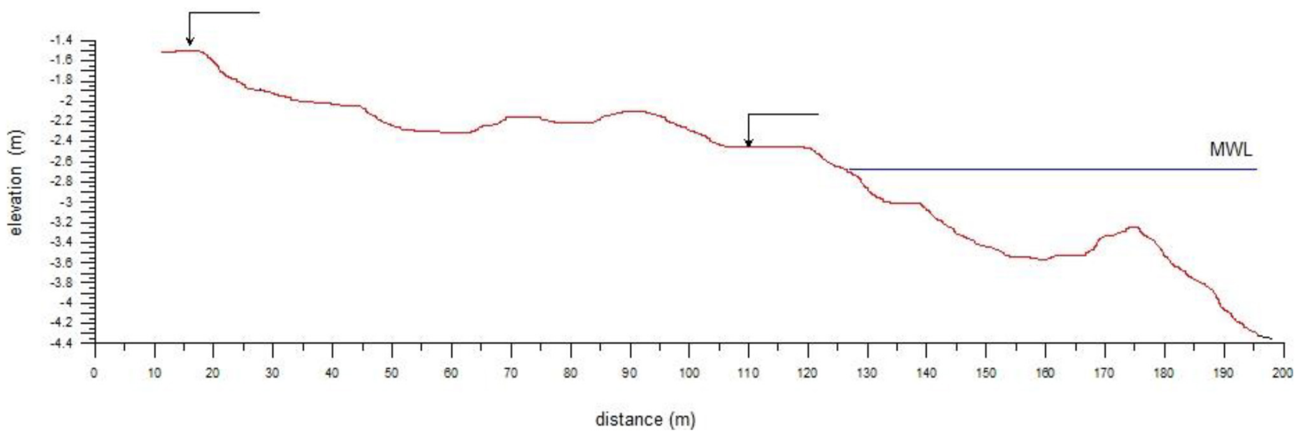

FIGURE 9 | Beach profile (red line) from the Ebro delta in the Spanish Mediterranean coast, referred to the still water level (blue line) and depicting the inner submerged breaker bar (right hand side) together with the various berms (left hand side), whose level is indicated by arrows. This profile geometry, referred to horizontal cross-shore distance (*X* axis) and vertical level (*Y* axis) corresponds to typical geometries commonly found in microtidal coasts, but presents similar traits for other beach environments, illustrating the difficulty to define the berm level (B variable in text), which depends on the energy level of incoming waves and the time scale of the analysis.

berm (**Figure 9**) leaving the final value selection to technical expertise and ethical considerations, given its direct relevance for estimating sediment volumes which directly condition the cost of the engineering intervention.

Sediment transport rate predictions, relying on a set of state-of-the-art formulations, aggregate various sources of uncertainty stemming from hydrodynamics/morphodynamics and their interactions (wave/storm parameters and granulometry distributions, etc.). Moreover, these formulations represent the potential transport capacity (actual transport depending on sediment availability) and have been calibrated for conditions that normally do not coincide with those at the studied site. One of the simplest (yet more robust) approaches is the CERC formulation (USACE, 1984), still amply used in coastal engineering projects. The CERC equation is based on the assumption of a linear relationship between the sediment transport rate (Q) and the incident wave energy flux at breaking ($Pl_{s,b}$), which may be written as:

$$Q\left(\frac{m^3}{s}\right) = \frac{K_{CERC}}{(\rho_s - \rho_w)\, g\,(1-p)} Pl_{s,b} \quad (1)$$

$$Pl_{s,b} = \frac{1}{16} H_b^2 \rho_w g \sqrt{g h_b} sin\,(2\alpha_b) \quad (2)$$

being K_{CERC} the proportionality factor, g the gravitational acceleration, ρ_s and ρ_w the sediment and water densities, p the porosity and H_b the wave height at breaking, which occurs at a depth h_b with an angle of wave incidence of α_b.

The proportionality coefficient K_{CERC} includes all uncertainties due to the limited accuracy of this formulation and the role of all variables not present in the expression, but which from basic physics should affect (Bailard, 1984; Kamphuis, 2002; Smith et al., 2009) sediment transport rates (e.g., wave period, breaker type, granulometry, and beach slope, etc.). K_{CERC} has been empirically derived from different field experiments (**Table 1**), with values ranging from 1 to 0.2, being a value of 0.77 the most widely accepted option if the formula is fed by H_{rms} or a value of 0.29 if it uses H_s under the assumption of a Rayleigh distribution function for the incoming wave field. As a result, the evaluation of longshore sediment transport and the associated sediment budget present important uncertainties and error intervals, not always made explicit, which leads to transport results that can vary by more than one order of magnitude. The large number of parameters and error intervals that are included in sediment transport or budget evaluations result in important uncertainties that affect coastal decisions, where final conclusions may depend more on vested interests than on objective criteria. Here, again, an ethical basis underpinned by an explicit uncertainty estimation, is of paramount importance to provide a robust and balanced approach to coastal decision making.

Longshore sediment transport and budget calculations are usually referred to yearly intervals (Kraus, 1989; Stive et al., 2002) to avoid instabilities or cumulative errors from shorter or longer, respectively, scales of analyses. Resulting estimations should provide explicit bounds for error levels, which sometimes have been proposed in the literature with different degrees of acceptance. Available proposals for variation intervals in K_{CERC} (**Table 1**) and the main hydro-morpho-dynamic parameters (**Table 2**) indicate the wide range of aggregated error intervals, since the expressions relating these variables are highly non-linear. Building from state of the art equations that combine these variables, the total uncertainty in longshore transport can be estimated by means of a Taylor series expansion (Kraus and Rosati, 1998), making explicit the contribution from each variable. The expected range of variation of the main geometrical parameters (see **Figure 7**) appears in **Table 3**, based on results from multiple surveys for the Catalan coast in the Spanish Mediterranean (CIIRC, 2010) under representative oceanographic conditions.

TABLE 1 | Average values proposed by different authors for K_{CERC} and experimentally determined variation intervals (in parenthesis), modified after Soulsby (1997), where Soulsby's book includes all references under the "Source" column.

Source	Dn_{50} (mm)	K_{CERC}
Watts (1953)	0.4	0.89 (0.73–1.03)
Caldwell (1956)	0.4	0.63 (0.16–1.65)
Moore and Cole (1960)	1	0.18
Komar and Inman (1970)	0.6	0.82 (0.49–1.15)
	0.18	0.77 (0.52–0.92)
Lee (1975)	?	0.42 (0.24–0.72)
Knoth and Nummedal (1977)	?	0.62 (0.23–1.00)
Inman et al. (1980)	0.2	0.69 (0.26–1.34)
Duane and Janes (1980)	0.15	0.81
Bruno et al. (1981)	0.2	0.87 (0.42–1.15)
Dean et al. (1982)	0.22	1.15 (0.32–1.63)
SPM'84	0.2–0.6	0.39–0.92
Dean et al. (1987)	0.3	1.00 (0.84–1.09)

TABLE 2 | Some common variation intervals for the main parameters that affect sand transport calculations, modified after (Soulsby, 1997).

Parameter	Notation	Uncertainty interval
Sea water density	ρ_w	±0.2%
Sediment density	$\rho_{sediment}$	±2%
Kinematic viscosity	$\nu = \mu / \rho$	±10%
Sediment grain size	$d_{50}, d_{10\ldots}$	±20%
Water depth	h	±5%
Current velocity	U	±10%
Current direction	θ	±10°
Wave height	H_s	±10%
Wave period	T_z	±10%
Wave direction	θ	±15°

TABLE 3 | Typical variation intervals for the geometric parameters defining control cell volume (**Figure 6**) in Spanish Mediterranean sandy beaches, adapted from Gracia (2005) and CIIRC (2010).

Parameter	Average estimator (m)	Uncertainty interval (m)
Alongshore cell length, L	1000	±0.01
Beach berm height, B	1,5	±0.5
Depth of closure, DC	7	±0.2
Cross-shore variation, ΔX	3	±0.5

TABLE 4 | Condensed average wave climate for the Spanish Mediterranean coast, indicating the number of days (ND) and peak direction of wave incidence at the breaker line (θ_b).

Average wave climate			Longshore transport uncertainty	
H_{sb} (m) classes	Direction α_b (°)	Number of days	Q_l (m3/yr)	Q_l (m3/yr) error interval
1	4	100	196.134	±78.454
1,5	5	20	134.873	±53.949
2	6	25	414.374	±165.749
2,5	7	5	168.459	±67.383
3	8	3	151.384	±60.554
1	−3	100	−147.310	±58.924
1,5	−5	75	−505.776	±202.310
2	−8	25	−549.353	±219.741
2,5	−11	10	−521.703	±208.681
3	−4	3	−76.436	±30.574
Total		365	−735.354	±294.142

*This information has been obtained for each wave height class, defined in terms of the significant wave height at the breaker line (H_{sb}). The longshore sand transport rate (Q_l) has been calculated with the CERC formulation and the total error level in Q_l has been obtained from a Taylor series expansion of the error in terms of the key controlling variables presented in **Tables 1–3**.*

From here a sensitivity analysis to assess longshore transport error intervals can be developed, based on a typical costal stretch of 1000 m length and located in the Spanish Mediterranean coast, with a total height (DC + B) of the active beach profile of 8.5 m (Gracia, 2005), typical of deltaic systems in the Spanish Mediterranean and with uncertainty intervals as in **Table 3**, and derived from repeated surveys in the Ebro delta coast. The calculated volume of the sedimentary cell (**Figure 7**) presents an uncertainty in the total cell volume estimation between 19 and 25%, resulting from the different parameters, which in turn present different maximum and root-mean-square error limits. For instance, the total active height of the profile shows a root-mean-square error of 0.5 m and an upper bound for the variation interval of 0.9 m for the studied Ebro delta coast and similar coastal profiles.

The considered coastal stretch experiences a relatively uniform gradient in the longshore sediment transport, typical of a rectilinear coast such as is the Trabucador barrier beach in the Ebro delta, subject to oblique wave incidence without excessive bathymetric induced perturbations. The resulting sediment budget is also affected by overwash processes that take sand from the outer coast toward the lagoon side (Jiménez and Sánchez-Arcilla, 1993). In spite of these difficulties, which condition longshore transport estimations at yearly time scales and should reflect the aggregation of transport pulses mainly under storm events, the validation with coastal morphodynamic evolution requires such a sediment budget aggregation to derive stable estimates (Schoonees and Theron, 1993; Wang et al., 1998; Wang and Kraus, 1999). By condensing the available wave data into a schematised yearly scale variation (**Table 4**) and introducing the presented error intervals for the key variables controlling longshore sediment transport, it is possible to develop a Taylor series expansion for the error (Taylor, 1997). Applying this procedure to the Spanish Mediterranean coast and the control cell of **Figure 7**, it is obtained that the total error level in longshore sand transport, using the presented CERC formulation, is of about 40%. This level of error explains the mismatch often found in any comparison between calculated potential transport and actually verified transport from field data (**Figure 10**). In this case longshore averaged sediment transport was inferred from aerial orthophotos, multiplying shoreline advance/retreat by the active profile thickness (berm height plus closure depth) and the length of the studied coastal stretch. The resulting volumes indicate the net erosion/deposition over the period covered by the aerial images and have been expressed in cubic meters per year, corresponding to typical values for this part of the Spanish Mediterranean coast. The steeper (black) line corresponds to net sediment transport rates averaged over a few years for a typical Spanish Mediterranean coastal stretch, with estimated transport rates close to measured data and an error upper limit below 10% (average fit coefficient is 1.08), which is quite exceptional and denotes the quality of the performed calculations and subsequent model calibration. The red line represents calculated longshore transport values which are about twice the measured ones, corresponding to a deltaic beach that is sediment starved and where the potential transport estimated by the formula cannot take place in the field. There are some points (dashed areas) where the calculated transport value is almost an order of magnitude larger that the value inferred from aerial photographs, underpinning the potential transport character of the estimates provided by the sediment transport formulation.

The discrepancy between actually measured transport, in this case from a comparison of orthophotos characterizing shoreline evolution, and the estimates from potential transport formulations, highlight an important uncertainty in coastal engineering. Such uncertainty must be made explicit and assessed form an ethical perspective, avoiding biases by vested interests that may lead to poorly designed coastal interventions and a loss of confidence on expert opinion. The mistrust in engineering calculations may grow from these discrepancies, hampering anticipatory decisions, and the baseline optimism needed for a shared work toward coastal sustainability.

COASTAL RISK ASSESSMENTS: HAZARD AND VULNERABILITY ESTIMATIONS

Coastal storms, particularly impulsive ones like those in the Mediterranean (Pérez et al., 2021), reshape beaches out of wave equilibrium and may generate important risk levels for highly pressured coastal zones like those in the Mediterranean. These risks, estimated as the product of hazard, vulnerability and exposure, actually happened during storm Gloria, the considered study case, which affected the Spanish Mediterranean coast in January 2020. Storm Gloria stalled for several days over the western Mediterranean Sea, generating large waves (see section "Field Data and Statistical Processing: Uncertainty in Diagnosis") and storm surges (Pérez et al., 2021) that were forewarned by the Spanish Meteo Agency (AEMET) with red (maximum risk level) warnings between January 19th and 20th, extended to January 21st for the Catalan coastline. This storm, selected to illustrate the uncertainties in extreme impact assessments, resulted in personal losses (14 casualties and 3 more missing) and material damages to agriculture, infrastructure, and other socio-economic assets, with insurance claims exceeding 76 million €, while total economic impacts were estimated to be around 200 million €. Resulting coastal impacts were analyzed by the Spanish Ministry (CEDEX, 2020), considering the main damages reported, which affected 137 beaches, and applying state of the art valuation techniques and indicators (Botero et al., 2015; Lucrezi et al., 2016). Based on the considered indicators, coastal vulnerability was assessed specifically for each beach and then for longer coastal stretches with a subset of indicators reported for all beaches in the selected stretch. The subset of selected indicators characterize storm impacts based on the main controlling processes that can be related to: (1) beach profile volume/shape (*bp*); (2) coastal protection structures (*cs*); (3) beach services (showers, accesses, and facilities) (*bs*); (4) back-beach dunes (*bd*); (5) urban (public) infrastructure (*ui*); (6) private property (*pp*); and (7) debris accumulation (*da*). The individual beach analysis (called in what follows "first approach" to vulnerability) estimates vulnerability from the seven indicators just described, which may be not be available for all beaches within a generic coastal stretch.

A comparative more regional analysis, developed for a longer coastal stretch (called in what follows "second approach" to vulnerability) retains only the indicators that are available for all beaches, which are normally numbers 1 (*bp)*, 3 (*bs)* and 5 (*ui)*. Vulnerability has been estimated for both approaches in terms of a damage index (*di*), without considering exposure that cannot often be properly assessed due to insufficient data. For all indicators and the two proposed vulnerability approaches a value of 1 for the indicator represented very significant damage (equivalent to total loss or destruction), while a value of 0 represented no damage reported. In the first approach to assess vulnerability *di* is calculated as the mean of all seven considered indicators:

$$di = \frac{bp + cs + bs + bd + ui + pp + da}{7} \tag{3}$$

In the second approach *di* is calculated as the mean of the three more relevant indicators, which tend to be more easily available for all beaches. However, for coastal systems with a back beach buffer zone formed by dunes, whenever these dunes, representing the last defense line of the coast, were damaged by the storm, a value of 1 was selected because the mean value of the indicators resulted in an underestimation of vulnerability, according to the available evidence (Pérez et al., 2021)

$$\left.\begin{array}{r} \textit{if no dunes present or} \\ \textit{present but no damage} \end{array}\right\} di = \frac{bp+bs+ui}{3} \qquad \left.\textit{if dunes damaged}\right\} di = 1 \tag{4}$$

The illustrative analysis, performed for a typical stretch of the Spanish Mediterranean coast, resulted in 133 beaches, out of the 137 studied, with significant damages after the impact of the selected extreme storm. From the first vulnerability approach, considering all indicators, it was found that most beaches presented significant vulnerabilities, related to shoreline retreat and urban infrastructure damage, while damages to coastal infrastructure and private property was present only in about 10% of cases. The highest level of the *di* index was 0.71 and there was a beach without damages with *di* = 0.0. These estimates, although spatially characterizing vulnerability during storm Gloria, should be handled with care since there are many possible criteria to assess damage and, when multiplied by the probability of climatic pressure (wave height in the presented analysis) exceedance (see section "Field Data and Statistical Processing: Uncertainty in Diagnosis") or the combined probability of combined climatic factors (wave height and storm surge in the presented analysis) exceedance, risk estimates will present even larger uncertainties. The fact that the average vulnerability level was 0.41 for the province of Tarragona (southern Catalan coast) and 0.33 for the provinces of Barcelona (central coast) and Girona (northern coast) indicate higher vulnerabilities in the southern part of the Catalan coast, where the fetch for wave generation was also larger and led to more energetic incident waves acting on the southern part of the coast. The high risk levels for the Ebro delta coast indicate a sediment-starved and low-lying deltaic system (e.g., Grases et al., 2020), subject to higher waves (southern part of the coast) and enhanced storm surges because of the wider continental platform and submerged prodelta, which increase the sea surface elevation due to the combined wind velocity and low atmospheric pressure.

The performed risk assessment illustrates the relation between hydro-morphodynamic processes and resulting risks, indicating the need to combine physical and socio-economic data with explicit error levels. These errors should be worked out both for the hazard and the vulnerability factors, together with a sensitivity assessment for different types of damages and combinations of meteo-oceanographic factors. A non-negligible part of the risk uncertainty comes from the selected valuation techniques (e.g., Luisetti et al., 2014) and from the fact that risk will evolve with storm development or recurrence (risk increases) and with natural coastal recovery (risk decreases), requiring a dynamic estimation to consider how risk evolves with time and space. Such risk dynamics must also consider the stabilizing effect of selected natural processes, such as onshore transport and beach debris, which integrate marine and riverine sources and illustrate the importance of natural accretive transport and protection, more relevant during storm decay stages and for chained storm events, such as those that affected the studied Spanish Mediterranean coast from February to May 2020. Physical and geological settings also produce a spatial variation of risk, that should be made explicit in regional analyses to provide a holistic characterization of risk propagation. Such a risk propagation pattern appeared during storm Gloria for the coast south of the Ebre delta, where the sheltering effect of this delta, seldom made explicit in cost/benefit analyses, became apparent for the coast downdrift, which is the Castellon province, located south of the Ebre. The deltaic sheltering effect explains why the Castellon province coast experienced smaller storm impacts than its neighboring provinces, introducing a clear spatial pattern in risk distribution that must be considered in regional coastal analyses.

A spatially distributed risk pattern, taking into account the "fixed" protection elements (such as the deltaic protuberance in the selected example) and the evolution with time of risk levels, including the error bounds assessed from limited knowledge, is the only approach to build socio-economic confidence on risk assessments. This confidence will require an ethical basis to assess risks and uncertainty from limited data and presenting clearly the error levels in the considered social-ecological interactions, which will always represent a simplification of the actual coastal system. The vulnerability levels obtained, ranging for the selected example from 0.41 to 0.33 for the first approach, and from 0.89 to 0.67 for the second approach, illustrate such uncertainties, since vulnerability should be largely insensitive to the calculation procedure. Such a dependence on the selected approach and the variability with space (e.g., along the coast) and/or time (e.g., during the storm) highlight the need to present vulnerability results from an ethical basis, making explicit the error intervals and providing a neutral (fair) assessment of the estimation. In the presented study case, and because of the limited amount of reliable information to estimate the selected indicators, vulnerability results only provide an approximate measure of relative damage levels, which showed a growing trend toward the south of the Catalan coast due to the presence of the highly vulnerable Ebro delta. Below (further south) the

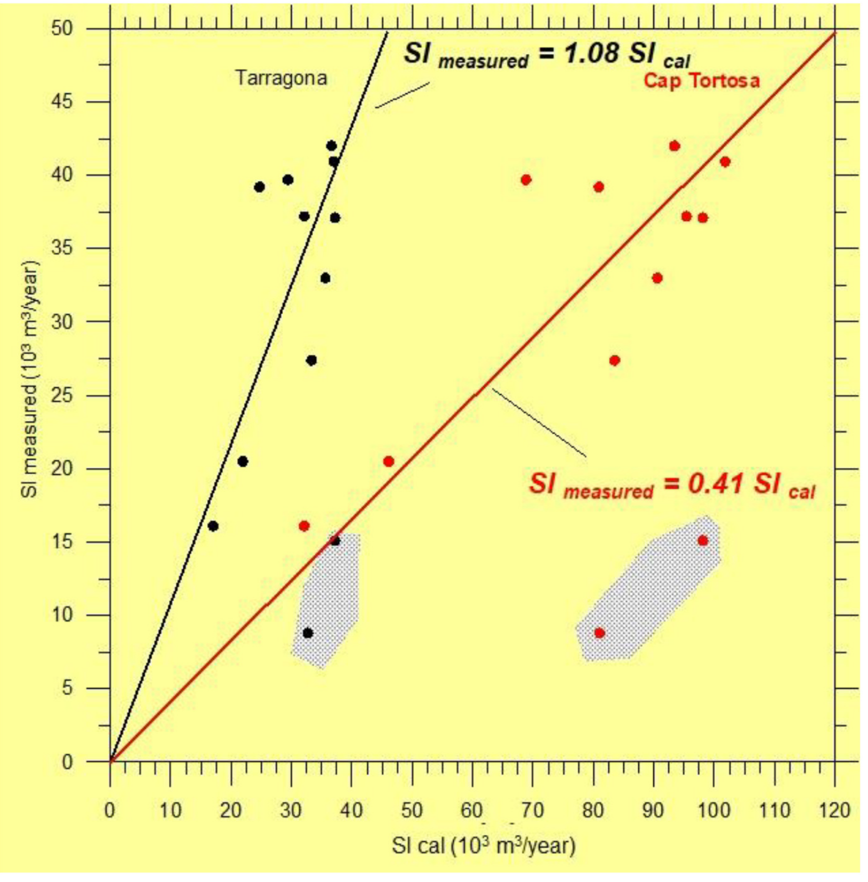

FIGURE 10 | Measured (vertical axis) and calculated (horizontal axis) longshore sand transport rates for a typical stretch in the Spanish Mediterranean coast (black line corresponding to the Tarragona province) and for a sediment starved coastal sector in the Ebro delta (red line corresponding to the Cap Tortosa area). The dashed areas indicate profiles where the calculated transport exceeded by almost an order of magnitude the measured one, highlighting the fact that transport formulations provide a potential transport capacity rather than the actually verified transport.

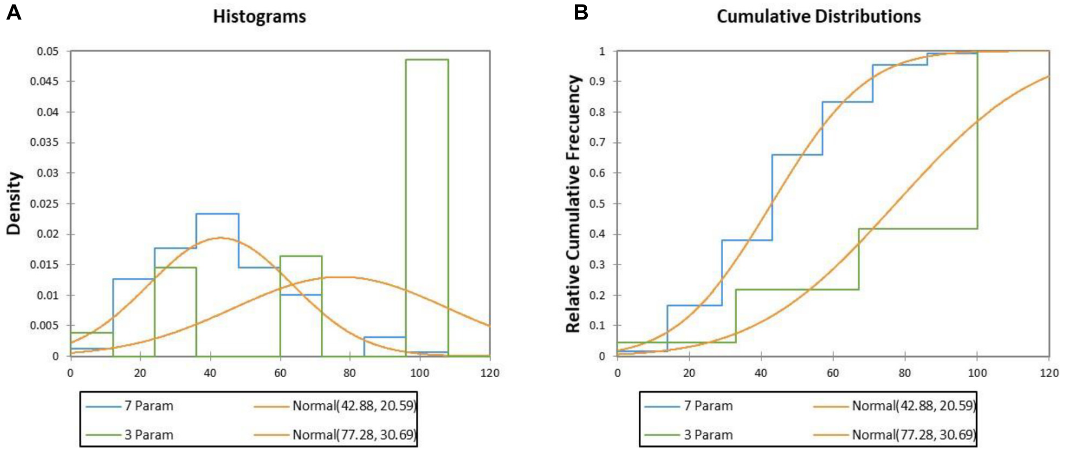

FIGURE 11 | Relative (left panel **A**) and cumulative occurrence (right panel **B**) of vulnerability levels for beaches along the Spanish Mediterranean coast after the impact of storm Gloria (January 2020). The number of beaches affected, given by frequencies in the vertical axes of the two panels, and the different levels of risk, indicated by the variations in shape between the orange (vulnerability from 7 indicators) and blue (vulnerability from 3 indicators) lines, indicate how the analysis depends on the approach selected. The calculated frequencies have been fitted to a Normal distribution, whose parameters appear between parenthesis.

delta vulnerability decreased due to the sheltering effect of the deltaic form.

