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Review

Beach–Dune System Morphodynamics

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Abstract: Beach–dune system morphodynamics is probably one of the most classical coastal engineering problems. While the topic has been studied extensively and literature is plentiful of considerable research contributions, from the authors' knowledge the subject is still challenging for coastal and environmental sciences. As a part of the Special Issue entitled "Beach–dune system morphodynamics" of this Journal, the present paper reviews traditional issues and design advances building bridges between potential risks and adaptation measures. The benefits of nature-based and hybrid solutions and the need for multidisciplinary studies and approaches to promote sustainable and resilient conservation of the coastal environment are emphasized. Considering the importance and complexity of the subject, this work cannot be fully complete. It is limited to providing a general overview and outlining some important directions intending to serve as a springboard for further research in the field of beach–dune system morphodynamics.

Keywords: wave–beach/dune interaction; resistance; resilience; adaptation; nature-based solutions; hybrid approaches

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1. Introduction

Coastal dunes are known both for their aesthetic qualities and also their functions in ecological systems, providing a unique habitat that has a high value due to their biodiversity of flora and fauna (Figure 1) [1]. They also represent the land's boundary with the sea and act as a protective natural barrier against flooding due to storm surges and wave attacks for millions of people living near the coasts around the world.

Beach–dune systems are highly dynamic features, exposed and vulnerable to extreme events. Their evolution is mainly governed by the mutual and complex exchange of sediment through hydrodynamic and aeolian processes. In particular, during storm-induced surges, the action of waves and wind can cause severe erosion of beach dunes with widespread morphological changes and possible damage to nearby infrastructures [2]. Therefore, to reduce this vulnerability, it is imperative for coastal engineers to study the exposure of beach–dune systems, their sensitivity to hazards-driven changes, and their adaptive capacity to determine safety adaptation measures. Furthermore, despite the progress made in the literature, it is essential to improve the accuracy of empirical, numerical, and physical models for predicting wave-dune interaction phenomena.

Figure 1. A photo of a vegetated dune on the beach of "Alimini" in Salento, Adriatic coast, southern Italy. Photo courtesy of Giuseppe Roberto Tomasicchio.

From an adaptation perspective, both nature-based and hybrid solutions are increasingly seen as effective strategies [1,3–5]. Recent advances in coastal research and ecological sciences are being adopted to find innovative environmentally friendly approaches to increase the resistance and resilience of beach–dune systems. In this context, there is an urgent need to support viable policy responses and identify appropriate actions to mitigate risks and improve the environmental and social resilience of coastal communities that also impact ocean-based economic activities, including tourism and recreation [6].

This review paper is organized as follows: First, the main characteristics (morphology, resistance, resilience) of the beach–dune system are introduced. The interaction processes between wave, beach, and dune are described, followed by a brief discussion of the modeling approaches to predict beach–dune profile evolution. Adaptation perspectives are then presented, including both nature-based and hybrid solutions. Finally, the work ends with conclusions and some recommendations.

2. The Beach-Dune System

The beach–dune system is a natural, dynamic environment whose morphology is determined by a variety of factors including climate variability, relative sea level, wind and wave energy, sediment supply, and vegetation [7].

Basically, dunes can be divided into primary and secondary dunes. Primary dunes consist of sand blown directly from the active beach, while secondary dunes are formed by the subsequent alteration of primary dunes. Primary dunes are those dunes closest to the shoreline, dynamically associated with beach processes, and significantly affected by wave action: they are the subject of this paper (Figure 2).

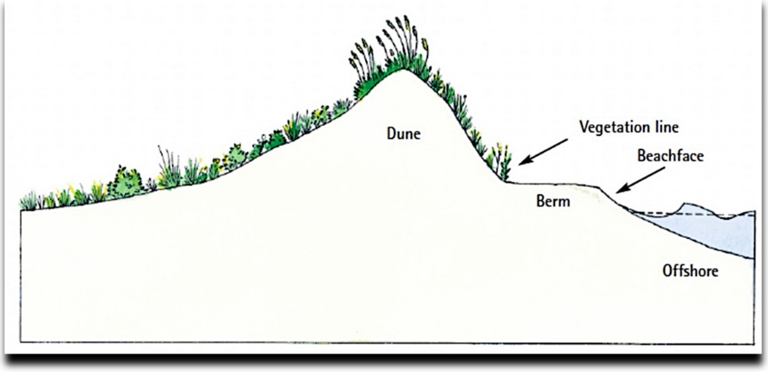

Figure 2. Schematic cross-section of a typical beach–dune profile.