To facilitate the development of regional adaptation pathways (e.g., Werners et al., 2021) for the Spanish Mediterranean coast, linking adaptation with risk levels, these vulnerability results have to be fitted to a probability distribution. Such distribution will enable the characterization of low, medium and high levels of risk (**Figure 11**) along this or any studied coast. By an empirical fit to common probability distributions, from which a Normal function has been selected in our study case because it provided the better fit, it becomes possible to analyze if the two vulnerability approaches deliver results from the same statistical population. Applying a Kolmogorov-Smirnov test to the relative frequencies of damage levels from the two approaches, it is apparent that in the studied case the results represent different populations, depending on the approach selected for the analysis. This is another indication of the lack of robustness in many vulnerability and risk assessments, which therefore need an expert judgment based on ethics and balanced comparisons. The role of advanced statistics may enable improved conclusions, provided the data sample is large and characteristic enough, resulting in improved decisions for coastal adaptation.

In spite of the discussed uncertainties, the applied quantitative techniques enable an objective estimation of risk levels along the coast, showing that commonly only a small percentage of beaches experience total damage during extreme events. For storm Gloria, based on the 7 indicators approach, this percentage was about 1%, while the percentage obtained with the 3 indicators was approximately 60%. Such discrepancies, unless tamed by ethics, will prevent decision making and will increase the mistrust on expert analysis or even numerical results in general, with direct consequences for coastal investments. And yet the quantitative information stemming from knowledge-based analyses is an excellent basis to make decisions or reach consensus, provided that the derived estimates are based on ethics and, whenever possible, associated to error bars that indicate the underlying uncertainty. The vulnerability results from the 3 indicators (second approach) is clearly biased toward high damage values, with higher statistical moments than those obtained for the 7 indicators (the first moment is 42.88 for the 7 indicators and 77.28 for the 3 indicators). This behavior, showing a larger uncertainty and wider variability for a reduced set of indicators that, however, could be quantified for a larger number of beaches, illustrate the difficulties to extend this type of analysis to regional cases, spanning longer and more heterogeneous coastal sectors.

The performed risk assessment, although simplified, illustrates the conundrum of deriving quantitative estimators for coastal adaptation decisions. From a technical point of view, the use of a reduced set of indicators (3 in the presented example) should lead to a more robust and regional analysis of coastal vulnerability, focusing on the beach area and infrastructure whose physical integrity was more directly affected by extreme storms. However, the limited information provided by just three indicators, with fuzzy estimations of the impact and dynamic response depending on beach morphology and presence of infrastructure, may result in fragile criteria for coastal decisions, excluding the key role played by factors such as dune integrity or the natural protection exerted by accretive transport or debris accumulation. Moreover, risk and vulnerability assessments should consider all socio-ecological factors relevant for coastal adaptation and risk characterizations, discarding variables only after a proper (knowledge-based) justification. Such limitations in risk analysis illustrate the need for explicit error intervals and a fair technical assessment based on ethics, where coastal stakeholders should be informed of the strengths and weaknesses of the data and analysis method. The obtained results should be ethically presented, comparing different options in statistical, physical and valuation techniques, so that the estimation is explicit and transparent, reflecting the limits in knowledge and data. Only from such an ethical basis it will become meaningful to incorporate risk and vulnerability assessments into coastal adaptation pathways, resulting in better decisions that reconcile short/long term priorities and build up a wider consensus.

SHARED COASTAL FUTURES: ETHICS AND OPTIMISM

The presented analyses illustrate the inherent error in coastal risk assessments with present knowledge/data and how the prevailing uncertainties may vary within the Spanish Mediterranean coast. The development of coastal adaptation pathways and particularly the quantification of tipping points, deadlines for urgent coastal decisions, will suffer from the same error levels, stemming from meteo-oceanographic factors characterizing hazards (section "Field Data and Statistical Processing: Uncertainty in Diagnosis"), coastal impact/response calculations (section "Lab Data and Error Intervals: Morphodynamic and Engineering Consequences"), and vulnerability/risk assessments (section "Coastal Risk Assessments: Hazard and Vulnerability Estimations"). And yet, there is a growing consensus (e.g., Haasnoot et al., 2020) that such uncertainty should not preclude decisions on coastal adaptation, since the do-nothing option may lead to larger mid/long-term impacts and costs, further exceeding what could be achieved by anticipatory decisions. The required transformation to preserve present coastal systems and facilitate shared coastal futures, should combine biophysical and socio-economic science, often unbalanced in technical assessments, and the aggregation must reflect an ethical dimension that presents error intervals and the limits of the performed analyses. Making the risk and impact estimation more transparent and ethical is considered to be key for avoiding recent past blunders in coastal decision making, where adaptation pathways and particularly their tipping points became controversial subjects that precluded timely decisions. As a result, reactive decision-making or even the "do nothing" option were favored, leading to a steady degradation of coastal systems and increasing risk levels for population and economic/natural assets. A proactive approach, with anticipatory action that incorporates long-term priorities and builds upon robust (science-based) knowledge, should promote a balanced perception by stakeholders and general society, avoiding biased expert decisions or flattening public opinion rather than incorporating it into the knowledge basis for decision making. Such an approach, grounded by ethics, has proved to be a better long-term strategy for sustainable stakeholder cooperation, linked to a level of knowledge-based optimism (Seabright, 1993) that will facilitate a durable engagement.

Recent advances on models and observations (e.g., Sánchez-Arcilla et al., 2021) enable such an anticipatory approach which, however, may be hindered by vested conclusions and implicit error levels that hide a lack of ethics in the sense of promoting results that comply better with the interests of the more powerful stakeholders. Such a lack of ethical basis may erode the optimism necessary for anticipatory action, hampering the development of environmentally friendly and socially shared decisions, explaining why present societies balk at investments or interventions with mid/long-term benefits, and limited short-term returns. Such a short term bias, often accompanied by a too limited environmental responsibility, can be linked to the cumulative effect of limited ethics in environmental assessments, climatic analyses and valuation of coastal assets during the last decades. Promoting an ethical basis that combines short term with long term priorities and is not distorted by powerful stakeholders, will slowly demonstrate the benefits of explicit error intervals and fair decisions under uncertainty, favoring a return to the threshold level of optimism required for anticipatory coastal decisions. Below that threshold level, only short term coastal priorities will be considered, in a societal drive toward lower environmental responsibility, particularly toward future generations. Such a drive should be prevented, since it will severely limit the sustainability of present coastal systems, hampering the legacy of multifarious benefits from healthy coastal zones to future generations. That dangerous evolution should prompt an accelerated introduction of ethics in coastal assessments and adaptation decisions, so that error intervals for hazard and vulnerability estimations are made explicit, generating enough confidence and optimism to preserve coastal values for shared benefits.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article can be made available by the authors upon request, without undue reservation (except costs of data recovery).

AUTHOR CONTRIBUTIONS

AS-A coordinated the manuscript and prepared the approach and data treatment for assessing uncertainty. VG dealt with longshore transport estimations and morphodynamic analyses. CM carried out the damage and vulnerability estimations. IC tackled the lab data analysis and their extrapolation to field conditions. DG-M was responsible for the sustainability and adaptation aspects. JG dealt with the field data processing and probabilistic fitting. All authors contributed to the article and approved the submitted version.

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Grounding Ocean Ethics While Sharing Knowledge and Promoting Environmental Responsibility: Empowering Young Ambassadors as Agents of Change

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Actions addressing youths and marine science for "ambassadorship" are increasingly implemented *via* dedicated programs at the European and global level within the relevant policy frameworks, as a way for fostering the exchange of knowledge and cross-fertilizing practices among the Countries and basins. These programs are conceived to address the future generations of scientists, entrepreneurs, policymakers, and citizens, and to promote the awareness and shared responsibility on the sustainable use of marine resources in an authentic and credible way, through the empowerment of young researchers and professionals, communicators, or activists. Thus, such ambassadors are well-positioned to act as agents of change, improving the dimension of Ocean Ethics related to inclusive governance, especially necessary for an equal, just, and sustainable management of multi-actor and transboundary socio-environmental contexts. Pivoting on the Young Ambassadors' Program developed in the framework of the BlueMed Research and Innovation (R&I) Initiative for blue jobs and growth in the Mediterranean area as case practice, the article aimed to propose some reflections about the long-term perspective of such experiences. Outlining an emerging physiognomy of the "One Ocean Ambassadors," it discusses their potential to build the next generation of responsible scientists, citizens, and decision-makers and to embed ethical principles in research-based marine governance. In addition, it addresses process-related elements, such as balancing advocacy and ethics and reflecting on the role of science communication. To further consolidate this practice, this article finally seeks to incorporate the intercultural aspects to connect the local to the global dimension toward a sustainable and value-based ocean governance.

Keywords: young ambassadors, Ocean ethics, Mediterranean Sea, Responsible Research and Innovation, governance, communication, youth empowerment

INTRODUCTION

The ocean is necessary to the health and well-being of Earth and humans. It is an essential regulator of climate and life, providing vital goods and services and contributing to the socio-economic prosperity of coastal communities [(Avelino, 2017; The Intergovernmental Panel on Climate Change (IPCC), 2019; Food and Agriculture Organisation of the United Nations (FAO), 2020)]. In the last few decades, the sustainability of marine ecosystems has been posed at risk, due to the cumulative impacts of multiple anthropogenic stressors and to dramatic impact of climate change (Andersen et al., 2020; O'Hara et al., 2021; Vassilopoulou, 2021).

To underline the importance of science in developing reliable knowledge on the still poorly understood functioning of the oceans and the human-ocean interaction (Brennan et al., 2019) and provide evidence-based information to respond to the global challenges, the United Nations declared the years from 2021 to 2030 as the Decade of Ocean Science for Sustainable Development[1]. Deployed as a common framework to ensure that ocean science can fully support countries to achieve the 2030 Agenda (United Nations (UN), 2015), the initiative calls for international cooperation of multi-stakeholders to address the priority social outcomes.

When dealing with improving participation and building inclusive governance, outlining processes is not less important than defining concepts: we propose in this study our experience and reflections on the engagement of the BlueMed Young Communication Ambassadors, describing the value of including societal actors as an important way to integrate ethical aims in research-led initiative oriented to promote a sustainable blue economy, building shared stewardship of the sea. The potential of young ambassadors to boost knowledge circulation and to raise awareness around the Mediterranean area has determined our observation that they can actually become agents of change, promoting environmental responsibility. We also propose a preliminary outline physiognomy of the "One Ocean Ambassadors," emerging from the networking and synergies ongoing among the current programs and oriented to address the challenges of all the basins as interrelated natural and socio-political environments.

The Mediterranean has been for millennia at the heart of human cultures. However, a coherent, shared, sustainable, and knowledge-driven operational plan targeting the maritime activities was never promoted until 2014, when BlueMed, the intergovernmental R&I Initiative for blue jobs and growth in the Mediterranean area, implementing the European Blue Growth Strategy [(European Commission (EC), 2012)], developed a shared framework, resulting in the co-design of a Strategic Research and Innovation Agenda [(European Commission *ad hoc* advisory group of the BLUEMED Initiative (EC), 2015)].

The adoption of a holistic, trans-disciplinary, and inclusive approach constituted the core of this science-to-policy initiative, which intensively engaged stakeholders across the basin. In this vision, citizens are recognized to have a right to participate in the management of the "commons" (Vogler, 2012), i.e., common goods and services like those offered by the Mediterranean Sea, where conflicting uses of shared spaces and resources are likely to arise. BlueMed has built a network of actors, enabling national and inter-national policy-related dialogues *via* dedicated platforms to connect the shores of the basin. The youths were specifically addressed by the innovative Young Ambassadors' Program, aimed at sharing the BlueMed vision while building the next generation of marine science diplomats.

DEDICATED FRAMEWORKS FOR YOUNG AMBASSADORS AND OCEAN SCIENCE: PLACING ETHICS

Global mobilizations promoted by, or involving, young people standing up against the systematic inability of societies to address the climate crisis and other environmental issues, have had in recent years a new rise, e.g., the Fridays for Future global movement[2]. Not only they can push the claims higher in public policy debate, but also trigger a rethinking in the researchers and educators about the features and types of knowledge that are necessary, in formal and informal contexts, to tackle these inherently transdisciplinary, multi-interests challenges.

These mobilizations call for a paradigm change to frame economic and technological pressures in a sustainable, equitable, and prosperous picture, showing that reflections and public debate on ethical human-environment interplay cannot be further postponed.

From the perspective of a practitioner, we define ethics in this context as a living reflection on the values and principles guiding the conduct of humans. Analogously, we refer to Ocean Ethics as the ethics of human interplay with marine environments, both at individual and collective levels.

Complementing and integrating the approaches to the ethics of research and specifically of marine observation [as shown in UNESCO, 1999a,b; European Commission (EC), 2005; Owen et al., 2012; Avelino, 2017; Barbier et al., 2018; L'Astorina and Di Fiore, 2018], our perspective on Ocean ethics concentrates on the dimensions dealing with the principles driving collective behaviors, which are particularly relevant when multi-actor, transdisciplinary, and transboundary issues are involved and shared decisions are at stake, as in the case of marine environments. Specifically, we frame Programs of the ambassadors in the development of more inclusive governance of the common marine environments, basing on reflexive and balanced incorporation of scientific knowledge.

Academic reflection has underlined the relevance and delicacy of the knowledge-deliberation interface (e.g., Jasanoff, 2005; Fricker, 2007) and has suggested the need for widening societal inclusion, especially when dealing with issues at the intersection of different disciplinary visions and involving the interests, expectations, and concerns of diverse social groups. Moreover, enlarging the community of actors collaborating in the construction of knowledge is deemed necessary to improve the

[1]https://www.oceandecade.org/

[2]https://fridaysforfuture.org/

quality of knowledge itself and its social robustness (Funtowicz and Ravetz, 1993; Gibbons et al., 1994).

Transdisciplinary research can allow for knowledge co-creation and exchange, as well as social learning, including in the marine realm (Wehn et al., 2018; López-Rodríguez et al., 2019), enabling the formation of networks of stakeholders, and strengthening institutional frameworks. However, to be genuinely oriented to societal inclusion, a knowledge-based approach to the management of marine resources needs to be anchored to a shared governance (Kooiman et al., 2005), designed to be suitable to socio-ecological systems (Barbier et al., 2018). Effective institutional management should be based on inclusive, participatory decision-making, in which all actors are represented, and the awareness of relevant scientific evidence is complemented with broad ethical principles (Thompson, 2012). The integration of ethical values, transparency and social justice in practices and norms are necessary to balance processes involving multiple interests. This integrated approach can also pave the way towards effective, transparent and inclusive planning and management of human interactions with marine ecosystems (Morf et al., 2021), as also recognized by the ecosystem-based management approach (Cormier et al., 2017).

The key to the integration of scientific knowledge in plural socio-political arenas is a reflexive communication of scientific contents, aware of the debate on the societal value and orientation of science, and being able to stimulate a critical, value-based, public discourse on science and society (Davies, 2020).

Inclusive governance and reflexive science communication constituted the core of the activities of BlueMed Young Ambassadors. The BlueMed Ambassadors' Program experimented with new processes to engage young people, with particular emphasis on the key environmental problems of the Mediterranean Sea, promoting their civic roles, empowering them with up-to-date and transdisciplinary scientific reflections, and engaging them in the decision-making process.

The Mediterranean young ambassadorship is not a single case. The programs of marine ambassadors specifically focusing on the different basins and/or encompassing a European and global dimension have been developed in recent years: among others, the All-Atlantic Youth Ambassadors[3]; the Black Sea Young Ambassadors[4]; the European Marine Board (EMB) Young Ambassadors[5]; and the United Nation Education, Scientific and Cultural Organization/Intergovernmental Oceanographic Commission (UNESCO/IOC) Early Career Ocean Professionals (ECOPs)[6].

These programs focus on the different geographic areas and are anchored to diverse institutional frameworks (**Table 1**), but share; however, they have in common a super-national approach and an awareness-raising breath. All the programs valorize the networking of ambassadors as all citizens of One Ocean (Wilcox and Aguirre, (2004)), sharing sustainable behaviors and reinforcing the bonds between the ocean, conceived as an entity *per se* and not just as a void space among lands, and the citizens (Alexander et al., 2019). Thus, they support the development of Ocean ethics. They embody the connection between high-level knowledge-based political initiatives/organizations and the engagement and mobilization floor of citizens. In doing so, their actions regularly build on the ethical core of a collective assumption of responsibility for the common Ocean.

Looking at the increasing number of initiatives dedicated to young marine ambassadors for advocating a specific blue vision in the "One Planet One Ocean" framework, **Table 1** proposes a synoptic view of a selection of programs of ambassadors targeting marine science and youth empowerment, presented by geographical focus, institutional framework, number and disciplinary background of ambassadors and duration of a program. In the Atlantic, the Mediterranean, and the Black Sea, the programs are pivotal for supporting European internationalization strategies, fostering scientific cooperation across borders, and promoting the respect of fundamental values and principles [(European Commission (EC), 2021; Polejack et al., 2021)]; EMB Ambassadors stemmed within the leading European think tank in marine science policy and are engaged to promote marine science and EMB activities; ECOPs have a central role in designing and implementing the activities of the global UN-Decade of Ocean Science. These programs have been selected for the scope of the present article due to their common approach, as well as considering the networking action by the BlueMed Initiative for developing synergies, as explained next. Though, the assessment is not assumed to be exhaustive[7].

An initial set of value-based commitments for Ocean ethics shared by the programs emerges from the descriptions that each organization provides for promoting the engagement of the ambassadors (**Table 2**). Although different in size and geographical scope, they share the objectives of enabling change and building the next blue generation, as well as of fostering peer-to-peer networking and of facilitating local-to-global communication, leveraging on agile use of social media, and supporting travels and participation to international events. On the other side, building future citizens and empowering youth in contributing to co-designing strategic activities appears explicitly described only in some cases, while in others it is considered rather an impact or legacy of the ambassadorship action itself.

Figure 1 sketches the features emerging from the synoptic view of the programs, enabling to draw a preliminary outline of the future "One Ocean Ambassadors," stemming from the acknowledgment of the interrelation of all the basins and possibly arising from the promising synergies ongoing among the programs. The young ambassadors are mainly students or early-career professionals aged 20–35 years, coming from marine sciences but also from science communication, science diplomacy, or environmental activism; they are network builders and creative and skillful users of communication means, able

[3]https://allatlanticocean.org/view/atlanticambassadors/introduction#; Twitter account: @AtlanticYouth.

[4]http://connect2blacksea.org/outreach/youth-ambassadors/; Twitter account: @BlackSeaYouth.

[5]http://www.marineboard.eu/emb-young-ambassador-Program

[6]Twitter account: @OceanDecadeECOP.

[7]Mediterranean Youth Forum to empower the youth for regional cooperation.

TABLE 1 | A comparison of the main features of selected marine ambassadors' programs.

	All-Atlantic youth ambassadors	**BlueMed young communication ambassadors**	**Black sea young ambassadors**	**European Marine Board young ambassadors**	**UNESCO-IOC ECOPs**
Geographical focus	Atlantic Ocean 	Mediterranean Sea 	Black Sea 	European Seas 	All Oceans and Seas 
Institutional framework	EU-Atlantic cooperation action within the All-Atlantic Ocean Research Alliance[1]	Mediterranean cooperation action within the BlueMed–Research and Innovation Initiative for blue jobs and growth in the Mediterranean area[2]	EU-Black Sea cooperation action within the Blue Growth Initiative for Research and Innovation in the Black Sea[3]	Program of the European Marine Board,[4] the strategic pan-European Forum for seas and ocean research and technology	Program of the UNESCO Intergovernmental Oceanographic Commission[5]
N° of ambassadors	23 (first cohort) 25 (second cohort)	5	17	2 (first cohort) 2 (second cohort)	Not-fixed
Ambassadors' background	Early-career ocean professionals	Marine sciences students and communicators	Student or post-doc in different disciplines, science communicators, environmental activists from Non-Governmental Organizations (NGOs), science diplomats	Marine science students	Early-career ocean professionals
Program duration	2019–2020 (first cohort) 2020–2021 (second cohort)	2018–2021	2020–2022	2020–2022 (first cohort) 2021–2023 (second cohort)	2020

[1] *https://allatlanticocean.org/whoweare*
[2] *https://www.bluemed-initiative.eu/about-the-bluemed-initiative/*
[3] *http://connect2blacksea.org/about-the-initiative/*
[4] *https://www.marineboard.eu/about-european-marine-board*
[5] *https://ioc.unesco.org/*

to effectively raise the shared public awareness on critical issues and behaviors. They are trained on up-to-date science, with a focus on inter and transdisciplinarity, enabling them to frame the scientific knowledge base in the complex socio-ecological and political context. They are called to act in the responsibility roles (spokespersons, organizers of the events, and leaders of movements), achieving an impact on an international level. In terms of driving core values, these programs ground their activities on intergenerational diversity, cultural exchanges, wide and equal inclusion of all concerned voices (scientists, citizens, stakeholders), assumption of responsibility over the sustainable use and management of the Ocean resources, and respect for human and non-human environments.

THE CASE OF THE BLUEMED YOUNG COMMUNICATION AMBASSADORS' PROGRAM

The signature of the Valletta Declaration in 2017 (Malta EU 2017, 2017), during the Malta Presidency of the EU Council, marked the enlargement of the BlueMed Initiative toward non-European Mediterranean countries and their full engagement into the activities. Among the enlargement actions that have been developed to ensure sharing of the BlueMed vision in such contexts, the BlueMed Young Ambassadors' Program[8] was deployed as a tool of science diplomacy oriented to facilitate international science cooperation and improve international relations (The Royal Society, 2010) to finally consolidate the dialogue across all shores of the Mediterranean Basin.

The objective of the program was to engage and coach a group of highly motivated young people from non-EU Mediterranean countries, to share the BlueMed vision in their contexts, and set the grounds for the development of a pan-Mediterranean network of "BlueMed Ambassadors," aiming to promote the research-based approach for a sustainable blue economy at the Mediterranean scale and beyond. Following a gender-balanced selection from a group of candidates proposed by the delegates of non-EU Mediterranean countries, five youths from Algeria,

[8] http://www.bluemed-initiative.eu/the-young-communication-ambassadors/

TABLE 2 | Description of the ambassadors' programs published on the websites of home institutions or in official documents (in a single case in which a description was not publicly available, the authors report the exchanges with the Program coordinator).

All-Atlantic	**(…) to enable the next generation to become actors of change in their communities, by promoting stewardship** of the sustainable development of the Atlantic Ocean. Equipping a broader community of early-career ocean professionals with the skills, education and training to enable them to drive movements of positive change and sustainable development along and across the Atlantic Ocean. The Youth Ambassadors program is the cornerstone of a larger effort to build the Youth Forum that will **integrate (…) communication and outreach** and will become a **major vehicle to promote young people's competences and skills** (From the Initiative website[1]).
BlueMed	(…) to **engage and coach**, in line with the priority goal on "building capacity, blue skills and blue professionals," a group of **highly-motivated young people** from non-EU Mediterranean countries, **to share the BlueMed vision** in their contexts (…) toward a sustainable Blue Economy at the basin scale and beyond. **Empowering youth** with the **appropriate knowledge** on global challenges and with an adequate **interdisciplinary vision** facilitates their **becoming agents of change** (Source: European funded project BlueMed Coordination and Support Action, Grant Agreement N. 727453).
Black-Sea	(…) **passionate, engaged and creative** Young Ambassadors willing to play an important role in **advocating for the Blue Growth** in the Black Sea by means of creative communications. As well as promote RandI goals enhancing the visibility and increasing countries' potential, **linking with the community of stakeholders and building new communities.** Interested in science diplomacy, public engagement, education, and training, following some learning about the Black Sea issues they will **design and develop awareness campaigns** for seas and oceans and be ready to **act as spokespersons** for the Black Sea Initiative, actively participate in related activities and have the opportunity to present their work at major events (Source: coordinators of the European funded project "Connect to Black Sea").
European Marine Board	The European Marine Board (EMB) ambassadors will play an important role in **advocating for and promoting the relevance of marine science and the ocean** in general to their peers and wider networks **making sure that the voices and ideas of young researchers are reflected within the EMB's future work**, including by using their creativity, imagination, communication and interpersonal skills. EMB ambassadors (…) are requested to participate in various activities, including attending and participating in one or more EMB plenary meeting(s) and/or other external events or workshops (From the EMB website[2]).
UNESCO/IOC	Early Career Ocean Professionals (ECOPs) are a significant **focus of the UN-Decade of Ocean Science for Sustainable Development 2021–2030** and have been directly engaged during the preparation phase. ECOPs can make crucial contributions to the Decade by **actively participating** in Decade Actions, **acting as** Decade **ambassadors**, and **continuing the Decade's legacy** (…). Bringing intergenerational diversity and ocean expertise into the Ocean Decade, they will benefit from **professional development opportunities** (…) join and lead scientific collaborations and partnerships (Source: UN-Decade of Ocean Science Implementation Plan.[3]).

[1] *https://allatlanticocean.org/view/atlanticambassadors/introduction*
[2] *www.marineboard.eu/emb-young-ambassador-Program*
[3] *https://oceanexpert.org/document/27347*

Egypt, Morocco, Tunisia, and Turkey were appointed as BlueMed Young Communication Ambassadors.

The first step of their involvement was a training event held in Barcelona in 2019 at the Union for the Mediterranean premises, where they could exchange experiences and visions and be taught on the BlueMed priorities (Trincardi et al., 2021). In coordination with the BlueMed Pilot action for a Healthy Plastic-free Mediterranean Sea[9], marine litter was chosen as a thematic special focus. This global challenge requires indeed urgent cooperation, not only among the governmental bodies but also among stakeholders and coastal communities. The training was not limited to the scientific perspective, but it was conceived to be markedly interdisciplinary, including high-quality sessions on science diplomacy and science communication. Informal gatherings and non-mediated interactions, including *via* social media groups, proved as beneficial to build and consolidate collaboration and trust, and possibly foster the circulation of ethical values and perspectives.

Indeed, the focus on reflexive communication was a distinctive trait of the program, especially in conjunction with the transnational perspective offered by the science diplomacy frame. Thanks to the involvement of science communication researchers, the ambassadors could be acquainted with the basis of the contemporary vision on science communication, overcoming the severe limits posed by the traditional top-down approach, based on an incomplete vision of the public (L'Astorina and Valente, 2011). The Responsible Research and Innovation frame (RRI) (Ferri et al., 2018) was another important conceptual reference, and relevant participative methods were showcased (e.g., MARINA project[10], Sea Watchers platform[11]). The actions of ambassadors were shaped accordingly: not only aimed at amplifying and diffusing the BlueMed concepts but including also local knowledge and expectations in a perspective of cultural reciprocity. In particular, communication was not intended solely as a powerful technical Ocean Literacy[12] means to advocate for BlueMed and raise awareness, but as a fundamental network-building instrument, able to offer the public a more multi-faceted perception of science, possibly contributing to a higher democratization of knowledge and, hence, to a higher quality of public engagement.

The mandate of ambassadors was structured around the development of actions targeted to explore the complex political, socio-economic, cultural, and behavioral dimensions of the marine litter problem, from prevention to mitigation and removal, with the final aim of achieving a real change, from

[9] http://www.bluemed-initiative.eu/pilot-action-on-a-healthy-plastic-free-mediterranean-sea/

[10] www.marinaproject.eu/
[11] www.seawatchers.net/
[12] https://oceanliteracy.unesco.org/?post-types=all&sort=popular

FIGURE 1 | The physiognomy of the "One Ocean Ambassadors" emerging from the comparison of current marine ambassadors programs.

the environmental regulations and policies to the shared awareness of the stakeholders and citizens, to the practices of the Mediterranean coastal communities. Beach clean-ups, educational initiatives, and communication campaigns focused on the need to cut down plastics waste: all actions were planned in relation to country-specific or local contexts, under the common theme of "*pollution needs no visa.*" The motto was chosen by the ambassadors themselves, also echoing some of the difficulties they experienced in participating in the activities (e.g., due to VISA needs!), and underlining how anthropogenic litter—differently to people—can travel and reach anywhere without permit.

The ambassadors were able to link the local with the global dimensions, embracing the slogan "think globally act locally" which is pertinent to all global challenges, from climate change to marine litter. They succeeded in developing campaigns, able to speak in local contexts while retaining the complexity of the musings shared among the international community of scholars and practitioners (Vassilopoulou et al., 2021). For example, the Tunisian BlueMed Young Ambassador produced a short video documentary on the shift from traditional fishing practices to single-use plastic traps and on its environmental and socio-economic impact on the Kerkennah Archipelago community[13]. The Ambassador interviewed local handcrafters and involved voices of different generations, finally opening viable options to revert the path toward sustainability. The video was shot in Arabic and French, with English subtitles, for reaching local and international communities. The Turkish and the Algerian Ambassadors supported the production of video clips showing how the human plastics-based economy and related behaviors affect the underwater world[14], to be disseminated locally (e.g., on public transportations) as well as on social media. All the ambassadors were also active on the educational side, organizing workshops for children and students, and beach-cleaning campaigns geared to raise the environmental awareness of local communities.

[13]https://youtu.be/yTizuSeQyDg
[14]https://youtu.be/8wY5bpxy9zc

Another structural pillar of the program was the active participation to design the international conferences and events where ambassadors were given the floor to share knowledge, experiences, and visions and build a network of exchanges with their peers.

Their involvement in the European Science Open Forum 2020 was framed as a story-telling conversation between them and high-profile policy and scientific officers from the EU Commission and delegates of the BlueMed initiative[15].

The opening session of the BlueMed Conference "One Mediterranean: practices, results, and strategies for a common Sea"[16] organized in 2021, represented the first edition of a cross-basin and global dialogue among Young ambassadors, linking the Mediterranean Sea shores, the European basins, and the global Ocean. The process through which actors gain the capacity to mobilize resources and institutions to achieve a goal the BlueMed Ambassadors (Avelino, 2017) autonomously organized and chaired the session, exchanging views with their peer ambassadors from other basins and programs and conducting the conversations toward the identification of possible synergies and cross-basins network building.

It is worth noting that although the COVID-19 pandemic restricted physical interactions, these remote events enabled successful exchanges with peers and the audience. Positive hints of how the ambassadors are interpreting their mandate and on the most significant advantages from participating in such programs were informally gathered after the BlueMed Conference: they valued it as an enriching science diplomacy experience, allowing to learn about the actual challenges, as well as to interact with all sectors of society; a valuable exchange of visions, where empowerment derives from the ability to exchange views and a powerful capacity of networking; an incubator of new ideas having the potential to arise and flow.

DISCUSSION AND CONCLUSIONS: EMPOWERING YOUNG AMBASSADORS AS AGENTS OF CHANGE

The considered ambassadors' programs, although at different stages of maturity, show the emergence of a group of crosscutting ethical foundations inspiring the actions and visions of the involved youths. These includes the assumption of co-responsibility, the richness coming from intergenerational, cultural and geographic diversity, the importance of reaching and involving all concerned voices, an ecological vision of environmental respect and, most important, the assumption of collective responsibility over the sustainability of One Ocean as a global commons.

Establishing synergies among the young ambassadors' programs was recognized as an important future objective to emphasize the interrelation of basins for homogeneity and improve the impact of the ambassadors. However, to ground Ocean ethics, these initiatives need to be considered both as instruments of knowledge sharing/sustainability advocacy and as open.

Young and motivated people proved ready to act coordinately to improve inclusive governance and contribute to the socio-political, cultural, and behavioral change in the field of marine sustainability. Along with their mandate, the ambassadors succeeded in sharing their thoughts and perspectives with relevant policy officers and delegates at national, European, and intergovernmental levels, and their contributions were valorized as the voices of the future generation inheriting this Planet. In particular, the BlueMed Program especially fostered the awareness of ambassadors of the delicacy of the knowledge-society interface, as well as improved their science diplomacy and science communication skills. Such skills are flourishing also beyond their mandate, in the diverse contexts in which they have been invited to contribute.

An emerging physiognomy of the future "One Ocean Ambassadors" can be outlined from the reasoned comparison of selected programs, as depicted in **Figure 1**.

In our perspective:

- recognizing that marine citizenship requires an enhanced awareness of environmental issues as well as an understanding of the role of personal and collective behavior (McKinley and Fletcher, 2010), an inter- and trans-disciplinary training is a crucial attribute. This should include science studies, reflexive science communication, and science diplomacy in addition to ocean science, and promote a critical rethinking of paradigms and values as well as the adoption of environmentally friendly behaviors;
- the programs of ambassadors need to remain flexible to embrace cultural differences and interests but clearly define roles, goals, and mandates. As young ambassadors, in most of the cases, volunteer their time and effort, a clear win-win framework of activities should be established where both the ambassadors and the programs' managers are supported and motivated. Not only identified benefits would contribute to the positive outcome of the program, but also the ethical issues related to involving volunteers would be duly addressed.
- to take stock from these experiences and further consolidate the promising work of existing programs, while incorporating Ocean ethics, a necessary step will be improve the trans-boundary approach: a dedicated, institution-supported platform such as the Youth4Ocean Forum[17] should represent the starting point to envisage a structured cluster of the One Ocean young ambassadors routinely contributing to the ocean governance, at the science-to-policy and society-to-policy interface;
- improved support from relevant national public bodies to international projects and fora involving young ambassadors would increase their impact;
- it is still unclear at what level the role of young ambassadors can contribute to governance processes. Nevertheless,

[15] https://youtu.be/xXaVG4LtR6M.

[16] http://www.bluemed-initiative.eu/bluemed-final-conference/

[17] https://webgate.ec.europa.eu/maritimeforum/en/frontpage/1484

under the umbrella of trans-border and multi-stakeholder governance framework, a science policy advocacy group enriched with the voices of motivated youths, able to connect the local and international levels in a balanced, holistic, and ethically informed perspective, has the potential to mobilize policy circles and communities to act change, in line with the UN 2030 Agenda [(United Nations (UN), 2015)], targeting, in particular, the Sustainable Development Goal 14 "Life below Water."

We also underline that any view of the youths solely as "loudspeakers" of concepts developed elsewhere should be avoided since, as we have shown, trusted and empowered young ambassadors have the potential to pursue the paradigm change necessary to trigger the unprecedented socio-environmental challenges that contemporary society is facing.

The regular assessments and analyses, *via* surveys and informal conversations, integrating social science and humanities, need to be put forward as tools for setting up a coherent framework for actions, as well as a reflexive monitoring process, such as qualitative and quantitative indicators to benchmark activities, results, and impacts. Getting inspired by the inclusion of representatives from the 14 European Young Academies in the latest meeting of the European Commission official Group of Chief Scientific Advisors (Nature Editorial, 2021), we propose as a pilot indicator within R&I actions to measure how open decision making bodies are to youths. Potentially, this approach could be beneficial to consolidate the role of young ambassadors in the public policy debate.

In addition, efforts are needed to focus on the viable paths to further develop the integration of ethical core values in initiatives involving young ambassadors and to promote Ocean ethics as an explicit debate theme. At least three relevant ethics dimensions are indeed addressed within this article: towards future generations, for cooperation between countries, and towards the ocean as a whole.Thus, this approach would enable to build the next generation of scientists, citizens, and decision-makers, more aware of the complexity of the socio-economic, ecologic, cultural and political ocean-landscape, and equipped with adequate instruments to manage this complexity.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

MC, RG, and AL'A contributed to conception, design, and preliminary drafting of this perspective article. Based on the design and co-development of the BlueMed Young Ambassadors' Program and related activities in the framework of the BlueMed EU funded project, EK and VV contributed to relevant sections. All authors contributed to manuscript revision, read, and approved the submitted version.

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Maximizing Benefits From Punctual Ocean Infrastructure: An Ethical Perspective

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Ethics are becoming a component of best practices in ocean science and observing systems, with the research community facing a duty to society to maximize the efficient use and benefits that stem from investments in ocean science/monitoring. Sustained ocean observing systems on issues of global importance are coordinated, internationally sanctioned and making the most out of the resources accorded to them and consequently fulfilling their duty to society. However, globally huge investments are made annually in establishing infrastructure for shorter-term, punctual studies that address targeted as opposed to broad science needs. More could be done to maximize the benefits and impacts of these punctual efforts. Given punctual infrastructure's small and frequently transient nature, connections to enable sharing will probably be done locally, and both potential additional users and owners of the infrastructure will need to be energetic, receptive and flexible. The accommodation of new uses will have to be balanced against any costs of these additional activities, which could pose an ethical dilemma in themselves if they compromise the infrastructure's ability to meet its original intent. However, such adaptive infrastructures may be the most efficient way to provide the resources needed to identify and monitor emerging or new ocean stressors.

Keywords: ethics, ocean, observation, punctual infrastructure, communication

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INTRODUCTION

The launch of the United Nations Decade of Ocean Science for Sustainable Development ("the Decade"[1] marks a period of great hope for a global transformation of humankind's caring for and use of the ocean. Hailed as a once in a lifetime event that will provide the science we need for the ocean we want, the Decade has focused on major ocean themes (e.g., climate change, deoxygenation, marine plastics, acidification/decarbonization) with hopes to make major progress in addressing these critical stressors by its end.

A huge portion of the ocean economy and consequently human impacts on the ocean is driven by local developments within the coastal communities of nation states. Coastal communities have always looked to the ocean for their subsistence needs and socioeconomic well-being. Such communities pursue traditional activities such as fishing and shipping, while actively

[1] https://en.unesco.org/ocean-decade

seeking new or "underutilized" opportunities to maintain or grow the benefits they can obtain from the ocean. On their own, many of these activities have minor impact, however, collectively they may negatively impact productive, coastal waters (e.g., McCauley et al., 2015). Ocean observing systems in the broadest sense are our "Eyes on the Ocean"[2] and provide pivotal measures and information to guide the avoidance or mitigation of harmful anthropogenic stressors and protect the social and economic benefits that the ocean provides.

Current sustained ocean observing systems (e.g., Argo floats[3]; WMO drifter buoys)[4] are well coordinated and conduct offshore, internationally significant work addressing issues such as the Decade challenges. These activities are nationally and internationally endorsed, coordinated and resourced. By contrast, in coastal areas a massive amount of punctual scientific work is underway, some undertaken by national and regional authorities, but with huge contributions from academia, the private sector, governments, non-governmental organizations, and more recently citizen science. Limited efforts have gone into documenting and protocoling the scope of these contributions. Assuming science funding provided to researchers in the academic and institutional sector is primarily directed to punctual (short-term, narrow focus) projects, a sense of the current activity can be developed. In Canada, funding to the academic ocean sector from various agencies was conservatively estimated to average about $92 M (Can) per year in the 2002/03–2011/12 period, and the estimate was believed to cover one quarter to one third of total university spending on ocean science (Expert Panel on Ocean Science, 2013). Isensee (2020) provided estimates of academic and institution ocean research spending from 26 countries, with values for individual countries ranging from a few million dollars (US) to nearly $600 M (US) per year.

Punctual studies especially in the academic sector differ from the previously described coordinated offshore work. Such studies are frequently conducted as independent, varied, short-term and/or geographically limited, coastal projects that address fundamental science issues and are laser focused on meeting the science and reporting needs of the investigation team. Various infrastructures (examples: submerged moorings with oceanographic or other instruments attached), e.g., using commercial lobster trap deployments as infrastructure and placing temperature recorders (Fishermen and Scientists Research Society)[5] or acoustic receivers on the traps as per Goulette et al., 2014; instrumented buoys anchored at fixed stations, e.g., Boknis Eck Time Series stations in Eckernförder Bay (southwestern Baltic Sea)[6]; periodic sampling of fixed or variable stations from research, commercial or education vessels) are developed to conduct this work. All of these are highly valuable resources that could utilized for multiple uses if owners of the infrastructure are aware, willing and able to accommodate additional scientific uses and users.

[2]https://ioos.noaa.gov/communications/eyes-on-the-ocean-ioos-bi-weekly/

[3]https://www.aoml.noaa.gov/phod/argo/

[4]https://www.aoml.noaa.gov/global-drifter-program/

[5]https://obis.org/dataset/68670603-4fca-4b3b-ab33-f50b859e3afc

[6]https://www.bokniseck.de/de

THE ETHICAL CHARGE

Ethics can be defined as "well-founded standards of right and wrong that prescribe what humans ought to do, usually in terms of rights, obligations, benefits to society, fairness, or specific virtues" (Velasquez et al., 2010). In a review of ethics in scientific research, Weinbaum et al. (2019) identified 10 ethical principles common across scientific disciplines: (1) duty to society; (2) beneficence; (3) avoiding conflict of interest; (4) informed consent; (5) integrity; (6) non-discrimination; (7) non-exploitation; (8) privacy and confidentiality; (9) professional competence; (10) professional discipline. We believe that the conduct of ocean science activates a duty to society for researchers because their research is either funded by or providing results of interest to the public.

The sustained ocean monitoring systems under the Global Ocean Observing System (GOOS) encapsulate a number of key attributes. These systems are mission orientated and internationally coordinated.[7,8] GOOS monitoring has been community driven in its development (e.g., Task Team for an Integrated Framework for Sustained Ocean Observing, 2012), and addresses grand scientific imperatives whose impacts can put human and/or ecosystem welfare globally at risk (one example is GOOS' lead role in monitoring trends in ocean temperature globally). Furthermore, they have the backing and resourcing needed to provide credible and trusted information that informs policy makers and managers (e.g., Muller-Karger et al., 2018; Estes et al., 2021). GOOS also has the communications tools needed to provide explanations to the public so that they understand the significance of the issues being addressed. This work is firmly rooted in the duty to society principle.

By contrast, punctual, fundamental research in coastal areas is curiosity-driven, important, beneficial, and generally ethical, but it is not coordinated in the same way and does not have the longevity that sustained observing systems have. On their own the studies that are underway may not have immediate relevance to current issues, and in the public's eyes may seem of little value.[9] Alternatively, punctual studies may be focused on critically important but very local practical issues. For example, the siting of a fish farm that could affect local fisheries can become a locally explosive issue but not one with the same scope as the changing ocean heat budget. Accessing field sites provides particular and expensive logistical challenges for all ocean studies, driving up costs. We suggest that this issue poses an ethical charge on researchers to maximize the benefits that flow to the public from the resources invested in putting us to sea.

UNIQUE ADVANTAGES TO PUNCTUAL OBSERVING INFRASTRUCTURES

The culture of academic and government ocean research differs. To take a Canadian example, Canada's Department of Fisheries

[7]https://ioc.unesco.org/node/2

[8]https://www.goosocean.org/index.php?option=com_content&view=article&id=272&Itemid=411

[9]https://www.goldengooseaward.org/01awardees/sea-soy-solution

and Oceans (DFO) is by far the dominant ocean research institution in the country (Expert Panel on Ocean Science, 2013). The Minister who oversees DFO receives a mandate letter identifying clearly defined ocean priorities of the Federal government on which DFO is to focus.[10] Subjects that are not on the list are addressed when and if time and resources permit. By contrast, academic funding agencies in the country are now asking that a diverse set of criteria be met by the researchers that are requesting funding. There is an expectation, if not an obligation, that in addition to addressing the science of research proposals, that the successful investigators also contribute to the training of future generations of diverse early career professionals, support industry in developing new technologies and economic opportunities, and communicate results of their work to a broad range of stakeholders. This predisposes the researchers to novel collaborations. The ocean infrastructure established for punctual research studies may be particularly beneficial to meet the diverse needs of the multiple and varying sectors in that:

- In being coastal or inshore, such infrastructure is easily accessible enabling frequent trips to the sites to retrieve timely results.
- For many Small and Medium Enterprises (SMEs), the cost of field-testing their new technologies and instrumentation can be a significant burden. Testing on an established, easy-to-access infrastructure at low-to-no cost is highly attractive.
- In collaborating different groups can network and tap into each other's technical and communications capabilities, improving work capabilities and facilitating information exchange about each other's work. Individuals maintaining punctual infrastructures are frequently "site attached" to a particular place in the ocean. While their study foci and the infrastructures used may vary over time, in working within these same areas for extended periods of time, they develop a deep knowledge of local conditions as well as trust relationships with local stakeholders. In meeting the needs of more user groups, punctual research can help to fill knowledge gaps for decision makers, and put punctual research on the high ground with regards to use of public resources.

OBSTACLES AND QUESTIONS

There are potential costs and risks in enabling the sharing of infrastructure for purposes other than those it was originally intended to serve. Meeting the scientific needs for which the infrastructure was originally established is the paramount ethical responsibility for investigators and also an issue of great concern to funders. Doing so is directly relevant to the duty to society, professional competence and professional discipline principles. Failure to do so because resources were diverted to addressing other topics poses a serious risk of censure of the current and future activities for the investigators and the funding agency alike. Secondly, taking the lead in communicating the opportunity and organizing the logistics of sharing the infrastructure capabilities is time consuming and can detract from primary research activities. Scientists are career-driven and work in a hierarchy where failures or delays in delivering results can significantly impact careers (Fortunato et al., 2018). Third, there are potential liability risks involved in sharing infrastructure. Defining who bears what risk, especially in terms of damage or loss to equipment that is co-deployed, is necessary. Fourth, there will be a limit on how much sharing can occur on any given infrastructure. When demands for co-deployments exceed the capacity of an infrastructure to accept them and still fully support its core mission, some sort of fair and transparent procedure to evaluate which co-deployments are to proceed could be needed. Finally, many investigators are reluctant to participate in research collaborations and/or share data, for complex and varied reasons that depend on factors such as intellectual property issues, whether the person is naturally altruistic and the type of institution in which they work (Nguyen et al., 2017).

FAILURE AND SUCCESS: THE CASE OF THE OCEAN TRACKING NETWORK

The Ocean Tracking Network (OTN; see Hussey et al., 2015; Iverson et al., 2019) is a global technology, infrastructure and research platform headquartered at Dalhousie University, Halifax, Nova Scotia. Starting in 2008, the OTN began deploying acoustic receivers and oceanographic monitoring equipment in key global ocean locations to document the movements and survival of marine animals carrying electronic tags, and to link both to oceanographic conditions. Annually, OTN deploys approximately 2000 moorings globally. Some of these deployments are semi-permanent, whereas others change from year to year.

OTN has benefited in its work by opportunistically deploying acoustic telemetry equipment on mooring systems established for other purposes. The most expansive of these is the PIRATA (Prediction and Research Moored Array in the Tropical Atlantic) buoy network which spans the Tropical Atlantic Ocean between Africa and Brazil (Bourlès et al., 2019). This has enabled OTN to provide receiver coverage in an area that OTN could not otherwise afford to cover, to the benefit of the international network of scientists who work with the OTN. OTN has been consciously seeking to return this favor by finding opportunities for others to benefit from working with OTN's own moorings. This has met with mixed success.

At certain predictable locations and depths, extended OTN mooring deployments are prone to extensive biofouling. Based on this, OTN anticipated that its moorings and established maintenance schedules providing access (at our expense) could be of considerable interest as test beds to researchers and companies attempting to find new solutions to reduce biofouling. Such solutions would also be of direct benefit to the OTN by reducing the amount of future labor needed to remove biofouling. However, to date none of the outreach has generated

[10]https://pm.gc.ca/en/mandate-letters/2019/12/13/minister-fisheries-oceans-and-canadian-coast-guard-mandate-letter

interest in using our infrastructure to study new methods of biofouling control.

By contrast, this biofouling on these moorings proved to be of great interest to another community investigating deep-sea sponge grounds. OTN learned of the European Horizon 2020 SponGES project[11] through an early morning interview on a local radio station in Nova Scotia. The interview described the challenges being faced by Canadian members of SponGES from the DFO as they worked to obtain samples of glass sponges (*Vazella pourtalesii*) off Halifax. This was despite having access to a large research vessel, and the highly capable ROPOS (Remotely Operated Platform for Ocean Science) remotely operated vehicle.[12] Fortuitously, a line of OTN receivers had been placed through the target sponge grounds. OTN worked with the SponGES team and brought some of these to the surface to see if the sponges had colonized them. Hundreds were present, providing unique insights into settlement patterns, growth rates, and reproduction of the species. The sponges also arrived at the surface in great condition making it feasible to transport them alive to the laboratory where controlled experiments could be undertaken. Additional tissue samples were distributed among the investigators of the network for genetics, microbiotics and marine biopharmaceutical research, with some work published (e.g., Busch et al., 2020) and much still ongoing.