Dunes are a natural habitat for a variety of species, increase the recreational value of an area, and attract tourism [8]. In general, the beach–dune profile is part of a "sand-sharing" system influenced by variations in wave energy, sea-level rise, currents, and mobilization of sand from one zone to another [9,10]. The beach–dune profile at a given location is usually directly related to the sediment that is added or removed from a coastal system over time (the sediment budget [11]).

Dunes are dynamic in that they can increase in length due to wind action, increase in height due to the accumulation of sand grains, or change shape due to wind speed and direction and the type of vegetation [12]. The near-surface wind vector (speed, direction) is thus the most influential factor in the shape and size of dunes and the main driver of erosion and accretion patterns which is included in standard formulations of aeolian sediment transport models [13,14].

Wind speed is usually reduced by vegetation, which favors the deposition and retention of wind-blown sand with leaves, branches, and roots. However, wind can also accelerate locally in gaps between plants, especially tussocky plants. Vegetation is thus a crucial element in the evolution and dynamics of the beach–dune system. Studies of the effects of vegetation on the transport of wind-blown sand have shown that when the wind blows over a smooth, unobstructed surface, the shear stress acts uniformly over the entire surface, but when non-erodible roughness elements are present, some of the shear stress is absorbed by the roughness elements on the underlying erodible surface. The degree of protection is a function of their size, geometry, and spacing [15,16]. Field and wind tunnel experiments indicate that the most important influence of vegetation depends on the threshold wind shear velocity for transport [17–19]. Ecologists have studied the response of plant communities (e.g., spatial sorting, zonation, and diversity) to physical and chemical gradients (including sand burial, wind action, salt spray, soil moisture, groundwater salinity, soil pH, and nutrients), many of which are influenced by topography [20–23]. Although the importance of dune-forming grasses [24,25] has been recognized, most geomorphological research has focused on the role of sand supply (a combination of sediment budget and wind-transport potential) as a function of beach morphology and wind regime in the process of dune formation [26,27].

Beach–dune systems are subject to recurrent natural disturbances (wind speed and direction, sediment supply characteristics, vegetation availability, duration, and intensity of storms) and human impacts that exert strong pressures that alter their dynamics and reduce resistance and resilience. The former refers to the "ability of a system to withstand a force without any change", while the latter is a "measure of its ability to respond to the consequences of a disturbance and return to its original state" [28]. Resistance is the capacity exercised before the system is perturbed, while resilience is measured once the perturbation has occurred: it indicates the extent to which the system is capable of restoring its dynamic equilibrium.

3. Wave–Dune Interaction Processes

Storms can have varying degrees of impact on the beach–dune system. A scale for the impact of storms based on the morphological response of beach–dune systems to hydrodynamic conditions was proposed by [29]. The scale consists of four regimes of wave-dune interaction processes: (1) swash regime, where wave run-up is confined to the foreshore; (2) collision regime, where wave run-up erodes the base of the dune, and dune sediment is transported offshore; (3) overwash regime, in which the wave overtops the dune crest, and the overwash sediment is deposited on the backside of the dune; (4) breaching and inundation regime, in which the dune crest is generally overtopped and the beach topography subsequently flattens. A schematic of storm impact regimes is given in Figure 3.

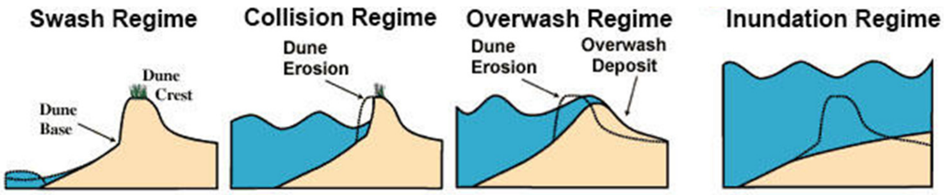

Figure 3. Schematic of storm impact regimes.

As an illustrative case, Figures 4 and 5 show the wave-dune interaction processes observed during large-scale laboratory experiments performed by the authors. The physical model tests have been conducted at the CIEM wave flume of the Universitat Politecnica de Catalunya in Barcelona, within the framework of the Hydralab-III European "BOB" project [2,30–33]. Specifically, as shown in Figure 4, waves broke directly on the sloping dune front (Figure 4a). As a result, the dune front steepened until it was nearly vertical (Figure 4b). The geometry of the dune front changed due to scarping and slumping. Eroded sand from the dune was transported offshore by a strong undertow and sediment suspension in the proximity of the dune was high, resulting in a large offshore transport capacity [34] (Figure 4c). The incoming breaking waves that encountered the outgoing reflected broken waves (wave collision) generated a large amount of turbulence (Figure 4d). However, the eroded sand remained in the region of the active profile and formed a new profile with a bar where the waves broke. The new profile was more efficient in dissipating the energy associated with the incoming waves. The underwater bar prevented the offshore sand from migrating. Consequently, dune erosion rates decreased as the storm was in progress (Figure 4e). The dune face retreated under the impacting waves: part of the dune face collapsed, and large chunks of sediment fell or slid down (Figure 4f). In agreement with [35], the observed low run-up did not allow overtopping of the waves.