MAKING CONNECTIONS HAPPEN

Small scale, diffuse, anthropogenic ocean impacts such as municipal waste discharges or the impacts of a fish farm will typically manifest themselves at local as opposed to global scales. The practical significance of this is that local people will first identify stressors at this scale. A corollary to this is locally networked scientists will be the first to be sought out to try and help with such problems. Thus, opportunities to connect potential infrastructure capacities with people who seek to address the issues will need to occur at the local level. Probably most of this will be done by word of mouth, and for this to be effective both the owners of the infrastructure and the research teams seeking access to it will need to be energetic, receptive, and flexible.

The groundwork that needs to be laid to make it probable that timely connections occur is in communication with local groups about the available research infrastructure and about the expertise of local investigators. When receptive minds learn about the infrastructure and expertise, connections will form. The OTN SponGES link mentioned previously is a good example of this. While many connections may occur informally, we also have examples of sophisticated and directed networks that could serve as models. Otlet[13] was formed to provide a global open-access platform to share and source marine biological samples. It was developed to address the waste of time, money and world class research opportunities that occurs when haphazard (informal) means are used to try and establish scientific collaborations. Otlet is a data system that matches those seeking samples with those who have them. Their system currently catalogs 22,000 samples from 330 species and has 645 scientists engaged.

Regional ocean observing associations also have the potential to foster connections. In both the United States and Canada, associations such as the Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS),[14] the St. Lawrence Global Observatory[15] and the Canadian Integrated Ocean Observing System-Atlantic[16] are established or nascent, have talented, permanent staff, and draw on regional investigators and investigations. In their instigation and networking of the ocean observation efforts underway in their area of operations, these regional organizations also network the investigators who collect the data. Through their regular network meetings, and their communications channels and stable staff that maintain institutional memory, they could serve as a valuable vehicle to broker connections of existing infrastructure with new opportunities either directly through targeted matchmaking, or indirectly through conversations.

Key considerations for tagging along on an existing infrastructure is that the equipment be robust, as small as possible, be easily mountable, and have its own power source and data storage capabilities. While it might be possible to integrate new instrumentation into the power supplies and communications linkages of existing moorings, this is typically time consuming, expensive and troublesome and reduces the enthusiasm for co-deployments.

What should be avoided is draconian attempts to force connections. Requiring scientists to make links to areas where they may have no expertise and punishing them if they do not is a recipe for friction and stifles collaboration.

DISCUSSION

Despite the opportunities and undoubted advances that will offered to us by the Decade, when the Decade is done the ocean will most probably still be under stress from human activities (Donovan et al., 2021; Sydeman et al., 2021). We need to keep sight of how we can use the opportunities offered by the Decade to position ourselves for what comes after. In other words, the Decade is not only an opportunity to fundamentally change conditions in the ocean and ocean-dependent communities, but also in how we observe, study and interact with the ocean going forward. For the future professionals we are training, the long-term vision for the Decade's "once in a lifetime opportunity" must also mean positioning ocean science at a new level of networking and efficiency. This will provide the next generation of practitioners with the tools needed to cope with the impacts of the stressors that will endure beyond the Decade. At the same time, transforming the conduct of ocean science will enable more effective responses to challenges that arise as

[11] https://spongis.org/the-sponges-project/
[12] https://www.ropos.com/
[13] https://otlet.io/
[14] http://www.neracoos.org/about
[15] https://www.ogsl.ca/en/about-slgo/
[16] https://cioosatlantic.ca/about/system

advancing technology fosters new economic developments and impacts on the ocean.

Established, global, sustained observing systems address known, critically important issues and have been embraced internationally. However, these systems measure only some of humanity's impacts on the ocean and we turn to local, punctual studies to provide knowledge of other stressors and the condition of the coastal and open ocean. A great deal is invested in these studies and given the importance and rapid pace of ocean change it is an ethical imperative to derive the maximum benefits from as many investments as possible that we make in ocean science infrastructure.

While few would disagree that finding a way to get more out of the investments we are already making is a win for all, the challenge for the smaller scale, punctual, independent, less coordinated infrastructure initiatives is how to incorporate additional users in a way that is not punishing and prohibitively draining for those who established the infrastructure. Making things as simple as possible is one key, but unlike for global efforts the smaller-scale and highly varied nature of punctual infrastructures means opportunities for co-deployments will probably arise at the grass-roots level. This makes the good will of the participants and awareness of possibilities the key to success. The first step is for researchers to think about possibilities for and the benefits of extending access to their infrastructure to others. Busy scientists focus on their own programs, not what we might do to assist others. However, many scientists are altruistic, and should the process of designing field studies and setting infrastructures ask not only how these assets support the primary task but also how they could be used by others, people will become aware of and open to collaborative opportunities on a more widespread basis. Next, those willing to collaborate need time, additional financial support, and diffusion mechanisms to communicate the opportunities/assets they have to offer. Funder mandates that move in these directions would be powerful, as long as those mandates are backed up by resources and do not place unreasonable demand on research teams.

Achieving these objectives is a communications issue, and could be addressed through word of mouth, email lists, networks such as the OTN, xylosystems.org or data through public access data systems (e.g., Reef Life Survey, Atlas of Living Australia, Oceans Network Canada, OTN). Social media networks or websites related to particular sampling locations or infrastructures similar to that produced by the Otlet network could be created, highlighting collaborative opportunities and making contact with potential partners. Even something as simple as including an "aside" slide in conference and seminar presentations of existing facilities and asking if anyone could make use of them could have big impacts. Once collaborative possibilities are identified, it is likely that each will be highly unique. Researchers will have to assess their feasibility and desirability, based on potential benefits and costs. In many if not most cases, the pull of the benefits will outweigh the costs both in terms of public good, but also for individual careers in terms of contribution to public good, networking, opportunities to contribute to multi-disciplinary studies, learning new skills, and potential co-authorships in scientific publications (Nguyen et al., 2017; Fortunato et al., 2018). Persistent communication will be needed to maintain this level awareness over time, however, every success puts us a bit farther ahead in ocean monitoring toward a sustaining future of humankind.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

MB organized the ethics symposium at which this work originated. FW provided the original concept for the piece. All authors contributed ideas and text for this Perspectives piece.

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Knowledge Co-construction by Citizens and Researchers to Create a SNAPSHOT of the Marine Environment During and After the Covid-19 Lockdown

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Lockdown measures adopted in Italy to contain the diffusion of Covid-19 altered many variables influencing the anthropogenic pressure on marine ecosystems. Public reactions included surprise at how quickly changes in human activity seemingly improved natural recovery and, at the same time, a generalized anxiety to restart economic activities. In this situation several Institutions from the Italian National Research Council (CNR) made a joint effort to quantify the effects of the unprecedented experimental conditions induced by the reduction of many anthropogenic pressures. The resulting project was conceived with a holistic, interdisciplinary approach, geared to combine scientific, economic and cultural observations to promote collective actions suitable to the governance of socio-ecological systems, reconciling respect for the environment with human activities and wellbeing, and thus grounding an ethical approach to marine resources. Alongside collecting considerable amount of scientific observations, the project is working to complement samplings and analyses with the non-formal knowledge carried by the inhabitants of a set of coastal zones, thus enriching the generated knowledge and widening inclusion and pluralism in defining the challenges at stake; simultaneously it focuses on stimulating a reflection in the research community over the process of knowledge co-construction, its meaning, role and responsibility in the societal context. After a brief contextualization of this activity, we present here the perspective adopted by researchers to build a responsible marine research plan, inclusive on the grounds of both involved actors and knowledge sources. We comment the process- and community-related features, explore limits and opportunities, and propose a set of recommendations, based on a preliminary review of our experience and oriented to promote the development of a shared Ocean ethics.

Keywords: Mediterranean Sea, local knowledge, RRI, knowledge co-construction, lockdown, governance, community empowerment, participatory research

INTRODUCTION

On March 9th, 2020 Italy entered the first lockdown phase. To contain the spread of Sars-Covid 19 coronavirus infection, non-essential economic activities were interrupted and the population was induced to stay at home until May 4th. Other European and Mediterranean countries followed with similar measures. In the following months, the usual activities were gradually resumed, although other restriction periods occurred.

Lockdown measures altered, among the other factors, mobility, population density, industrial, commercial, farming, fishing, and aquaculture activities, and consequently affected road and sea traffic and noise, civil and industrial discharges and fishing mortality. Notable interest arose on monitoring and quantifying the effects on marine ecosystems (Braga et al., 2020; Callejas et al., 2021; Lotliker et al., 2021; March et al., 2021).

In this context, the SNAPSHOT project[1] was promoted, under the coordination of the Italian National Research Council (CNR), in the frame of the European Coordination and Support Action BlueMed.[2] Currently ongoing, it aims at observing and possibly measuring the effects on marine ecosystems of the unprecedented experimental conditions, unique in their kind, induced by the modification of anthropogenic pressures during the lockdown period and the subsequent periods of partial limitations to activities. The project focused on some test areas along the Italian coasts, chosen as they are subject to strong anthropogenic pressures (large urban settlements, industrial and port activities, highly polluted river mouths, etc.) and sites of historical measurement series of marine abiotic and biotic variables.[3] Starting from the awareness that a publicly supported scientific initiative has the ethical mandate to be inclusive, both on the ground of involved actors and of knowledge sources (Barbier et al., 2018), the project was conceived with a holistic, interdisciplinary approach, geared to combine scientific, economic and cultural observations to promote collective actions suitable to the governance of socio-ecological systems, reconciling the respect for the environment with the human activities and wellbeing. For this reason several research groups from eleven different Institutions have taken part in the project, with the final goal to detect and describe any occurred change, and discuss if they can be causally ascribed to the reduction of anthropogenic pressures. They are collaborating in activities ranging from satellite data analysis to coastal waters sampling, collecting economic and social indicators, evaluating fish stocks and measuring underwater noise.

However, since the project's final aim is to sustain and promote change in environmental research approaches as well as in socio-economic behaviors, activities could not be confined to involving the academic sphere alone, but needed to be anchored to a wider actors' involvement. Moving from the production of scientific knowledge to societal change claims for the engagement of the different stakeholders since the beginning of the process, and for the integration of their different epistemic views. For this reason, the equity of inclusion of all the concerned actors was a driving ethical principle for the project's structuring and actions. By bringing stakeholders and communities in the knowledge creation process, the research aims both at building a reliable and socially robust knowledge-base (Nowotny et al., 2003) and at enhancing the legitimacy of the process. Moreover, alongside collecting non-scientists' observations, the research project acknowledged the importance of personal visions and collectively held imaginaries of the human-environment relationship – in this case, specifically focusing on coastal areas –, held capable to shape the viable options for desirable futures' scenarios (Felt et al., 2007; Jasanoff and Kim, 2015).

In this perspective piece, we reflect on key elements of project design and process that have enabled inclusivity and, in our opinion, will foster the creation of better outcomes, for ourselves as interdisciplinary community of researchers (especially in terms of reflexive thinking on the societal role of scientific research and on the diverse sources of knowledge) and our research (more policy relevant, more inclusive, more socially robust). In the following, after an overview on literature (section "Involving Communities in Knowledge Co-construction") and on our ethical approach (section "Credibility, Saliency, and Legitimacy of Knowledge"), we briefly describe the projects' actions tied to inclusion and reflexivity (section "The Investigation Path"), while referring readers to the project website[4] for more information about the project itself. Finally we share our reflections and conclusive recommendations (section "Strengths, Criticalities, and Recommendations for the Advancement of Inclusive Ocean Research").

INVOLVING COMMUNITIES IN KNOWLEDGE CO-CONSTRUCTION

In recent years, the increased interest to an innovative and more inclusive environmental governance, and the acknowledgment of local and traditional experiential knowledge (Wynne, 1992; Giordano et al., 2008; Benham, 2017), led to a change of the classic "top-down" pattern in the relationship between science and policy (L'Astorina et al., 2015; Pasquier et al., 2020). This increasingly widespread participatory approach is more adequate to face complex, transdisciplinary and multi-actor challenges, and more consistent with the perspective of realizing a responsible marine research project (Ferri et al., 2018) and of setting the grounds for a universal right of scientific citizenship in democratic societies (Irwin, 2001, 2015; Greco, 2018).

The foundations of such an approach rely on the observation that involving all concerned actors since the definition of the challenge is important to adequately include all visions, concerns and expectations, as well as to acquire non-formal knowledge and better understand the issue at stake. Although many factors can limit the development of socio-political change, an open, pluralistic engagement during the phases of problem-setting and

[1] Synoptic Assessment of Human Pressures on key Mediterranean Hot Spots: http://snapshot.cnr.it/

[2] Research and Innovation for Blue Growth and Jobs in the Mediterranean Area: http://www.bluemed-initiative.eu/

[3] Details on http://snapshot.cnr.it/campionamenti/

[4] http://snapshot.cnr.it/

knowledge production is recognized as a keystone to ground any subsequent development in terms of deliberative policy-making (Cvitanovic et al., 2016). Moreover the quality of both research process and of scientific knowledge improves as a consequence of the inclusion of a diversity of voices (Funtowicz and Ravetz, 1993; Ziman, 2000; Nowotny, 2003). Widening participation in problem-setting is an ethical asset of research in democratic societies, allowing all social groups to contribute on a fair and equitable basis to address shared socio-ecological problems, possibly opening to a stronger communitarian assumption of environmental responsibility.

Several exercises of engagement have been performed within the framework of research projects aiming to manage different kinds of environmental problems. For example, the Environmental Impact Assessment due to the enlargement of heavy industry plants at Port Curtis (Australia) (Benham, 2017), the reduction of flood and drought risk in the Danube region (Giordano et al., 2020), the adoption of a novel system for earth observation in Italy (L'Astorina et al., 2015), the marine climate change impacts in Ireland (Chilvers et al., 2014) were discussed with the public participation. In the context of Covid-19 pandemic crisis, such a methodology was used to assess public perception of lockdown effects on the achievement of sustainable development goals and to design possible future scenarios in Bangladesh (Shammi et al., 2021).

According to the available literature, the present study is the first to use co-creation of knowledge for enhancing the understanding of changes in marine and coastal ecosystems due to lockdown effects.

Credibility, Saliency, and Legitimacy of Knowledge

In doing this knowledge co-creation exercise, we address three key issues related to the production and use of knowledge in decision-making processes, namely *credibility, saliency, and legitimacy* of knowledge (Cash et al., 2003). Most of the scientific approaches dealing with the collection and analysis of environmental data for supporting decision-making processes focus exclusively on the *credibility* of data. Researchers' concern appoint on enhancing the capability of data to describe the observed phenomena, and limited efforts are dedicated to enhancing their *saliency*. That is, scientific information or tools for environmental monitoring are rarely used by decision-makers and citizens, because they are not relevant for the decision-makers and/or too difficult to use or to communicate, and, therefore, they fail to help defining actions fitting the contexts. Moreover, traditional approaches for environmental monitoring consider scientific and technical knowledge as the only *legitimate* knowledge form, disregarding the many meanings, interpretations and ways of framing environmental issues that exist in the multi-actor setting, failing to empower stakeholders to participate meaningfully in the design and application of rules of use and management of the environmental resources.

Starting from these premises, we designed a research plan moving from a science-centered perspective in analyzing the environmental phenomena, toward a more community-oriented approach, with the aim of co-creating a knowledge base integrating scientific and local knowledge, while responding to *credibility, legitimacy, and saliency* requirements (**Figure 1**). Such an approach structurally incorporates the value of democratic inclusion of concerned voices on an equitable floor, while at the same time it promotes effectiveness of actions geared toward more sustainable and shared environmental policies.

The Investigation Path

We set up the research plan for public engagement in SNAPSHOT adopting a process-oriented perspective (Miller, 2013), attempting to move toward inclusivity, changes in environmental behaviors and future sustainability.

Alongside the scientific and socio-economic investigations, carried out by devoted teams, a three-phase process was articulated (**Figure 2**) by the public engagement working group, geared to capture a wide, inclusive picture, both in terms of knowledge base and of explored actors' perspectives.

The first phase was dedicated to describe a baseline of the emerging cultural representations in the online public debate about the lockdown effects on marine environments during the first pandemic wave, in which a complete lockdown occurred in Italy. Targeted searches were carried out on the web and on social networks, focusing on Italian citizens' and press observations and perceptions of the lockdown effects on marine and coastal environments. Textual analysis and subsequent insights into the

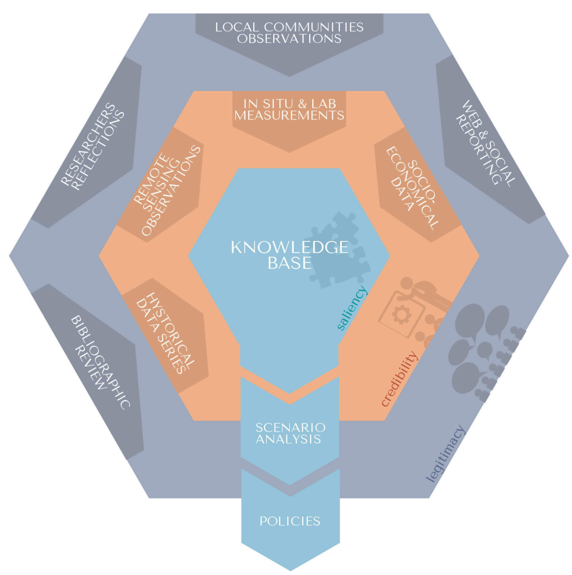

FIGURE 1 | A representation of the sources and the actors involved in the co-construction of knowledge in the whole SNAPSHOT project. While traditional research projects focus their attention on the production of scientific information, based on data and analysis ("credibility" layer), SNAPHSOT wanted to broaden the sources of knowledge to the perception of local communities, interest groups, media, and stimulate the reflections of the researchers involved ("legitimacy" layer). This broader vision on the processes taking place allows to bring out the knowledge base ("saliency" layer) necessary to face the analysis of the scenarios, from which future policies can derive.

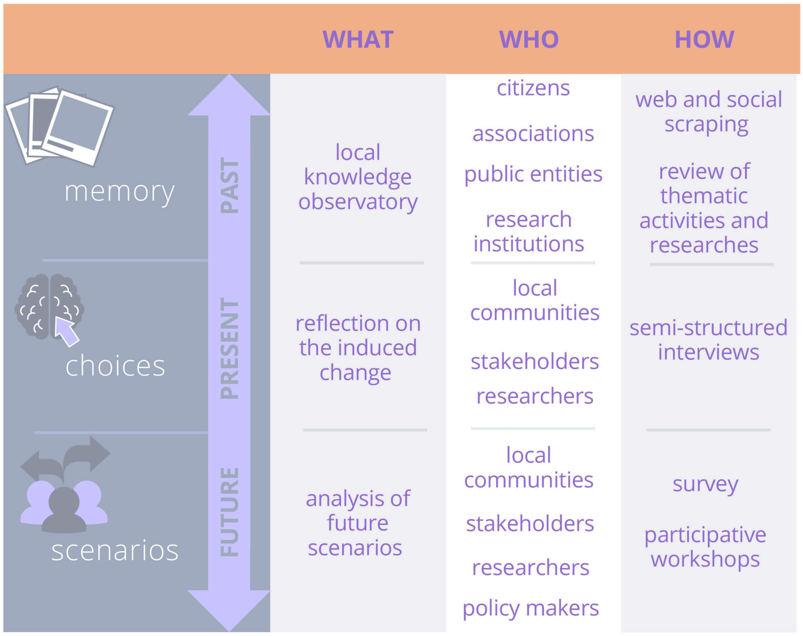

FIGURE 2 | Activities aimed at including stakeholders', researchers', and citizens' visions and knowledge in the SNAPSHOT overall picture. The schema defines the three main dimensions explored and, for each of them, indicates the subjects involved and the methods of investigation used.

results were targeted to capture the features of an emerging collective vision; results[5] were not considered, in any case, for the veracity of each observation, but were meaningful to return a sketch of the developing cultural representations regarding the unprecedented socio-environmental conditions induced by the Covid-19 lockdown. In parallel, a review of analog ongoing researches provided insights into how the scientific community was exploring the theme.

The second phase was aimed at stimulating reflexive thinking by means of conversations with stakeholders, local communities and researchers. The aim was to investigate their perceptions about the main impacts of the lockdown period on the coastal and marine environment, their observations regarding the impacts, their ideas about the causes of the perceived changes and their views regarding the policies to be implemented to preserve the positive effects of lockdown. In this phase, semi-structured interviews were conducted with a selection of involved researchers, experts, and stakeholders connected with marine activities. Different profiles were involved, such as physicists, marine biologists, fishers, coastguards, environmental activists, representatives of touristic activities, and marine museums. As a result of the crossed readings of the researchers' and non-experts' visions, we expect to establish a comparison in terms of identified variables, relevant actors, worth-mentioning phenomena, involved social groups and arenas, viable options for future behaviors, possibly identifying a set of shared indicators suitable to inclusively describe the change, i.e., overcoming the fracture between the perspectives of experts and non-experts.

The third phase was conceived as oriented to the development of shared scenarios for desirable futures, in which to confront the needs of economic, social and environmental sustainability and to creatively ideate viable paths for a common development. Workshops employing participatory co-creation methods will be organized at this stage to allow reflexive thinking and exchange of visions among the participants, facilitating the development of shared visions for the future. Policy makers, local administrators, scientists, representatives of citizens, and interest groups will be invited to contribute to the discussion. Due to continuing security restrictions for Covid-19, the start of this phase has been postponed until it will be possible to conduct face-to-face meetings in safety.

Finally, the outcomes of the public engagement research are planned to be returned both to participants and to the public debate *via* a final publication, designed to integrate the results from each distinct enquiry in a comprehensive picture of the effects of lockdown on Italian seas and coasts, including reflections on how to move toward more respectful management of marine environments, basing on the interdisciplinary and multi-actor knowledge acquired.

STRENGTHS, CRITICALITIES, AND RECOMMENDATIONS FOR THE ADVANCEMENT OF INCLUSIVE OCEAN RESEARCH

Our investigation path was designed to create an itinerary from the memory of recent experiences to the construction of a

[5]Some interactive representations of the results are available in Italian language on the web page http://snapshot.cnr.it/osservatorio-delle-conoscenze/

desirable future, taking advantage of lessons learnt during the lockdown and building on the inclusion of multiple voices to paint a high-quality picture of reality, unravel complexity, adequately represent actors' interest and values and ultimately support shared, transparent, equal and just political choices.

Although the experiment is currently ongoing, we want to highlight here a set of observations and recommendations based on the experience of our group on public engagement.

First, we want to underline the strengths deriving from having conceived the project as inclusive by design, since the very early design phases. It allowed us to outline a research plan able to deliver legitimate knowledge, i.e., capable of enriching scientific observation with the meanings, interpretations and framings of the environmental issues at stake by a wide range of concerned actors, setting the bases for their empowerment in building the future scenarios.

Our core conceptual premise is that crossing the actors' views and highlighting their different perspectives regarding practices at the boundary between environmental and socio-political arenas is *per se* a service to the building of a more inclusive and equal knowledge-based environmental management, hence playing a pivotal role in grounding Ocean ethics and stimulating the maturation of a scientific citizenship. Increasing awareness of the differences between non-scientists' and researchers' understandings of the same environmental issue could contribute to enhance the effectiveness of communication of the scientific data and to improve the actors' mutual understandings.

We have to point out that research activities were influenced by the restrictions imposed by the sanitary emergency. We experienced as particularly limiting the prohibition to organize in-person meetings, especially for interviewing stakeholders, and shared the perception that digital intermediation could restrict the breadth of the exchanges with the interviewees. Furthermore, it is necessary to consider that some voices could be cut out of the discussion due to digital divide. These are all reasons why we are carefully reflecting over the organization of the foreseen scenario workshops, since the same eventual restriction to meetings could prove very limiting in such participatory activities. On the other hand, the increase in diffused digital competences, activated by the lockdown, allowed to smooth the organization of computer-based interviews. It is interesting to observe that some of the interviewees reported how digital meetings facilitate the discussion with administrative offices and representatives, and allow them to participate in more activities than they could follow in person. Hence, we would advise future inclusive projects to carefully plan a balanced mix of methods to reach possible interviewees (physical and digital), considering digital tools both as opportunities and as limits – as they can alternatively facilitate or exclude some actors from participation.

Confronting on the integration of the diverse sources of knowledge is proving, also at this preliminary stage, to be an enriching, although challenging, exercise for the SNAPSHOT researchers community: hints of reflexive thinking on the nature of knowledge and on the role and responsibilities of research have emerged from the conversations with researchers, and have also been raised during the project plenary meetings (e.g., calls focusing on the need to overcome the temptation to do "research as usual", or statements respecting the non-scientists contribution to building the knowledge-base).

We can highlight also some peculiarities connected to the inclusion of diverse actors in the co-creation exercise.

The first concerns the evaluation of change, i.e., the very possibility of detecting transformations, and also of causally ascribing the differences to the reduction of anthropogenic pressure, by non-institutional and institutional actors (including scientists). Many non-institutional interviewees described how the reduction of daily activities created spared time for observation, from scientific research, to coastal monitoring, to citizens' everyday activities. A shared opinion was that the reduction of noises and disturbance caused by human activities clearly created the right conditions for the wellbeing of fauna in the coastal areas. People not directly engaged in institutions described changes in the quality of the ecosystem and in the number of fish species. Conversely, institutional actors and researchers reported to be aware of this generalized perception, but stressed the high uncertainty associated with establishing causal connections, considering the great resilience of environments and the long periods necessary to nature to react to changes, and the complexity of the scientific problem at stake. Therefore, they deemed it quite difficult to detect changes, due to the short period of lockdown, and to clearly distinguish them from the results of already ongoing natural processes. In other words, scientists and institutional actors were particularly cautious regarding the reliability – and the consequent credibility – of the acquired knowledge, while non-institutional actors could describe transformations without waverings.

A second emerging peculiarity covers the emerging diversity between researchers and non-scientists in showing trust for the practicability of future, sustainability-oriented, actions.

When prompted on possible environmental policy choices, consequent to the lockdown experience, the answers of scientists generally expressed pessimism on the existence of viable paths for action. Some underlined that some paradigm-changes toward a socio-ecological approach may be already ongoing in single persons, but they hardly saw the space for communitarian actions. Such a pessimistic vision points to a certain difficulty of scientists in perceiving themselves as possible agents of change, and even in imagining desirable futures as citizens, notwithstanding their being involved in a research project with an ethical orientation, and belonging to a social group with appropriate instruments to enter the public debate. Conversely, many non-scientists showed a rather positive attitude toward the perceived changes in the environment, and some of them suggested policy actions for making those changes permanent. In the perspective of fostering the development of a shared Ocean ethics commitment, more efforts should be focused on the researchers' self-perception as active players of the overall socio-economic and political arena, able to grasp the complexity of the diverse sectors' interests and interplays and not giving up to their civic role in support of the sustainability of anthropic pressures on marine environments.

We would advise an improved effort of knowledge circulation among and within the diverse groups – stakeholders, local communities, and researchers – in order to further nurture the community awareness process triggered during the lockdown and to allow the activation of a mutual learning process, able both to open up reflexivity paths and to set the ground for long-term change in visions and behaviors of the involved actors. A special attention needs to be devoted to publicly sharing the analysis results, e.g., exploiting the project website potential as reference for the involved scientific communities and the local non-academic networks.

The next step of the SNAPSHOT public engagement will focus on the participatory workshops, targeted to selected pilot groups of actors and aimed at co-building scenarios of desirable futures, which will allow the different actors to meet, to exchange their experiences and visions, to unveil values and interests and, finally, to engage in imagining common paths, balancing the expectations of economic restart with the respect for the environment.

The final research outcome will play a critical role for the possibilities of the project to trigger any change. It needs to be able to speak to all the diverse stakeholders' communities, including the citizenry and the decision-making circles at a local and national level; to imagine, describe and propose viable paths to achieve actual impacts, respecting the values, interests and positions of all; to be adequately communicated, in order to enter the public debate.

All these requirements are very demanding, if compared to the classical outcomes of research projects, but if properly handled they will represent an important opportunity for the involved marine community gathered to reflect over their research work and collectively imagine a communitarian, desirable and ethical future for the Italian marine environment.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because the raw data consists of audiovisual materials and interviews transcripts; they are still under analysis and currently are not anonymized. Some extracts from data are available at http://snapshot.cnr.it/osservatorio-delle-conoscenze. Requests to access the datasets should be directed to CL, criscuolo.l@irea.cnr.it, http://snapshot.cnr.it.

ETHICS STATEMENT

Ethical review and approval was not required for this study with human participants, in accordance with the local legislation and institutional requirements. The participants provided their explicit informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

LC, RiG, RaG, and APe wrote the manuscript. AL'A and APu contributed to define the conceptual layout. AD, GF, and GP finally revised the manuscript. LC elaborated the graphics included in this manuscript. AL'A coordinated the SNAPSHOT work package. All authors contributed to the research activities.

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Translating SSF Guidelines Into Practice With the Small-Scale Fisheries Academy

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The Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication (SSF Guidelines) have been adopted by FAO's Committee of Fisheries in 2014. In this short research report, we present action research with self-selected men and women in small-scale fisheries in Senegal, a country with a large and dynamic SSF, which suffers, however, from diminishing profitability as a result of multiple pressures. We report ongoing work on the principles and approaches of the Small-Scale Fisheries Academy as a way to support the implementation of these Guidelines. The first phase of developing the SSF Academy focuses on testing learning methods aimed at developing critical thinking, planning and action. Respectful dialogue in the secure space of the Academy made academy learners, particularly women and younger participants, gradually more confident, articulate, and active. They started harvesting the results of enacted planning. We cautiously argue that it would be useful to expand these tests combining dialogue, the art of hosting communication and visual thinking to different places in Senegal and elsewhere. They provide an opportunity to address sensitive social issues like gender equity and intra-household violence and open perspectives on other societal challenges that hamper the implementation of the Guidelines. Despite the difficult conditions of the pandemic and given the rather limited work during the pilot phase before, the Academy's participatory and inclusive learning and empowerment approach had an impact on the individual learners and the group and thus contributed to the implementation of the SSF Guidelines.

Keywords: Small-Scale Fisheries Academy, Gender Action Learning System (GALS), visual thinking, collective action, governance, SDG 14, Senegal

INTRODUCTION

The Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication (SSF Guidelines) have been adopted by FAO's Committee of Fisheries (COFI) in 2014. The provisions of the Guidelines are based on human rights recognizing the roles and importance of previously typically neglected men and women and their communities

(Chuenpagdee and Jentoft, 2011). They cover the guiding principles and how governments should translate these into responsible fisheries and sustainable development along entire value chains and ensuring gender equality. Governance, research and information, capacity development and efforts to support and monitor implementation are also covered. Their adoption followed an extensive, bottom-up consultation process between 2010 to 2013 that involved more than 4,000 stakeholders from governments, professional and civil society organizations and scientists from 120 countries (FAO, 2015). The voluntary nature of the SSF Guidelines allows flexibility in adjusting the concrete implementation to national and local conditions. While small-scale fisheries around the world share aggregate characteristics (Jacquet and Pauly, 2008) they lack a unique technical definition (Smith and Basurto, 2019). Sustainable Development Goal 14 Target B (SDG 14.B) gives further recognition to the need for explicit implementation efforts[1].

The last decade has seen numerous initiatives and research efforts to demarginalize small-scale fisheries and strengthen gender equity to counterbalance dominant technocratic policy approaches focused on industrial fisheries. Among these, the global network of researchers and practitioners "Too big to ignore"[2] has significantly increased the documentation of SSF across the globe (Jentoft and Chuenpagdee, 2015; Jentoft et al., 2017; Johnson et al., 2018), while FAO[3] focuses on keeping the SSF Guidelines on the political agenda and the "Sea Around Us" reconstructs marine catches, including those of SSF[4].

Gender has been an even more neglected dimension, not only in fisheries and aquaculture (Williams et al., 2005), but in many societal spheres (Gaye et al., 2010) notwithstanding some progress (Dorius and Firebaugh, 2010). We note an increase in attention to gender in fisheries following the adoption of the SDGs in 2015 (Nauen and Williams, 2019). Despite the scant gender differentiation in national accounting systems, Harper et al. (2020) even managed to estimate the contribution of women to fish food production.

Nevertheless, the implementation gap of global agreements remains high (Hudson et al., 2019). This is aggravated during the corona pandemic, which reversed advances in several areas and widened the gap between rich and poor within and between countries (Engzell et al., 2021; Fenner and Cernev, 2021).

Senegal has burgeoning artisanal fisheries (Fontana and Samba, 2013). Employment figures (Sall et al., 2006; République du Sénégal, 2007) are, however, difficult to ascertain under conditions where official statistics covered only a fraction of the reconstructed catches (Belhabib et al., 2015). The competition – and occasional cooperation – between industrial and artisanal fisheries together with very high levels of IUU fishing (Belhabib et al., 2015) and climate change weigh heavily on a shrinking resource base. These conditions reduced the profitability of SSF (Ba et al., 2017). This has particularly affected women because, without access to affordable credit, they cannot continue to pre-finance now more expensive fishing trips (Sall, 2018). Countering the associated weakening of social solidarity chains requires enacting reforms at the macro-level, such as phasing out harmful subsidies to industrial fleets (SDG 14.6) and social innovations at the micro-level for greater participation of SSF in governance.

Here we present the principles and approaches of action research for the development of the Small-Scale Fisheries Academy in Senegal as a way to help close the implementation gap. The first phase serves to test active and inclusive learning methods and spread awareness of the Guidelines to improve livelihoods and strengthen capacity for participation in fisheries governance.

METHODS

The methodological approach dwells on a broad foundation constituted by Freire's vision of dialogue (1987) as a mode in which an educator accompanies a learner to reflect, apprehend and act on the world around them. Boaventura de Sousa Santos' notion of ecologies of knowledges (2007, 2009) recognizes different ways of coding and expressing knowledge as legitimate. He demands their recognition and blending through dialogue processes as a way to address situational complexities in a non-hegemonic way.

Moreover, we apply the social communication for behavior change and art of hosting approach to leadership that scales up from the personal to the systemic using personal practice, dialogue, facilitation and the co-creation of innovation to address complex challenges (Nauen and Hillbrand, 2015). More specifically, we refer to the Gender Action Learning System (Mayoux and Oxfam-Novib, 2014) to operationalize the research and test these affirmed methods in a different context. The visual practices used ensure that adults with little or no formal schooling can actively participate in critical thinking and action for change at individual and collective levels.

This action research aims to enhance the planning skills of learners through a fun process of envisioning, clarifying thoughts and acting toward their individual and collective goals (Arraes Treffner, 2019a). The facilitation process during workshops ensures that all learners have equal rights in terms of time and space to speak about their experiences, their views and their perspectives. By encouraging learners to use drawings and symbols to articulate their dreams and a main objective they want to achieve within a year, the abstract becomes concrete. The process of drawing out what opportunities they expect to create during quarterly steps, but also reflecting on the obstacles they might encounter, requires them to critically analyze their change journey. Graphical facilitation offers the learners a range of tools to foster richer dialogues and to explore specific aspects more in-depth (Nauen and Arraes Treffner, 2021). An important part of the process is to motivate participants to discuss their individual plans with other participants, with family, neighbors and peers in order to enrich the reflection and make it more robust by building collective visions and mutual support around such plans. As the learners gain confidence, it is envisaged to

[1] https://sdgs.un.org/goals/goal14
[2] www.toobigtoignore.net
[3] http://www.fao.org/voluntary-guidelines-small-scale-fisheries/en/
[4] www.seaaroundus.org

support the development of collective plans, for example by women's savings groups, fishers, fish processors, or community members engaged in marine protected areas and co-management (Nauen and Arraes Treffner, 2021).

We thus design the SSF Academy as a multi-stakeholder space, where fishers, women fish processors and their economic interest groups, traders, boatbuilders and other professionals from the entire value chain can respectfully dialogue with one another as well as with representatives of administrations, scientists, civil society organizations and other resource persons. Such settings can produce locally adapted knowledge to generate innovative solutions and pave the way for more social justice and gender equity. It is intended "*as a secure place for co-learning and co-production of knowledge for wellbeing in the sector, protection of marine biodiversity and better governance*" (Nauen and Sall, 2017). Champions are expected to become facilitators for others in order to strengthen collective action to play a more adequate role in addressing the structural disadvantages of SSF value chain actors.

Participants were invited from the local communities of Hann and Yoff, Senegal, to test the methodologies. The engagement of organizational and religious leaders and men and women active in different segments of the value chain was encouraged for diversity and multiplier effects. The original schedule called for a 1-year pilot phase, which, however, had to be extended due to the covid-19 pandemic. A more detailed account of the methodology and the testing phase is provided in Arraes Treffner (2019a; 2019b; 2019c) and Nauen and Arraes Treffner (2021). In the following, we summarize some results up to early 2021.

RESULTS OF THE SMALL-SCALE FISHERIES ACADEMY PILOT PHASE

The inaugural event in November 2018 launched the SSF Academy in Senegal (**Photo 1**) with the active participation of some 60 men and women from all SSF related professions, age groups, associations and regions as well as academics and representatives of the fisheries department.

In the following, several training workshops took place with self-selected participants in both locations. They started with a contextualization, reminding academy learners of the SSF Guidelines as they relate to their own realities. Story-telling based on the experience of resource persons, an animated video in the local language, a documentary film on the status of fisheries in Senegal, and graphical recording supported deeper dialogue.

A visioning exercise inviting participants to draw what represents a good life to them allowed for individual and group reflections on what is important to them. As homework, the vision was then enriched by discussing each participant's drawing with family, neighbors and professional groups. The immediate "outreach" encouraged the integration of individual and small-group visioning processes in the wider community. The comparison of drawings also made the commonalities directly visible to all.

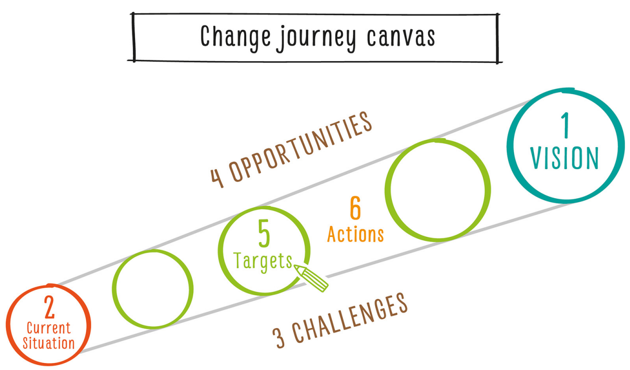

FIGURE 1 | Change journey canvas for individual or collective one-year action plans (adapted from Mayoux and Oxfam-Novib, 2014).

PHOTO 1 | Inaugural event of the Small-Scale Fisheries Academy in Dakar, Senegal, November 2018 (Photo Mundus maris).

PHOTO 2 | Intense group deliberation preceding the presentation and discussion of results in plenary (Photo Maria Fernanda Arraes Treffner).

On the strength of that vision for the future, the academy learners were invited to identify and draw a concrete objective they expected to achieve within a year, along with quarterly intermediate targets. This structured planning was supplemented by a reflection on possible roadblocks, but also opportunities and support that could likely be enrolled during the implementation of the action plan (**Figure 1**). The individual planning was reinforced through group discussions and through plenary presentations and exchanges within the academy, honing capacities for clear and structured presentations to others in the process.

The introduction of several canvasses also facilitated a more in-depth dialogue on the important features of life and livelihood. The visual exercises using the diamond canvas invited participants to explore the positive and negative aspects of their economic occupations in order to identify ways to improve their business organization.

A follow-up exercise allowed each participant's specific activities to connect with others as part of the SSF value chain. The conversations made them more aware of their interdependence in the value-chain segments (**Photo 2**). It showed how the improvement efforts in their respective segment could have positive or negative effects on others.

All academy exercises bring participants to prepare for action, in this case, identify how to increase synergistic effects for mutual benefits. Again, the drawings produced in gender-mixed groups by profession and then in plenary contributed to a deeper understanding of the interrelationships, prioritization and realization of operational gains.

These discussions also brought to light a number of social and gender issues (Nauen and Arraes Treffner, 2021). Such issues might have been considered taboo in a more traditional teaching context. In this case, given the principles of gender justice, explicit attention was paid to concrete individual and local group conditions and dynamics. Participants were first offered the diamond to reflect on these challenges in sex-specific groups to identify aspects that should be addressed as a priority. Among these was domestic violence. Using a tree canvas, each group then exchanged what participants saw as the root causes and what needed to be changed to promote a safe space where women would have a voice in the household, the business and the decision-making (**Figure 2**).

The need to end violence against women and children was considered desirable by all. The consensus was that the fruits of common labor needed to accrue to all members in an equitable manner for the family business to be strong and resilient.

Introducing external expertise through an academic resource person also permitted to animate a critical reflection on how climate change is already affecting the community and what could be done about it.

The pandemic slowed down face-to-face meetings and relegated mentoring to more sporadic and limited exchanges through WhatsApp groups enabling at least some exchanges between participants and a subsequently elected academy committee in Yoff. The committee features both men and women in responsible positions and ensures at least some contact continuity with other learners.

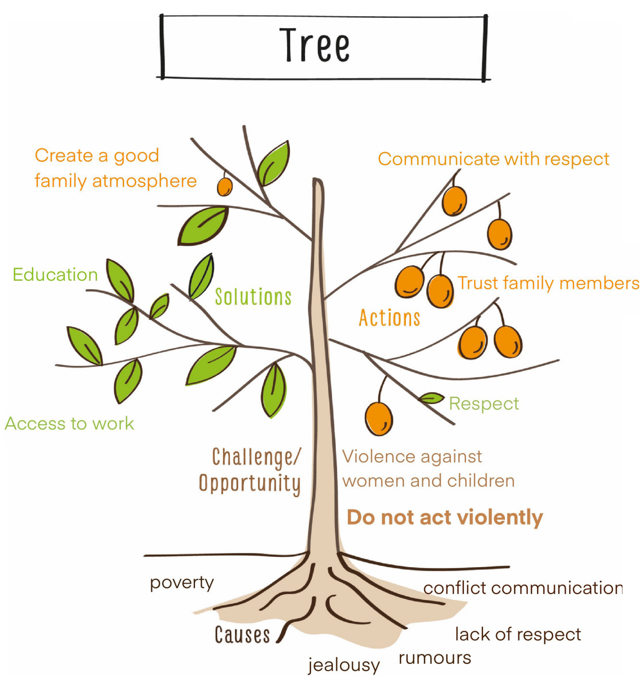

FIGURE 2 | The results of one group discussion applied in the generic canvas of an action tree – synthesis drawing made by the facilitator to capitalize on Academy experiences. All canvasses can be adapted to different topics.

At the end of February 2021, more than a year after the last substantive training, a short catch-up workshop was convened. The intention was to reconnect members of the entire group in a more structured way through an on-site meeting, to refresh memories and methods, and to test the feasibility of a hybrid format, combining a physical meeting with online co-facilitation. The greatest responsibility for facilitation rested with the local team to host the session.

Significantly, all previous learners attended. In small groups, they explained to each other how they had succeeded in relation to their annual action plans. Few examples could be presented in plenary. One particularly keen woman, Nabia, who had already set herself apart earlier by achieving her first quarterly target, had not only met her annual objective, but managed to earn enough to improve the roofing of her house. By systematically cutting costs through reducing non-essential expenses like clothes for social ceremonies, she had gathered sufficient investment money to increase her sales from one to six crates of fish a week, and also diversified into dried fish.

Other learners had dealt with unexpected adversities quite well by branching out into sheep husbandry and clothing sales, respectively. Diversification is not uncommon (Sall and Nauen, 2017), but not always within reach. Thus, some fishers had been prevented from going to sea and got indebted as they had been forced to use an operational loan for a fishing trip to cover living expenses.

In the event, the supportive online co-facilitation was only partially effective. Connection and translation difficulties prevented smooth interaction throughout. The members of the local hosting team were motivated, but did not yet have sufficient experience for autonomous facilitation. Nevertheless, the final appreciation of participants was to continue. Having one or more experienced facilitators "on the ground" is, of course, the preferred configuration for progressing in the development of the academy program and allowing the learners to become facilitators themselves and to strengthen collective action.

DISCUSSION AND CONCLUSION

Here we describe work in progress during the initial development phase of the SSF Academy in Senegal based on a range of conceptual (Freire, 1987; de Sousa Santos, 2007, 2009) and methodological approaches for engaging adults in the social process of learning to develop critical thinking, planning and action (Mayoux and Oxfam-Novib, 2014; Arraes Treffner, 2019a). As expected, the initial curiosity turned into greater commitment. Gradually, the women and younger participants became more confident, articulate and active over time, harvesting the results of enacting their planning. The methodological tests combining dialogue, the art of hosting communication and visual thinking exercises give rise to the expectation that the approach can be gainfully used in different situations and even allow to address sensitive social issues such as gender equity and domestic violence. It can gradually open to other stakeholders and offer new perspectives with external resource persons (Nauen and Arraes Treffner, 2021).

Even under the difficult conditions of the pandemic and considering the rather limited work during the pilot phase, the participatory and inclusive active learning and empowerment approach characteristic of the SSF Academy had an impact on the individual learners and the group as a whole beyond what could have been expected with more conventional training (see **Supplementary Material**). The participants clearly called for the continuation of the learning program. This request was particularly outspoken among those who were emerging as a new type of leader by appropriating the planning methods and implementing their action plans systematically. The set up and ongoing dialogue process in the Academy arena helps to manage this without creating conflict between the different sources of standing in the community.

The experience with the SSF Academy is still too recent to determine when the first group of learners will have reached a level of autonomy to act as champions/competent facilitators. But the first results not only justify to continue the next development steps in Senegal, but also try the approach in a different country and in other contexts to test its robustness and scalability.

The current pandemic illustrates the usefulness of reinforcing preparedness for the unexpected (Carpenter et al., 2008). Some elements are already present in the planning approach. Likewise, greater interaction between the public sector administration and the SSF Academy should foster improved governance by building trust and broadening perspectives brought to bear on the multiple challenges (Bohle et al., 2019).

In conclusion, the early results of this action research suggest that the SSF Academy's adult education approach holds potential to make progress toward reducing the implementation gap between global frameworks and local realities. By providing information on the SSF Guidelines and having participants develop what they can mean for their livelihoods, the Academy gradually strengthens their capacities for collective action, advocacy and active participation in governance.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**; further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the General Assembly of Mundus maris. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the relevant individuals for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

CEN and MFAT conceptualized the research, critically reviewed the draft and produced the final version. MFAT led on-site field work and provided graphics. CEN wrote most of the manuscript. Both authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

Supplementary video material: https://www.youtube.com/watch?v=DbcjY5PDUuc

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Coupling Relationship of Human Activity and Geographical Environment in Stage-Specific Development of Urban Coastal Zone: A Case Study of Quanzhou Bay, China (1954–2020)

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Owing to the development of the social economy, the geographical environment and ocean utilization patterns of urban coastal zones have changed. This change, in turn, has influenced the socio-economic development of urban coastal zones. Based on the Geographic Information System technology, the area, coastline length, and shoreland use function of reclamation areas were obtained from the geographic charts (1954–2020) and remote sensing data (1988–2017) of Quanzhou Bay. In this study, we analyzed the geomorphologic change process and the relationship between land use patterns and economic development in Quanzhou Bay from the perspectives of hydrodynamics, sediments, and human activity. Our results indicated that over the past 70 years, the bay area has reduced by 21.5%. The length of the coastline decreased from 208.36 km in 1959 to 149.11 km in 1988, whereas the shape index of the bay (SIB) decreased from 3.09 to 2.41 during the same period. Between 1988 and 2017, the coastline increased to 162.91 km, causing the SIB to increase to 2.72. The artificial index of the bay increased from 0.28 in 1959 to 0.90 in 2017. The intensity of bay the development (IBD) first increased from 0.27 in 1959 to 0.77 in 2006. During the transition to a more modern society (2006 to present), the IBD slightly decreased to 0.73 in 2017. Affected by human activity, the transformation of the reclaimed land in Quanzhou Bay can be divided into four stages that are closely linked to the economic development in the region. In the early industrialization period, reclaimed land in the region was used for agricultural production, whereas in the mid-industrialization period, it was gradually transformed into a combination of industrial (29.8%) and agricultural (56.1%) lands. In the later period of industrialization, the reclaimed land was gradually converted into urban industrial and port lands. Finally, with further refinement and upgrading of economic and industrial structures, the socio-economic and environmental benefits from coastal reclamation projects have been increasing, whereas the proportion of economic benefits (in the total benefits) has been decreasing. The results of this study can provide decision-making references for the optimization of utilization patterns and the economic development of reclamation lands in coastal areas.

Keywords: human activity, geomorphology, coupling relationship, stage development, urban coastal zone, reclamation land, Quanzhou Bay

INTRODUCTION

As a link between land and sea, the urban coastal zone is rich in natural resources and has a high biological productivity. It also plays an important strategic role in social and economic development as a port for international trade (Akan et al., 2020). Due to the availability of rich marine resources and rapid economic development in urban coastal zones, the population of urban coastal zones has been increasing. In 2021, the eastern seaboard of China accounted for 39.93% of the population, with an upward trend of 2.15% from 2010, whereas coastal cities in the United States of America (USA), such as New York City and Washington DC, have witnessed an increase in their populations in the last decade (data from the National Bureau of Statistics, 2021; U.S. Census Bureau, 2021). With the increasing intensity of human activity, Earth has entered the epoch of the Anthropocene era, and human activity has gradually become the dominant external force causing environmental changes on Earth (Day et al., 2021). Therefore, as a typical region evidently influenced by human activity, studying the characteristics of urban coastal zone changes can help understand the process, mechanism, and impact of anthropological activities on the environment. Notably, this is conducive to avoiding wastage of resources and can provide viable scientific references for regional sustainable development.

Changes in the geomorphology of the urban coastal zone have a certain process (Martínez et al., 2011). Due to the different degrees of economic development, cities around urban coastal zones also have different degrees of development, which results in different geomorphological changes (Aldasoro-Said and Ortiz-Lozano, 2021). In the past, the major industries in urban coastal zones were generally small-scale transportation, commerce, and agriculture, which have little impact on the evolution of urban coastal zone geomorphology (Pourkerman et al., 2020). In recent decades, most urban coastal zones in developing countries have been in the middle or late stages of industrialization. As a result of a large amount of human activity, the coastline and topography of urban coastal zones have changed significantly over a short period (Sun et al., 2020). However, in some developed countries, urban coastal zones have completed the process of industrialization, urbanization, and economic development; however, due to this development, the surrounding environmental and ecological problems have increased significantly (Naimi and Muhanna, 2021). Understanding the different stages of the impact of urban coastal zone geomorphology change factors can help us to understand human activity in the region and its effects on the environment.

During the entire development process of the urban coastal zone, the factors that affect geomorphologic evolution primarily include natural and anthropogenic factors (Feng et al., 2021). Natural factors include ocean current erosion and sediment deposition (Maren et al., 2016). With the economic development and population growth, human activity has gradually become the main factor affecting geomorphologic changes in urban coastal zones (Li and Wang, 1984). Notably, the human activities in urban coastal zones primarily include hydraulic structures and reconstruction projects, channel dredging, sand mining, artificial coast building, and aquaculture development (Giosan et al., 2013). The impact of human activities on the geomorphologic changes in urban coastal zones is primarily reflected in the changes in the hydrodynamic and sedimentary environmental conditions (Suo and Zhang, 2015). The construction of reservoirs and sluices in the upper part of the watershed can lead to a reduction in the runoff and sediment transport, causing topographic changes, such as erosion of the submerged delta or displacement of the coastline (Darwish et al., 2017; Maloney et al., 2018). Reclamation projects and artificial structures directly change the coastline shape of urban coastal zones and impede the circulation of sediment material and energy fluxes (Loh et al., 2018), resulting in changes in the velocity and amplitude of tidal currents (Yoon et al., 2020). At the same time, channel dredging and sand mining directly change the underwater topography and then, change the hydrodynamic environment of the corresponding region (Mossa et al., 2017). In addition, industrial production and aquaculture in the reclaimed area increase the influx of artificial compounds and industrial heavy metals into the bay, altering the material composition of the sediments (Fan et al., 2022). These pollutants can attach to the sediments and then, remain in the seabed and tidal flats, causing environmental degradation of coastal zones and threatening the sustainable development of the urban coastal zone society and environment (Deng et al., 2020).

In the past, the developers only considered the economic benefits of the land without considering social development and environmental protection according to the human and geographical environment of the region, which restricts the sustainable development of urban coastal zones and deters the full utilization of resources (Cao et al., 2020). At present, most of the research data on environmental evolution have poor spatial and temporal continuity, and the process of geomorphic evolution under the influences of human activity, along with the main driving factors of the process, are not fully understood (Martino et al., 2021). Future studies on the transformation process of the urban coastal zone topography and reclaimed land-use patterns are urgently needed to provide a reference for decision making to optimize the reclamation utilization pattern in coastal zones and promote sustainable development in urban coastal zone economies.

Quanzhou Bay is located on the southeast coast of China and is surrounded by well-developed cities as a typical urban coastal zone (**Figure 1**), with the total land area of the city being 1.10 × 10^4 km^2 and sea area being 1.28 × 10^2 km^2. The permanent population of the region was 8.78 × 10^6 in 2020 (data from Quanzhou Statistical Information Network, 2021). The sediments of Quanzhou Bay are primarily derived from the Jinjiang River, of which the annual sediment flux is 2.54 × 10^6 t (Lin et al., 2019). The sediment types in the bay were dominated by silt and clay, whereas the sand content was relatively low. Quanzhou Bay is a strong tidal bay, with a tidal current that has constantly alternating movement (**Figures 2B,C**), and its perennial wind and wave directions are primarily North-North-East (NNE) – North-East (NE) and South-South-West (SSW), respectively (Huang et al., 2018; Lin, 2020). Changes in the sea area (including coastline, shoreland, topography, reclamation projects, etc.) are closely related to local economic development and have distinct stage-specific development characteristics. Over the past 70 years, Quanzhou has undergone the entire process of transforming economic agents. Therefore, it is an ideal natural laboratory for conducting research and theory-guided practice on the topographic evolution of urban coastal zones under the impact of human activity.

Based on the historical geographic charts, satellite images, and economic data of Quanzhou Bay, in this study, we discussed the topographic change processes and main influencing factors of urban coastal zones under the influence of human activity over the past 70 years. The research results can provide a strategic reference for estimating future economic development in coastal cities and promoting sustainable development in urban coastal zones.

MATERIALS AND METHODS

Marine Map and Satellite Image Data

In this study, six large-scale geographic charts (for the period 1954–2017) of Quanzhou Bay were selected as the source of bathymetric and coastline data (**Table 1**), and the lowest theoretical datum was used for bathymetric data (Liu et al., 2020). The remote sensing data were satellite images from 1988, 1995, 2006, and 2017, respectively (from Google Earth) (**Table 2**).

All charts were converted to the WGS84 coordinate system and Mercator projection using ArcGis (Environmental Systems Research Institute, United States), to eliminate discrepancies caused by the differences in geographic coordinate systems and projection methods. The digital elevation model and raster data files were constructed using digital bathymetry data, according to Chen et al. (2020). The remote sensing information was referenced to a 1:35,000 chart and covered the entire research area. Each image had more than eight control points to carry on the geometric correction; then, the information for the coastline, including the reclamation method used in the region, was extracted. By comparing the charts of different years and the data

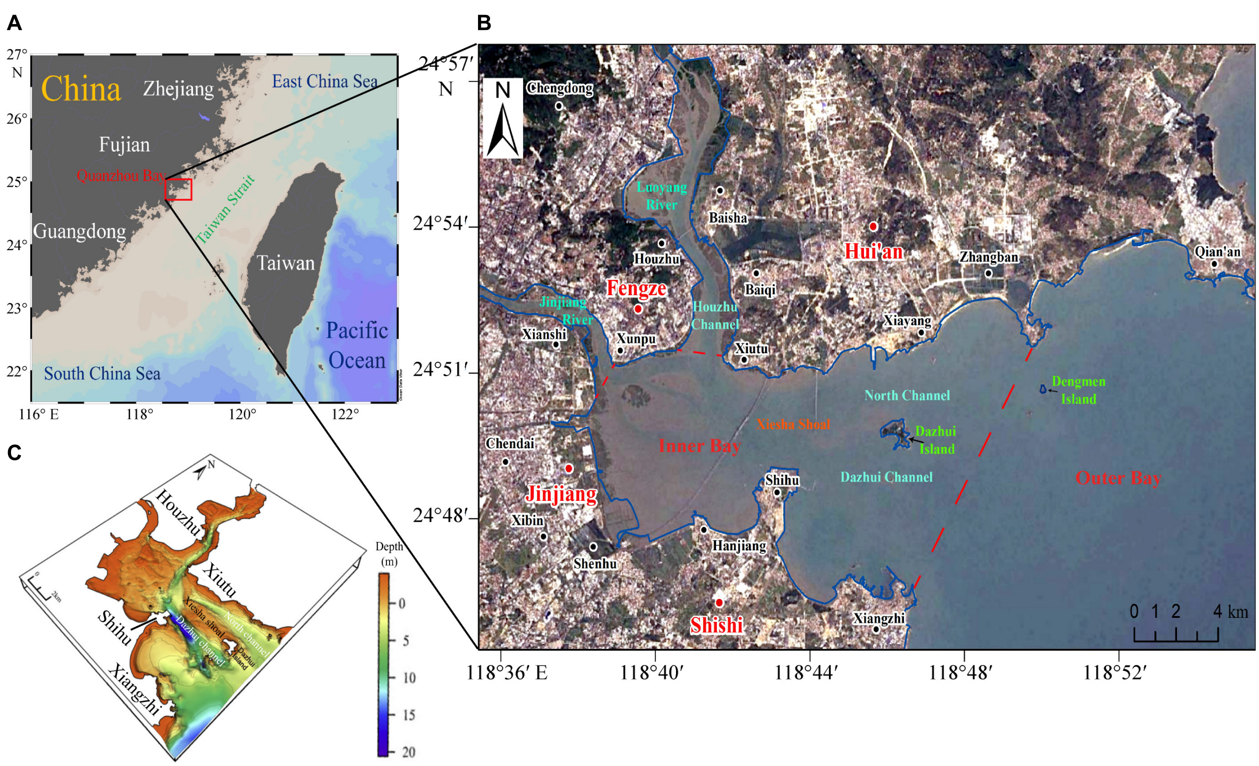

FIGURE 1 | Overview of the study area. **(A)** The location of the study area (From Ocean Data View); **(B)** The basic information of Quanzhou Bay, including cities, islands, channels, and rivers (The background image is a satellite image of Quanzhou Bay in 2020 from Google Earth Pro); **(C)** Landform and topography of Quanzhou Bay (Chen et al., 2011).

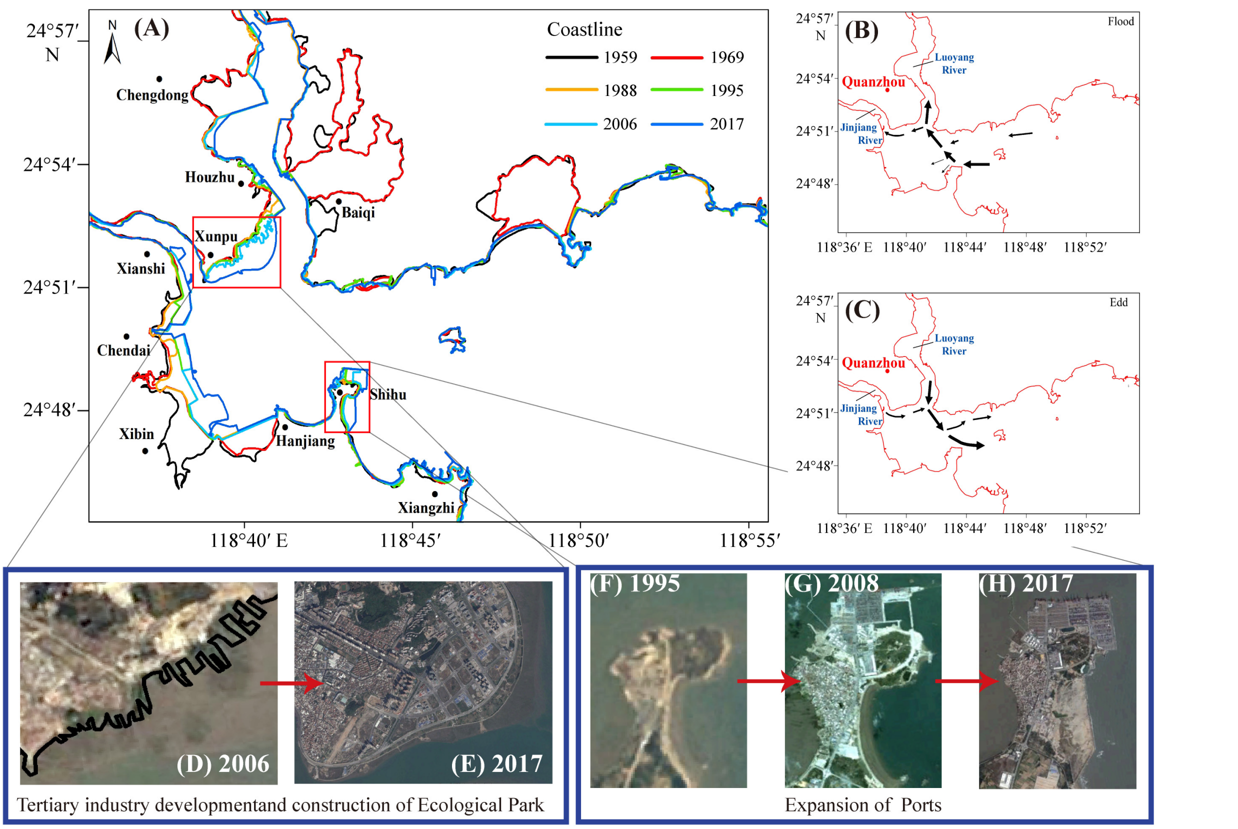

FIGURE 2 | Tidal current direction, coastline and reclamation changes in Quanzhou Bay. **(A)** Coastline change; **(B)** Flood current; **(C)** Ebb current; **(D,E)** Urban expansion in Fengze; **(F–H)** Shihu Port expansion [**(D–H)** images are from Google Earth Pro].

extracted from remote sensing (Li et al., 2018b), changes in the isobath and coastline were analyzed, and the rates of erosion and deposition were obtained to determine the evolutionary processes in the regional topography.

TABLE 1 | Status of historical marine map data.

Marine map name	Marine map number	Scale	Coordinate system	Time of publication
Nanri Island to Quanzhou Bay	10–56	1:100,000	–	April 1973
Quanzhou Bay	5,616	1:50,000	Beijing54	September 1975
Quanzhou Bay	14,181	1:35,000	Beijing54	April 2000
Quanzhou Bay	14,181	1:35,000	Beijing54	April 2003
Quanzhou Bay	14,181	1:35,000	WGS84	May 2008
Quanzhou Bay	14,181	1:35,000	CGCS2000	July 2019

TABLE 2 | List of remote sensing data used in the study.

No.	Scale	Coordinate projection	Resolution (m)	Data/year
1	$1{:}1.44 \times 10^4$	WGS 84	38.22	31 December 1988
2	$1{:}7.22 \times 10^4$	WGS 84	19.11	31 December 1995
3	$1{:}3.61 \times 10^4$	WGS 84	9.55	22 October 2006
4	$1{:}9.03 \times 10^3$	WGS 84	2.39	29 August 2017

Parameters

Shape Index of the Bay

By calculating the ratio of the circumferences of the bay and the circle of the equal area and comparing the similarity between the shape of the bay and the circle, the complexity of the shape of the bay was determined (Chen et al., 2020). The SIB was calculated as follows:

$$SIB = P/(2\sqrt{\pi A}),$$

where P is the perimeter of the bay (m) and A is the area of the bay (m^2).

Artificial Index of the Bay

The artificial coastline index indicates the degree of transformation from the natural coastline to the artificial coastline. Notably, it reflects the degree of interference of human activity with the natural coastline (Li et al., 2018b). The artificial index of the bay AIB was calculated as follows:

$$AIB = T/L,$$

where T is the artificial coastline length and L is the total coastline length of the study area.

Intensity of Bay Development

The IBD represents the intensity of human activity in the coastal zone (Song et al., 2019), which can be calculated as follows:

$$IBD = \sum_{i=1}^{n} (l_i \times p_i)/L,$$

where i is the type of coastline, l_i is the length of the type i coastline, n is the sum of the types of coastlines, L is the length of the coastline in the study area, and p_i is the environmental impact factor of the type i coastline (**Table 3**). Notably, the higher the p_i-value, the greater the negative impact of human activity on the bay.

Real Gross Domestic Product per Capita

Real GDP per capita is intrinsically linked to the process of urban industrialization and is related to the structure of the economy. It can objectively reflect the level of social development and the degree of development over a certain period (Wu, 2020). The structural changes and degree of industrialization of urban coastal zones can be determined by calculating the gross national product in different periods. The real GDP per capita can be expressed by the following equation:

$$\text{Real GDP per capita} = \text{GDP/Total population.}$$

RESULTS

Based on the data analysis and calculation, the geomorphological changes in Quanzhou Bay primarily include the sea area, length and types of coastlines, and shoreland reclamation land use patterns. These changes can be divided into different stages based on their different characteristics.

Changes in Coastline and Sea Area

Coastline and Sea Area Changes From 1954 to 1989

The period from 1954 to 1989 was the main period of reclamation in the bay. According to the results of coastline extraction and classification (**Figure 2A**), during this period, the coastline length decreased by 7.28 km from 1959 to 1969 and 51.97 km from 1969 to 1988, and the sea area decreased by 13.34 and 45.62 km^2, respectively.

This period can be divided into two sub-stages based on coastline length change. The first sub-stage was from 1954 to 1969. In this period, the main reclamation projects were the Xibin Farm Reclamation (along the north bank of the Luoyang River) and the urban expansion of the Baiqi village, with reclaimed areas of 2.83, 0.78, and 1.54 km^2, respectively. The length of the urban coastline increased by 11.01 km, whereas that of the aquaculture and reclamation coastline increased by 4.63 and 1.34 km, respectively (**Table 4**). The second sub-stage was from 1969 to 1988. The reclamation projects primarily included the Wuyi, Qiyi, and Chengdong reclamations, along with the extension of the Xibin Farms reclamation on the west side of Hanjiang, covering areas of 17.49, 13.03, 7.54, and 3.02 km^2, respectively. The natural coastline was reduced by 46.7% owing to the transformation to the artificial concrete coastline. After the reclamation project along the Luoyang River was completed, the berm coastline was reduced to 14.19 km. With the reconstruction of Houzhu Port and the development of coastal aquaculture, the port coastline and aquaculture coastline increased by 5.23 and 8.29 km, respectively (**Table 4**).

Coastline and Sea Area Changes From 1988 to 2017

A decrease in reclamation activity and a slight increase in coastline length occurred from 1988 to 2017 (**Table 5**). In 1988–1995, 1995–2006, and 2006–2017, the coastline length increased

TABLE 3 | Resource-environmental impact factors of different coastlines.

Coastline type	Environmental impact status of coastline resources	Impact factor
Natural coastline	The impact on coastal resources and ecological environment is very small	0.1
Urban coastline	It has a significant impact on coastal resources and ecological environment, and most of them are irreversible	1.0
Berm coastline	The utility model has less influence on coastal resources and ecological environment, and has the functions of resisting natural disasters, such as storm surge and protecting farmland, housing and people's property safety	0.2
Port coastline	It has a great impact on coastal resources and ecological environment, and most of them are irreversible	0.8
Aquaculture coastline	The impact on coastal resources and ecological environment is slightly greater, and part of it is irreversible	0.6

TABLE 4 | The variation of different coastline lengths from 1954 to 2017 in Quanzhou Bay.

Time	Length (km)					Total coastline length (km)
	Natural coastline	Urban coastline	Berm coastline	Port coastline	Aquaculture coastline	
1954	148.98	33.07	20.87	1.90	3.54	208.36
1968	124.69	44.08	25.50	1.93	4.88	201.08
1988	66.49	50.88	11.31	7.16	13.17	149.01
1995	57.39	54.31	13.25	8.36	18.06	151.37
2006	16.28	97.13	16.42	13.59	15.68	159.10
2017	15.94	84.52	23.11	23.20	16.39	163.17

TABLE 5 | The variation of parameters from 1954 to 2017 in Quanzhou Bay.

Parameters time	Coastline length (km)	Relative to the change in the previous year (km)	Sea area (km^2)	Relative to the change in the previous year (km^2)	Shape index of the bay (SIB)	Artificial Index of the Bay (AIB)	Intensity of bay development (IBD)
1959(1954)	208.36	–	362.63	–	3.09	0.28	0.27
1969(1968)	201.08	−7.28	349.29	−13.34	3.04	0.38	0.33
1988(1989)	149.11	−51.97	303.66	−45.63	2.41	0.55	0.49
1995(1998)	151.77	2.66	300.36	−3.3	2.47	0.62	0.53
2006(2007)	159.32	7.55	295.1	−5.26	2.62	0.89	0.77
2017(2014)	162.91	3.59	284.78	−10.32	2.72	0.90	0.73

The time of measurement for sea area is in brackets, and the time of measurement for land is out of brackets.

by 2.66, 7.55, and 3.59 km, respectively, whereas the sea area decreased by 3.3, 5.26, and 10.32 km^2, respectively.

The major reclamation works between 1988 and 2006 were carried out at the coasts of the Jinjiang River, Houzhu, and the northern part of Shihu, with a total reclaimed area of 2.77 km^2. During this period, the natural coastline decreased by 41.11 km, whereas the urban coastline increased by 42.82 km (**Table 4**).

The area of reclamation projects in Quanzhou Bay increased from 2006 to 2017. The reclamation projects were primarily located at the north bank of Luoyang River and the coast from Chendai to Hanjiang, covering an area of 4.09 and 3.84 km^2, respectively (**Table 4**). At the same time, the construction of the flood control seawall along the south bank of the Luoyang River was lengthened. The Shihu Port was further expanded, and the coastline was thus, straightened, turning the eastern coastline into an entirely artificial coastline. The natural coastline declined to 15.94 km, and part of the urban coastline was converted into port and berm coastlines. The expansion of Shihu Port led to a significant increase in the port coastline (from 13.59 to 23.20 km) and an increase in the aquaculture coastline (from 15.68 to 16.39 km) (**Table 4**).

Change of Topography in Different Periods

Changes in Isobath in Different Periods

Variations in isobaths in Quanzhou Bay primarily occurred in the Houzhu, Dazhui, and northern channels, among which the variations in isobaths at 0, 5, 10, and 20 m were more significant. The changes in the isobath can be divided into two periods (**Figure 3**).

From 1954 to 1989 (**Figures 3A,B**), after the large reclamation projects and the construction of artificial water control projects in the upper reaches of the river, the 0-m isobath from the Luoyang River estuary to Xiutu moved to the central axis of the channel. At the position of Gufu to Xiangzhi, the 0-m isobath moved seaward, with an average of 0.12 km. The 0-m isobath in the Xiesha Shoal extended outward, leading to a 0.15-km wide valley. The balance between erosion and deposition was maintained along the coast from Xianyang to Qian'an. In the Houzhu Channel, the isobath of 5 m was interrupted and contracted. The isobath of 10 m disappeared in the Houzhu Channel and moved landward on the direct line from Xiangzhi to Qian'an at the same time. The 20-m isobath at the southeast of the bay moved 2 km on average.

From 1989 to 2014 (**Figures 3B,C**), in the Houzhu Channel, the 0-m isobath continued to move toward the central axis of the channel. In the east of Shihu, the 0-m isobath retracted westward. The 0-m isobath of nearby the Gufu to Xiangzhi path moved seaward 0.2 km on an average. The area of the 5-m deep area of the Houzhu Channel was reduced. A channel appeared in the south of Xunpu, with an average width of 0.3 km. Meanwhile, two artificial channels with depths of 5 and 10 m appeared on the north and south of Dazhui Island, respectively. The position near the 20 m isobath maintained a balance between erosion and deposition.

Changes of Erosion and Deposition in Different Periods

The erosion and deposition changes of the seabed were obtained according to the information of the planar distribution of water depth and the longitudinal profiles of four characteristic locations (**Figures 3D**, **4A**), which indicated different characteristics at different periods.

Erosion during the period 1954–1968 ranged from −12.33 to 0 m (a negative value indicates the depth of erosion), whereas deposition during this period ranged from 0 to 9.47 m (**Figure 4A**). The west side of Xiutu and the northern part of Dazhui Island were raised by 1 m due to deposition. The maximum deposition area was located to the east of Xiangzhi, with an average annual deposition rate of 0.68 m/yr. Notably, the main eroding areas were located in the east of Houzhu and north of Shihu and Xiangzhi. The largest eroding sites were located to the north of Shihu (as section B-B) (**Figure 5B**), which indicated an eroding depth of approximately 2 m, with an average annual erosion rate of 0.88 m/yr.

After the construction of extensive reclamation projects from 1968 to 1989 (**Figure 4B**), erosion and deposition in Quanzhou Bay were significantly different. Erosion ranged from −8.05 to 0 m, whereas deposition was observed to be ∼12.32 m. During this period, the main sedimentation area was located in Houzhu Channel. As shown in section A-A (**Figure 5A**), the maximum deposition depth was 6 m, with an average annual deposition rate of 0.59 m/year. Massive deposition occurred from the northern part of Shihu to Xiutu, with a deposition range of 1–2 m in section C-C (**Figure 5C**). The depth of water along the coastline from Xiutu to Qian'an generally increased, and the largest eroded area appeared to the south of Dazhui Island, with an average annual erosion rate of 0.38 m/yr.

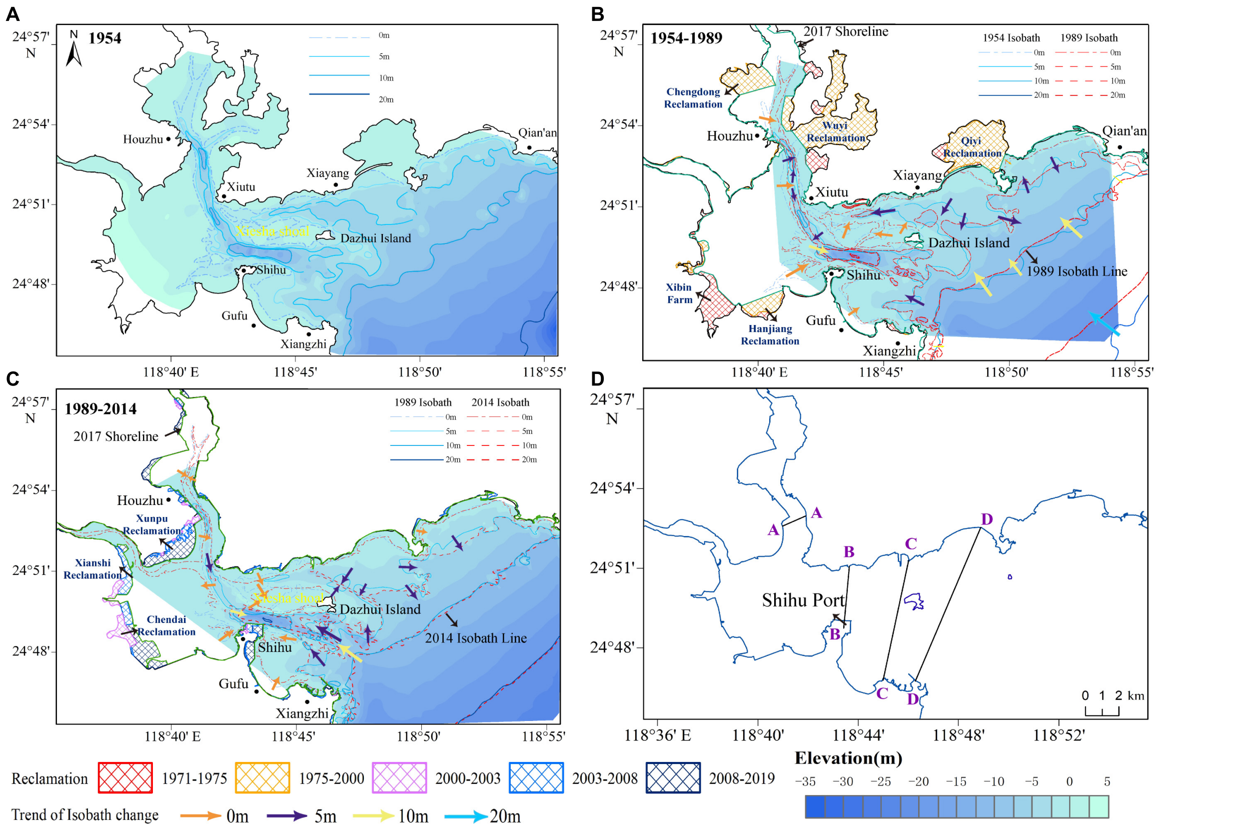

FIGURE 3 | Variation of isobath in Quanzhou Bay from 1954 to 2017. **(A)** 1954; **(B)** 1954–1988; **(C)** 1988–2017; **(D)** position of characteristic section. The arrows indicate changes in the isobath.

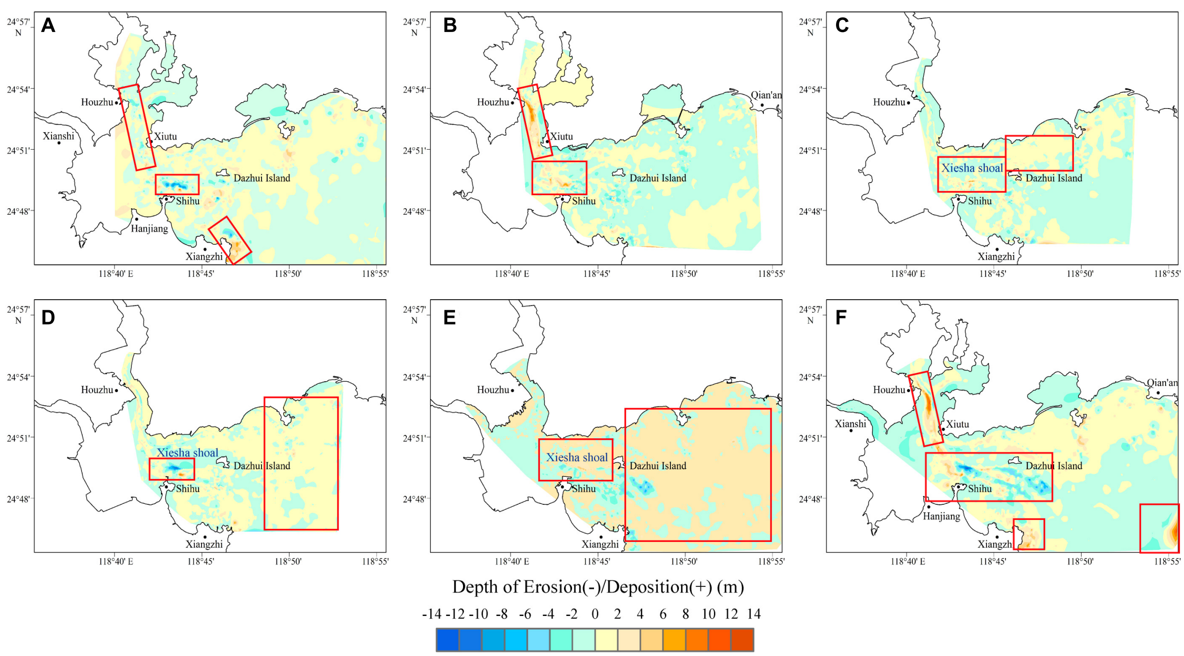

FIGURE 4 | Variation of water depth in Quanzhou Bay from 1954 to 2017. **(A)** 1954–1968; **(B)**1968–1989; **(C)** 1989–1998; **(D)** 1998–2007; **(E)** 2007–2014; **(F)** 1954–2014. Most of the blank areas in the bay were mudflats over 0 meters, and the blank area at the entrance of the bay was the repeated bathymetric information.

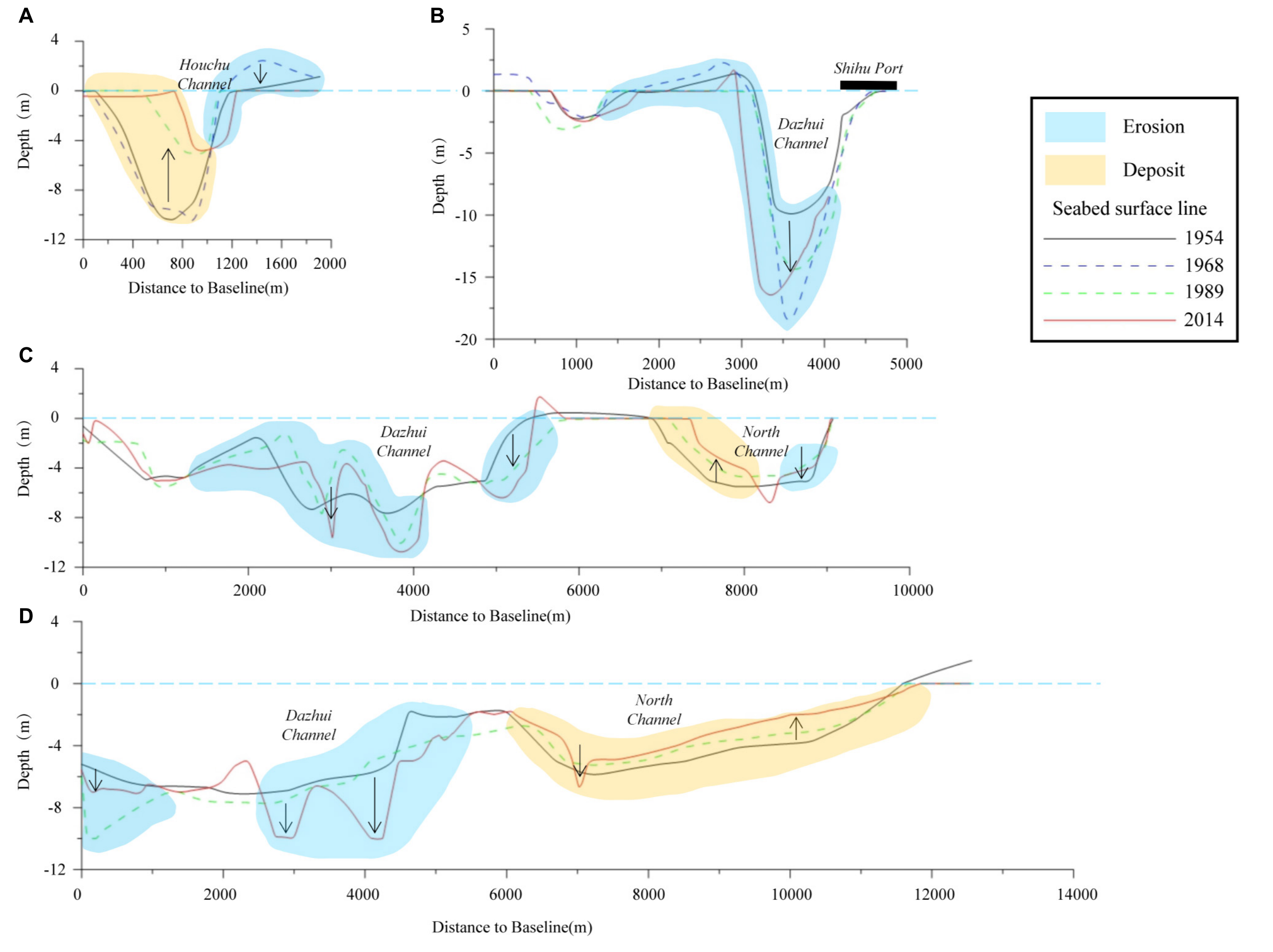

FIGURE 5 | Cross-shore topography variations along four profiles during the four different stages of industrialization from 1954 to 2017. The upward arrow indicates deposition, and the downward arrow indicates erosion. The elements in the section **(A–D)** are explained in part labels, where the blue areas represent erosional areas, the orange areas represent deposital areas, and different types of lines represent the seabed surfaces in the section for different years.

From 1989 to 1999, the erosion ranged from −6.92 to 0 m, whereas the deposition ranged from 0 to 9.30 m (**Figure 4C**). Notably, the main deposition areas were primarily concentrated in the inner bay. The Houzhu Channel subsidence was located on the south side of the channel, and the depositions in the north of Xiangzang and northeast of Dazhui Island were in the range of 1–2 m. The deposition in the northern part of Shihu was the largest, with an annual average sedimentation rate of 0.93 m/yr. The main eroding areas were in Houzhu Port, the eastern part of Shihu, and the Xiesha Shoal. The largest erosion occurred in the southern part of Dazhui Island, with an average annual erosion rate of 0.69 m/yr.

From 1999 to 2007 (**Figure 4D**), erosion ranged from −11.66 to 0 m, whereas deposition ranged from 0 to 9.29 m. During this period, the entire Houzhu Channel area was still deposited. There were small deposits in the northern part of Shihu and the eastern part of Xiangzhi. The largest deposition occurred in the northern part of Shihu, with an average annual deposition rate of 1.16 m/yr. The main eroding area was located in the Xiesha Shoal, with an average annual erosion rate of 1.46 m/yr.

From 2007 to 2017 (**Figure 4E**), erosion ranged from −10.72 to 0 m, whereas deposition ranged from 0 to 6.64 m. During this time, the Xiesha Shoal area was the main deposition area. There was a large area of deposition at the entrance of the bay, and the amount of deposition in this area increased compared with the previous period. The maximum deposition location was from the Xiesha Shoal to the Dazhui Island Channel, with an average annual deposition rate of 0.66 m/yr. The total water level in the Houzhu Channel decreased, and the maximum eroding area was in the southwest of Dazhui Island, with an average annual erosion rate of 1.07 m/yr. There were two artificial channels in the bay (**Figure 5D**), the changes in the estuary and the bay coast were small, and the balance of erosion and deposition was maintained.

There were two artificial channels in the bay (**Figure 5D**), the changes in the estuary and the bay coast were small, and the balance of erosion and deposition was maintained. During the period 1954–2014, it can be seen that the seabed changes in the inner bay of Quanzhou Bay were mainly concentrated in the area around Houzhu and Shihu Port (**Figure 4F**). The main features of the two areas are different degrees of deposition and obvious traces of artificial dredging.

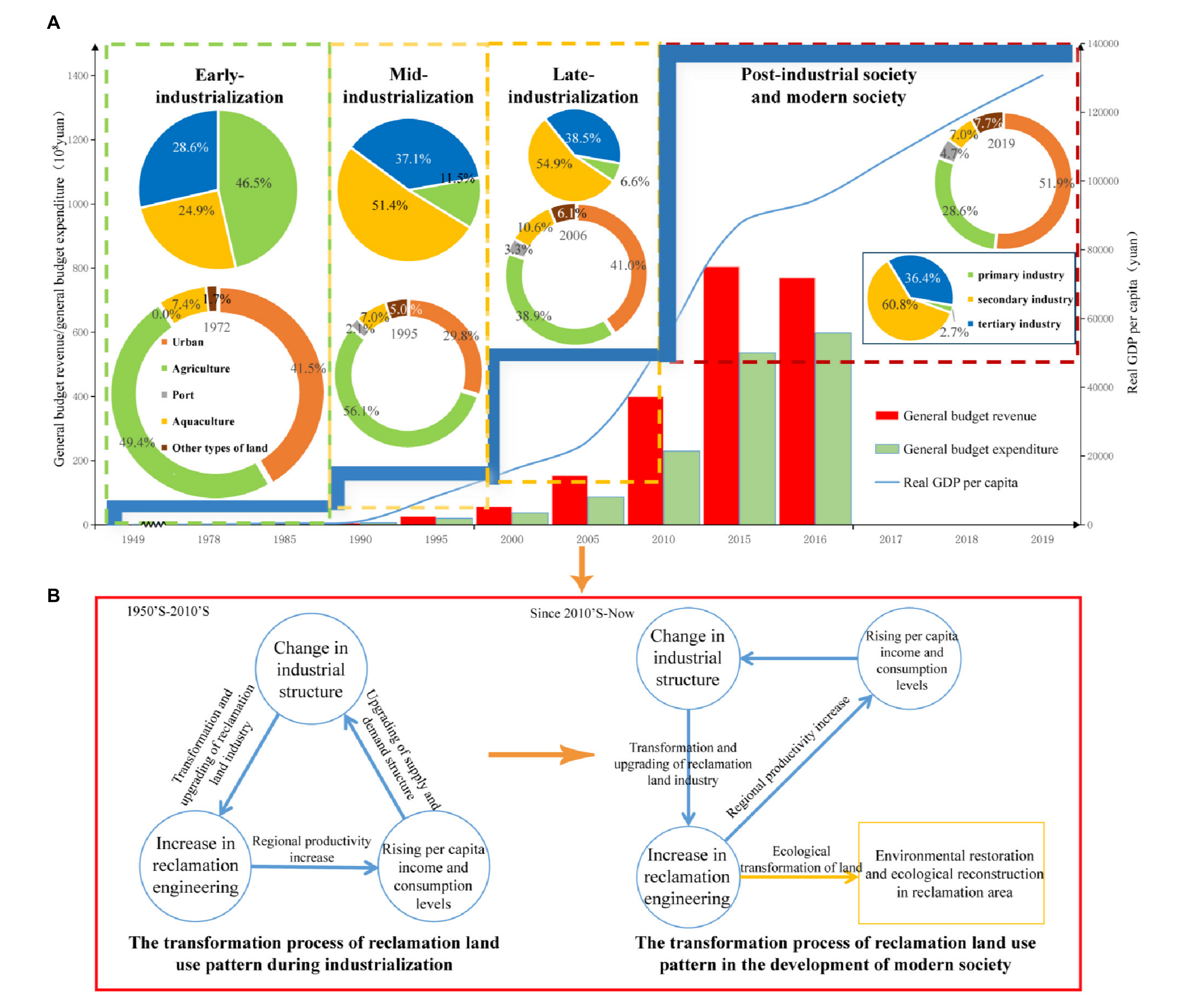

FIGURE 6 | (A) The stages division of land reclamation with economic structure in Quanzhou Bay. The pie chart shows the proportion of different industries; the circular chart shows the proportion of different land uses; GDP, population, General budget revenue, and General budget expenditure data from http://tjj.quanzhou.gov.cn/tjzl/tjsj/. **(B)** Conversion model of reclaimed land in Quanzhou Bay.

Changes of Land Use Pattern in the Reclaimed Area Around Quanzhou Bay

According to Chanali's theory of industrialization stage (Jin et al., 2018), the industrialization development in Quanzhou Bay over the past 70 years has occurred in multiple stages; the land use functions of reclaimed areas under different stages also differs (**Figure 6A**).

From the 1950s to the mid-1980s, Quanzhou was in the early stage of industrialization, with the per capita GDP increasing from 60 Chinese yuan to 6,000 Chinese yuan. During this period, the economic structure of Quanzhou was primarily composed of the primary industry. Notably, Quanzhou was in the early stage of economic development between the 1950s and 1960s. Reclamation projects were all carried out for agricultural production. The area of agricultural land accounted for 49.4% of the total reclaimed area, indicating that the reclaimed land was primarily used for agricultural production, and the total arable land area increased (**Figure 7C** and **Table 6**). However, the output values of the secondary and tertiary industries were relatively low, owing to the shortage of raw materials, low production levels, and low product values. Therefore, the primary industry grew faster than the other two industries (**Figure 7A**). Until the 1970s, large-scale reclamation projects were conducted. Part of the reclaimed land was used for agriculture and animal husbandry, and part of it was used for industrial development. During this time, the factories of saltworks, small-scale food, and handicrafts were established and began production, resulting in a rapid increase in the secondary industry output value. Even then, the primary industry remained as a pillar industry during this time (**Figure 7A**).

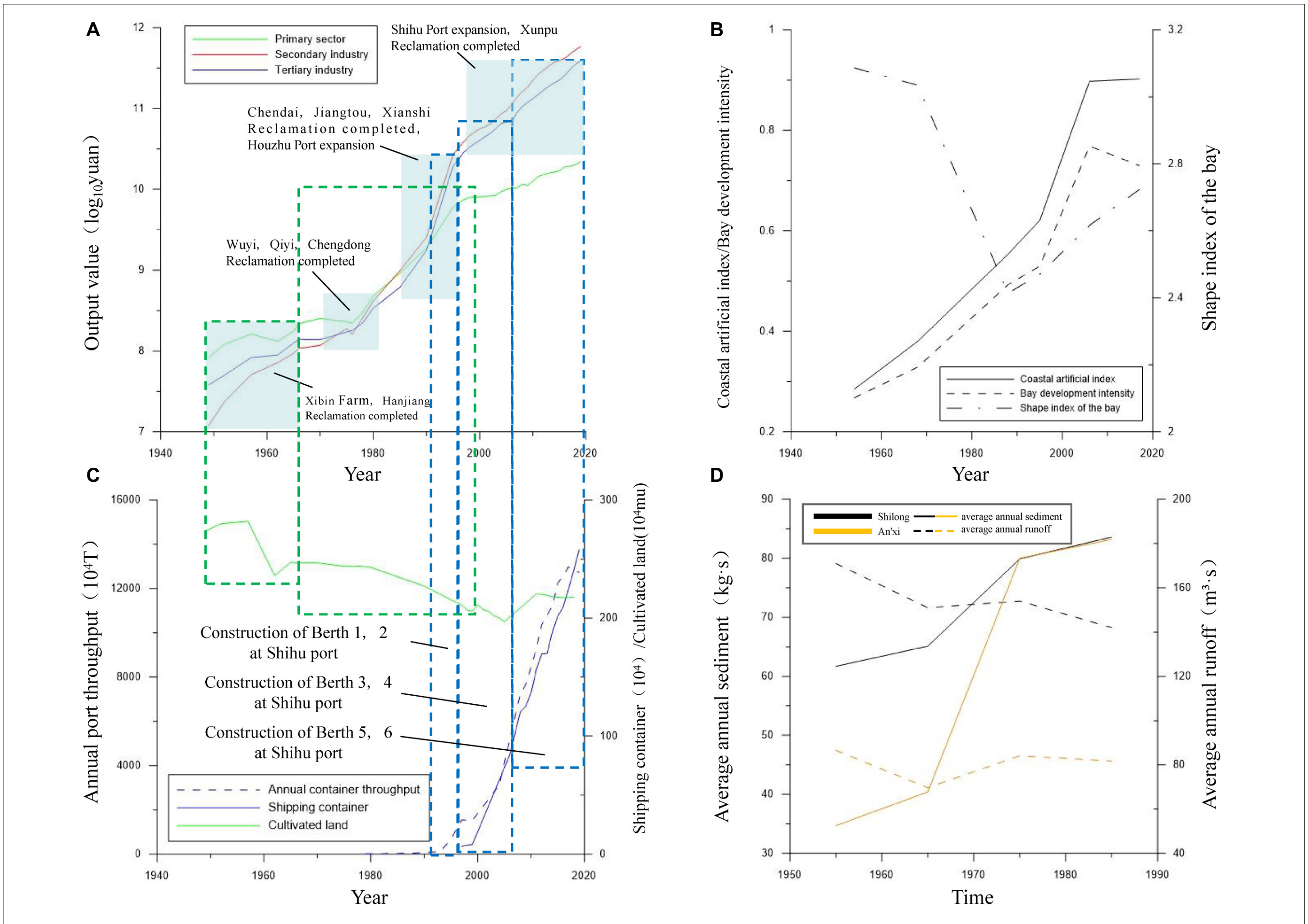

FIGURE 7 | Changes of industrial output value and correlation coefficient. **(A)** Annual changes in the output value of the three major industries (economy data from http://tjj.quanzhou.gov.cn/tjzl/tjsj/). **(B)** CHANGES of coastline parameters. **(C)** Area of cultivated land, shipping throughput and the number of containers, **(D)** Sediment transport and annual runoff variation.

TABLE 6 | The proportion of different land use patterns in the reclaimed area.

Year	Cities and industries (m^2)	Percentage (%)	Agriculture (m^2)	Percentage (%)	Port (m^2)	Percentage (%)	Aquaculture (m^2)	Percentage (%)	Other types of land (m^2)	Percentage (%)	Total area for reclamation (m^2)
1972	5.64	41.5	6.71	49.4	0.00	0.0	1.01	7.4	0.23	1.7	13.588
1988	12.60	22.3	39.10	69.0	0.80	1.4	1.39	2.5	2.74	4.8	56.628
1995	17.95	29.8	33.75	56.1	1.29	2.1	4.20	7.0	3.00	5.0	60.188
2006	27.21	41.0	25.82	38.9	2.22	3.3	7.06	10.6	4.07	6.1	66.378
2019	41.02	51.9	22.61	28.6	3.69	4.7	5.56	7.0	6.09	7.7	78.968

From the mid-1980s to the late-1990s, Quanzhou entered the middle stage of industrialization, and the per capita GDP increased to 18,000 Chinese yuan. With the Reform and Opening-up Policies, urban industrial land accounted for half of the reclaimed land, whereas small-scale processing industries began to construct factories and began operation. Thus, the output value of the secondary industry gradually approached that of the primary industry, leading to the beginning of changes in the industrial structure of this region (**Figure 7A**). Furthermore, the pace of transformation and upgrading of traditional industries accelerated with increasing foreign investment. During this period, the area of agricultural land gradually decreased, whereas that of urban land continued to increase (**Table 6**). The rapid development of labor-intensive industries, such as regional textile shoes, clothing, and craft products, led to the rapid expansion of the secondary industry. Furthermore, the reconstruction of Houzhu Port and the growth of the shipping-based transportation industry led to a rapid increase in the tertiary industry. By the 1990s, there was an evident change that took place in the regional demand, production, and foreign trade structures, and the demand for reclaimed land had also changed from agriculture and aquaculture to cities, ports, and industrial parks. Notably, the reclaimed land in the Jinjiang River estuary has been primarily used for aquaculture and industrial production. The urban industrial land in the reclaimed area was 17.95 km^2, and the aquaculture land increased by two times (**Table 6**). Furthermore, the annual port capacity and the number of container freight transport increased slightly, due to the expansion of berths at Houzhu Port, and the output value of all three industries increased during this time, with the secondary industry overtaking the primary industry as the main industry (**Figures 7A,C**).

In the 2000s–2010s, Quanzhou entered the stage of late industrialization. The reclaimed land was primarily around the expansion of Shihu Port and the expansion of the regional town of Hanjiang (**Figures 2F,G**), where ports and service industries became major industries in the reclaimed areas. The proportion of agricultural land in the reclaimed area decreased from 56.1 to 38.9%. Moreover, the traditional manufacturing industries around the urban coastal zone gradually changed to technology-intensive industries, such as the petrochemical, ship-building, and electronic information industries, leading to rapid growth in the output value of the secondary industries. Commercial and ecological construction began along the Xunpu coast, whereas new 100,000-ton berths were added to Houzhu Port and 1–4$^{\#}$ berths were built at the Shihu Port (**Figures 2D,E**). The port handling capacity and the number of container transports increased rapidly (**Figure 7C**), and the output values of the second and tertiary industries were higher than that of the primary industry.

In the past 10 years, Quanzhou has entered the transition period between the post-industrial and modern society. The newly reclaimed land was primarily used for expanding cities and building ports (**Figures 2F,H**), whereas the old reclaimed land was gradually transformed into the residential, financial business, and foreign-funded industrial areas, with an urban industrial land share of 51.9% (**Table 6**). With the expansion of the port and further refinement of the tertiary industry, the number of transport containers increased, whereas the growth rates of the output values of the second and tertiary industries increased again. The oil, handicraft-related industries, and ports around the reclamation project are currently integrated, resulting in increased industrial relevance, transportation industry operating rate, and degree of industrial convergence (**Figure 7C**).

DISCUSSION

Evolution Process and Influence Mechanism of Urban Coastal Zone

In this study, the geomorphologic evolution of Quanzhou Bay presented different characteristics at different industrialization stages. At different stages, the factors affecting the geomorphologic evolution were different.

Evolution of Urban Coastal Zone Environment Before Industrialization

From pre-industrialization to the early stage of industrialization, the reclamation projects were concentrated only in a few locations, which had little influence on the shape and topography of the urban coastal zone (Zhu et al., 2017). Thus, we could deduce that the evolution of the urban coastal zone environment is primarily controlled by natural factors, which include hydrodynamics (e.g., river discharge, waves, and tides) and sediment characteristics (e.g., supply, composition, and distribution) (Cao et al., 2021). Except for extreme weather conditions, the natural evolution of urban coastal zones tends to remain stable (Lin, 2020; Sun and Niu, 2021). Under the influence of extreme weather, e.g., typhoons and floods, the sediment particle input increases greatly in a short time, whereas the change in hydrodynamics during typhoons causes sediment resuspension and redistribution that affects the evolution of underwater topography (Lin et al., 2019).

Under natural conditions, hydrodynamics is the main factor that controls the changes in the coastline and topography of urban coastal zones (Li et al., 2020; Zarzuelo et al., 2021). The influence of hydrodynamics on topography results in the erosion of the seabed and coastline by natural ocean currents (Oiwane et al., 2011). As a typical strong tidal bay, the top of Quanzhou Bay is dominated by the river hydrodynamics of the Jinjiang and Luoyang rivers, whereas the middle and river-mouth areas are dominated by ocean dynamics (Wang, 2011). During the flood tide, the flood tidal current and river flow directions are opposite, and the two actions cancel each other, which lowers the flow velocity, reduces the erosion ability, and intensifies sediment accumulation (Feng et al., 2015; Du et al., 2016). During the ebb period, the ebb-tidal current and river flow are in the same direction, and the velocity of the total flow increases, which leads to the enhancement of the scouring capacity of the estuary (Styles et al., 2016). Notably, the bottom seabed on the north side of the Shihu Port was eroded by strong tidal currents caused by a sudden change in the topography of the cape (Lubke, 1985). The same process occurred in the area east of Xiangzhi, where the coastline was eroded and moved landward (**Figure 2**).

Sediment supply is also an important factor that affects the evolution of erosion and deposition in the bay. Generally, under natural conditions, the distribution of sediments in urban coastal zones remains stable (Martino et al., 2021). In our study area, the sediment particles flow down the Jinjiang River and converge with the Luoyang River into the bay area, where the traction load deposited in the estuary of Jinjiang has formed a large area of tidal flats, and the suspended load has been deposited in the weak hydrodynamic environment (Wang et al., 2015). At the same time, in the bay, the grain size distribution of sediments is primarily controlled by the hydrodynamic force (the grain size distribution was deduced to be inversely proportional to the force); thus, the changes in hydrodynamic conditions will affect the distribution of sediments, resulting in erosion or deposition in the coastline and changes in the topography.

At the beginning of industrialization (1960s) in the Quanzhou Bay, Liaodong Bay, Hangzhou Bay, and other urban coastal zones, topography changes were primarily controlled by natural factors (Zhang and Zhang, 2004; Yan et al., 2017). Notably, natural factors are still an important factor affecting the topography of urban coastal zones. Excessive erosion of the coastline will lead to the failure of flood protection facilities in coastal cities and will thus, increase the risk of flood disasters in the city (Mohamed Rashidi et al., 2021).

Period From Early to Middle Stages of Industrialization

From early industrialization to mid-industrialization (1950s–1990s), human activity has become the main controlling factor of environmental evolution in the urban coastal zone. Notably, one of the reasons for the changes in topography has been the change in hydrodynamics in the region (Liu et al., 2014). The development of industrialization in urban coastal zones changes the shape of the coastline and the area of the sea, which leads to hydrodynamic changes (Yang and Chui, 2020). Specifically, coastal construction in urban coastal zones has transformed much of the natural coastline into an artificial coastline and changed the original hydrodynamic strength and direction (Chen et al., 2011; Ondoa et al., 2018), thereby affecting the development of the urban coastal zone topography. In the meantime, extensive reclamation projects have reduced the area of the urban coastal zone, caused a decrease in tidal influx, and weakened the tidal intensity in the area. By the 2000s, the tidal energy at the Luoyang River and south of Xiutu decreased by 64.1 and 16%, respectively (Wang, 2007). Notably, the construction of reservoirs and sluice gates in the upper reaches of the Jinjiang and Luoyang rivers reduced the runoff volume and weakened the influence of runoff on tidal movements (Ying et al., 2018). Moreover, the reclamation embankment constructed during the Wuyi Reclamation Project reduced the tidal current velocity and increased the sediment flux (Tan et al., 2021), resulting in deposits that are 6 m in thickness in the Houzhu Channel. Due to the weakening of the hydrodynamics in the inner bay, the bay mouth was primarily eroded due to ocean hydrodynamics, which caused the 20 m isobath to move landward.

Another factor that influenced topographic changes was the increased amount of sediments, which were primarily derived from river discharge and erosion along the urban coastal zone. In the early and middle stages of industrialization, massive deforestation and excavation in the mountains in the upstream areas have caused serious soil erosion (Wang et al., 2011). Based on hydrological data from the Anxi and Shilong stations located along the Jinjiang River basin, a significant increase in sediment concentration was found in the Jinjiang River between the 1950s and 1980s (**Figure 7D**). The sediments discharged by the Jinjiang River, combined with those discharged by the Luoyang River, were deposited in the estuaries and formed a widely tidal flat, whereas the suspended load of sediments deposited in the weak hydrodynamic environment of the Houzhu Channel resulted in the continuous deposition of tidal flats in the channel (to the west) (Liu et al., 2014). Meanwhile, the Dazhui channel was gradually silted up (**Figure 5B**), owing to weakening hydrodynamics and increasing sediment flux. In addition, during the construction of the reclamation project, some of the filling structures were rushed into the bay by the water flow, resulting in an increase in the sediment concentration in the coastal water. However, human activities also affect the distribution of sediments (Radhouan et al., 2021). Notably, the hydrodynamic force in the bay has decreased, resulting in the tidal hydrodynamics not being sufficient enough to transport the fine-grained sediments out of the Houzhu Channel; thus, the particles carried by currents were accumulated on the banks of both the channels (**Figure 5A**). The shoal in the channel expanded rapidly outward, resulting in the disappearance of a 10-m deep groove in the Houzhu Channel and a significant extension of the 0 m isobath toward the center of the channel, which destroyed the original balance of erosion and deposition in Quanzhou Bay.

During this period, there was a great demand for land in urban coastal zones (Yu et al., 2020). During this period, the reclamation area in Quanzhou Bay was the largest during the entire process of industrialization. A typical example of this is Osaka Bay, which has an area of approximately 160 km^2 built over the centuries (Martín-Antón et al., 2020). During the period of industrialization, extensive reclamation activities in these urban coastal zones destroyed the original wetlands and freshwater resources. Additionally, sea reclamation caused the coastline length and sea area of the urban coastal zone to decrease, which in turn, affected the economic activity in the region (Guo et al., 2019). Most of the reclamation projects shorten the length and curvature of the coastline, resulting in a lower SIB (**Figure 7B**). Notably, with increased human activity, the natural coastline decreased, whereas the urban, port, and aquaculture coastlines increased. The AIB increased from 0.28 to 0.55, and the IBD increased from 0.27 to 0.49 (**Table 5**). An artificial coastline was also common in other industrial urban coastal zones in the nineteenth century, such as Maine Bay and New York Harbor (Köster et al., 2007; Guo et al., 2019). This indicates that, as the economy grows and the total reclaimed area increases, the levels of artificiality and development of coastlines gradually increase.

Period From Late Industrialization to Modern Society Era

From the later period of industrialization to the age of modern society (1990s–till date), the area of reclamation decreased. The topography changed primarily in the Houzhu Channel and northern Shihu. With the decrease in tidal hydrodynamic force and water exchange capacity, the venturi effect of the tidal channel between the inner and outer urban coastal zones weakened (Wang, 2011), which in turn, weakened the marine erosion in the Shoal and increased the deposition area. During this period, industrial and economic development along the coast altered the material composition of the sediments. Owing to the establishment of printing, dyeing, textile, and electroplating industries along the coast, the wastewater from the related industries and domestic sewage were discharged into the bay through sewage pipes or open channels, resulting in continuous increases in organic matter and heavy metal elements (e.g., Zn and Pb); this changes the physical composition of sediments in the Quanzhou Bay (Homira, 2021). Some ocean construction projects, such as sand mining and dredging, have also directly changed the seabed (Rahmawan et al., 2017). Since 2010, to maintain the use of the channel, dredging operations have been carried out in areas of the channel where deposition is severe and the water depth does not reach the required standard, resulting in artificially excavated channels in the Dazhui and North channels that are 10 and 5 m deep, respectively (**Figures 5C,D**). Simultaneously, the depositions in the channels facilitated the suspension and redistribution of surrounding sediments, which resulted in the deposition of the coastal sediments and periodic fluctuation in the terrain in the channel (Liu et al., 2014).

In addition to the changes in topography, the environment of Quanzhou Bay changed significantly during this period, because unplanned human activity (e.g., large-scale exploitation of sea sand, excessive discharge of industrial sewage, and excessive aquaculture) led to the gradual deterioration of the ecological environment in the urban coastal zones in the bay. Furthermore, with the increasing population in the reclaimed area and the rapid development of secondary and tertiary industries along the coast, the discharge of pollutants and organic matter into the bay has increased (Yan et al., 2020). Notably, the weakened hydrodynamics has limited the exchange of a large number of pollutants with seawater, affecting the dilution and diffusion of these pollutants, which has resulted in a significant increase in heavy metals and organic carbon in the bottom sediment (Yan et al., 2020). As a result, the water quality of the bay has deteriorated, and correspondingly, the environmental quality of the surrounding wetlands has declined significantly; this may have an impact on the cultural environment of the relevant marine organisms. Moreover, the large amount of coastal aquaculture has changed the pattern of water, sediment, and nutrient transport, which has, in turn, changed the natural environment where marine organisms live, resulting in the uneven distribution of hydrobionts and a decrease in the number of benthic organisms annually (Ge et al., 2021). Moreover, excessive aquaculture destroys the surrounding tidal flats and wetlands. Since the middle stage of industrialization, the aquaculture coastline in the coastal reclaimed areas has increased (**Table 4**), resulting in a large number of artificially excavated trench-ridge marks in the intertidal zone of the reclaimed area. This has completely destroyed the waterways of flood and ebb tides and sediment transport paths in the bay.

During this period, the reclamation works were large in number but small in area. Notably, during this period, the straight coastline area became complex and twisted again, resulting in an increase in the SIB (**Figure 2** and **Table 5**). The change in coastline type was primarily due to the change in the land function of the reclamation area. Over the course of this duration, natural coastlines have been transformed into artificial coastlines, with the percentage of natural coastlines decreasing from 44 to 10% (**Table 4**). There are two main reasons for this change. First, with the increased demand for the shipping industry, the Shihu Port has been expanding toward the sea, and thus, the coastline of ports has increased. However, in the later stage of industrialization, aquaculture increased due to economic growth, and part of the city coastline was transformed into aquaculture areas. In the process of the transformation of the bay area into a modern society, formerly large-scale aquaculture areas increased, whereas small-scale aquaculture production ceased. Notably, the IBD increased at first and then, decreased because of the difference in pi of different coastlines. This change in coastline and shoreland land-use patterns indicates that human activity in urban coastal zones has changed with economic development. In the later stage of industrialization, we observed that the land use in the urban coastal zone was primarily cities and industrial land (**Table 6**). Compared with post-industrial Japan, the purpose of reclamation projects has changed from farmland to airports and residential buildings (Kitazume, 2012). In the modern society, 95% of the coastline in Tokyo Bay has been transformed from natural to artificial (Atsushi and Jota, 2020). In some developed countries, the transformation of old reclamation areas is now a focus of urban coastal zone development; for example, Spain has also included parts of the reclamation areas in old industrial areas in reconstruction planning (Nogués and Arroyo, 2015). Thus, through the comparison of different urban coastal zones, we were able to deduce that shoreland land-use changes with economic changes.

Stage-Specific Development Mechanism of Coupling Relationship Between Human Activity and Geographical Environment in Urban Coastal Zones

As observed through the changes of the urban coastal zone geomorphology, it was evident that there was a stage change in the geomorphology features, such as coastline, isobath, and shoreland land use. This phase of change in the urban coastal zone during the stage of industrialization has a certain relevance (Kakisina et al., 2015).

Before industrialization, the cities around the urban coastal zone were small and sparsely populated, mostly dominated by agriculture and small shipping businesses. With the construction of reclamation projects, the productivity of urban coastal zones increased, and the per capita income and consumption level also increased, which led to the upgrading of the demand structure (Wu, 2020). At the same time, the change in the demand structure led to the transformation of resources of the industrial sectors, with an increased consumer demand. Thus, the economic structure was transformed, and the land use pattern of the reclamation area changed (**Figure 6A**).

Economic development has led to the functional transformation of shoreland reclamation land, further causing changes in the industrial structure of the entire region (Li et al., 2018a; Qiu et al., 2021). During the whole process of the industrialization of the urban coastal zone in the bay, we observed two different patterns of reclamation (**Figure 6B**). From the initial stage of industrialization to the later stage of industrialization, the reclamation project increased the economic benefits of and development in the area, leading to the transformation of the regional economic industry. Furthermore, the transformation of the economic industry increased the demand for land and promoted new reclamation activities (**Figure 6B**). In modern society, the awareness of people regarding environmental protection has increased, and locals no longer undertake reclamation projects without definite plans. At the same time, the per capita GDP and economic output of the reclamation area indicated an increase year by year, but the percentage of economic efficiency in the area indicated a decrease (**Figure 6A**), which may be due to the increasing cost of resources for ecological restoration and environmental improvement.

Future Development and Planning of Urbanization in the Urban Coastal Zone

In the past few decades, many reclamation projects have been carried out around the urban coastal zones of China, owing to the increase in population and the demand for land (Li et al., 2018a). Due to large-scale reclamation projects, the shape and economic model of urban coastal zones have significantly changed and are extensively developed (Qiu et al., 2021). From the example of Quanzhou Bay, since the 1970s, the morphology of the urban coastal zones of China has changed rapidly; the proportion of natural coastline and the area of urban coastal zones have been decreasing, and regional differences have become more pronounced (Suo and Zhang, 2015). With the continuous intervention of human activity, most urban coastal zones have experienced different degrees of channel deposition and environmental pollution (Feng et al., 2015). The number of channels in urban coastal zones that have not reached the design baseline has also been increasing (data from the China Dredging Association, 2021). Without manual intervention, these channels would not fit the transport demand, which may affect the economic development of cities around the urban coastal zone. However, the quality of water in the urban coastal zone may continue to decline the increasing deposition in the bay, which is caused by the weakened hydrodynamics in the bay and decreased water exchange rate between the inner and outer seas (Deng et al., 2020; Li et al., 2020). This may affect the development of aquaculture and production of agriculture around urban coastal zones, hindering the development of coastal economy and industrial upgrading and transformation in the region. In the future, if unreasonable planning surrounds urban development policies, the urban coastal zone environment will deteriorate further.

At present, the exhaustion of resources in urban coastal zones is a widespread problem, which is a concern not only in China but also in other parts of the world, e.g., the Tokyo and New York bays (Atsushi and Jota, 2020; O'Neil et al., 2020). The environmental degradation of these urban coastal zones after industrialization has urged the local governments to invest considerable resources in environmental management (Maiolo et al., 2020). The ecological problems of urban coastal zones are gradually becoming important issues for countries globally, and thus, the focus in urban coastal zones has gradually changed from economic development to environmental restoration (Oyetibo et al., 2019).

The development of urban coastal zones is unstoppable. To avoid the negative effects from the resource development of urban coastal zones and the aggravation of the surrounding environmental problems, it is necessary to coordinate with the surrounding ecological environment during development. Therefore, development in such areas should focus on marine spatial planning for future development. In terms of pollutants in the sediments, the input of heavy metals and man-made organic matter into the bay should be reduced. For economically developed regions, large heavy industry enterprises should be upgraded to eliminate the industries that use old technologies to reduce the emissions of harmful pollutants (Choi et al., 2021). Therefore, it is necessary to use advanced clean production technologies and strong environmental protection measures in heavy industry production to minimize environmental pollution. For regions that are still in the middle of the industrialization stage, industrial production areas should be planned in advance while considering the carrying capacity of the urban coastal zone environment and increasing production (Shen et al., 2020). In terms of ecological restoration, an economically developed urban coastal zone should be able to repair the damaged ecology over time. For example, the "Regeneration Action Plan" that was first implemented in Tokyo Bay was executed in Japan and included in the United States Wetland Protection Law (Steiner et al., 1994; Tokunaga et al., 2020). During the development of urban coastal zones, we should consider adopting a development plan that has a balance of ecology and development (Chen et al., 2011). It is more important to formulate a regional development strategic plan and carry out the spatial layout in the future development of urban coastal zones, which can coordinate with the regional ecological environment. Notably, in accordance with the principle of ecological priority, it is necessary to protect the original ecological resources, such as wetlands and forests, as much as possible. When formulating an effective bay development policy, the Integrated Coastal Zone Management (ICZM) system should be established along with ecological restoration (Caviedes et al., 2020). Simultaneous with the development of urban coastal zones, parameters, such as environmental impact assessment and ecological index of urban coastal zones, must be introduced, to comprehensively evaluate the construction of urban coastal zones. At present, this indicator is also widely used in urban coastal zone assessments worldwide, which has improved the environment of urban coastal zones and reduced the risks posed by human activities to the ecology of these zones (Reija et al., 2021). However, in the future, we should also consider the different socio-economic development levels and geographical locations of each region and select appropriate indicators, to evaluate the development of urban coastal zones in light of the specific situations in the urban coastal zones. Furthermore, to promote harmonious development between human beings and the environment of urban coastal zones, we should restore the vegetation in the coastal area, construct the bay nature reserve, and strengthen the protection and utilization of coastal wetland resources and biological resources.

Notably, it is important to pre-plan the use and activities that affect the marine environment while paying attention to long-term policies oriented toward the conservation of ecosystem services provided by urban coastal zone ecosystems. Since 2020, a project called Blue Bay has been carried out in Quanzhou Bay to improve the ecology of its urban coastal zones, with a total investment of 351 million Chinese yuan (data from The Jinjiang Government, 2021). This project aims to protect the marine ecological environment through different measures, including the control of *Spartina alterniflora* (Loisel), restoration of the mangrove ecological zones, creation of bird habitat, and ecological transformation of the coast; thus, the wetland ecosystem in the protected area was gradually restored, the self-sustainability of urban coastal zone ecosystems was improved, biodiversity and ecological balance were maintained, and regional economic development was promoted. Thus, only timely measures can guarantee the future sustainable development of urban coastal zones.

CONCLUSION

In this study, we analyzed the topographic changes and conversion process of reclaimed land function in Quanzhou Bay, based on the coastline, water depth, and economic data. The results indicate that there are distinct spatial and temporal differences in coastline length and function in the urban coastal zones of the bay. Before industrialization, the coastline changes were dominated by natural evolution and remained stable overall. During the industrialization period, human activity was the main factor that influenced coastline changes in the bay, with a significant increase in development and artificiality. At the same time, the negative impact of human activity on the development of urban coastal zones also increased. In summary, the topographic changes observed in the urban coastal zones in the bay are the result of both natural and human activity, and the main factors include hydrodynamics, sediments, and human activity, among which the weakening of hydrodynamic force caused by the reclamation project and the increasing sediment flux are the main reasons for the changes in the seabed observed in the urban coastal zones. Moreover, the land use pattern of the reclaimed area was closely related to the development process of industrialization, and the entire process was divided into four stages. With the development of industrialization, land use patterns of the reclaimed areas gradually transformed from agriculture into industry, such as transportation and services of tertiary industries, finally transforming into areas of ecological and environmental construction and restoration. The economic benefits of reclaimed land gradually decreased, whereas the social benefits gradually increased. With the development of society, the development and utilization of coastal areas increased; this must be applied globally. Thus, the natural environment and economic structure around urban coastal zones will further change globally. Based on the factors affecting the evolution of urban coastal zones, the development of these zones in the future should be reasonably planned while controlling the number of reclamation projects, and the resources of the zones must be developed using effective ecological concepts. The findings of this study can provide decisions for the rational planning and economical use of resources to reduce the negative impact of human activities on the environmental development of urban coastal zones.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

YhL conceived and designed the study, supervised the work, and co-wrote the manuscript. XX completed the extraction of bathymetric data from the chart, the calculation, and analysis of topographic change parameters and co-wrote the manuscript. FS and JH contributed to the analysis of the variation of water depth data and the interpretation of related parameter data. LW analyzed the cause of the change of sediment composition. XZ and WC collected and consolidated relevant economic data. YtL extracted the coastline information from satellite data and interpretation. BZ provided charts and explained the changes in the coastline. All authors contributed to the article and approved the submitted version.

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