When severe waves attack the beach, they often have enough energy to overtop the dune crest and cause landward transport of sediment (Figure 5a,b). A rapid increase in wave overtopping and sediment overwash, combined with the erosion of the dune crest, determined the dune breaching (Figure 5c,d). Similar behavior was also observed during small-scale flume tests conducted by [36], where dune breaching was caused by some overtopping waves at the location along the coast where the dune crest had previously been lowered by minor wave overwash.

Erosion of beach–dune systems can occur over several hours and days during a storm. However, resilience, as the ability of a dune to recover after a storm, varies [5]. It can take years, even decades, and is influenced by many factors depending on the response of the beach–dune system to sea-level rise, changes in the frequency and/or magnitude of storm surges [37], sediment supply [38–40], beach width, wetting and drying cycles, and the growth and condition of existing vegetation, and its ability to retain wind-blown sediment. In the case of a collision regime, the recovery process can fully restore the pre-storm beach–dune profile because no sediment has been lost from the beach–dune system. On the other hand, overwashed and breached dunes can only recover through aeolian processes or engineered (nature-based and/or hybrid) restoration efforts.

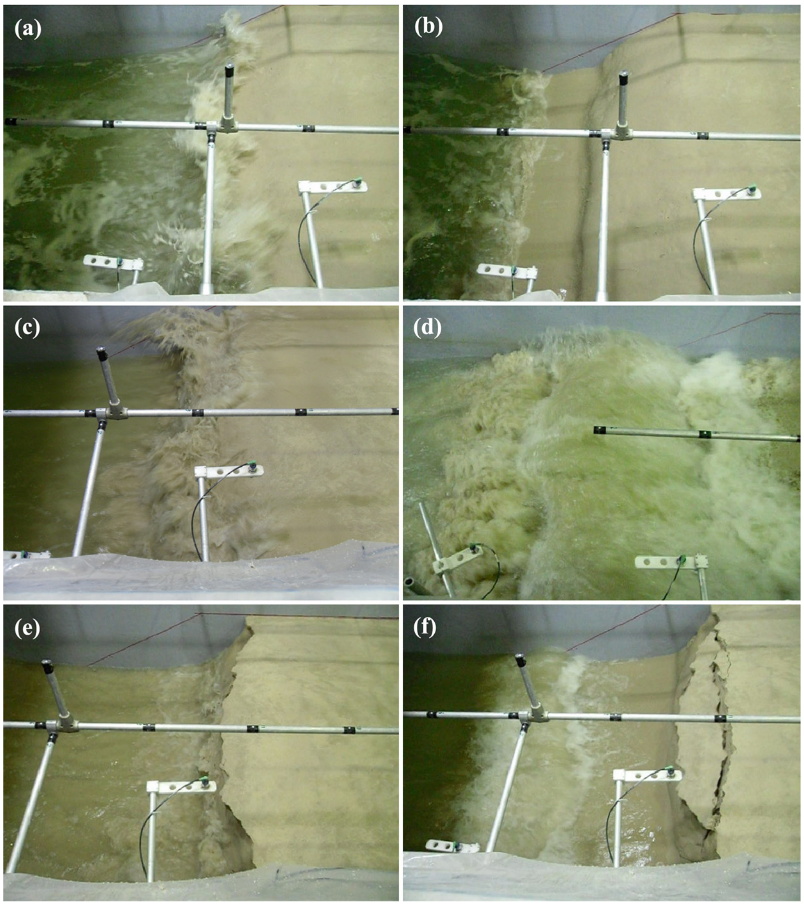

Figure 4. Observed collision regime. (**a**) Wave breaking on the sloping dune front, (**b**) formation of the dune scarp, (**c**) wave breaking and high sediment suspension in the proximity of the dune, (**d**) wave collision, (**e**) dune erosion, (**f**) collapsing of the dune face. Hydralab-III BOB project at CIEM wave flume. Photo courtesy of Felice D'Alessandro.

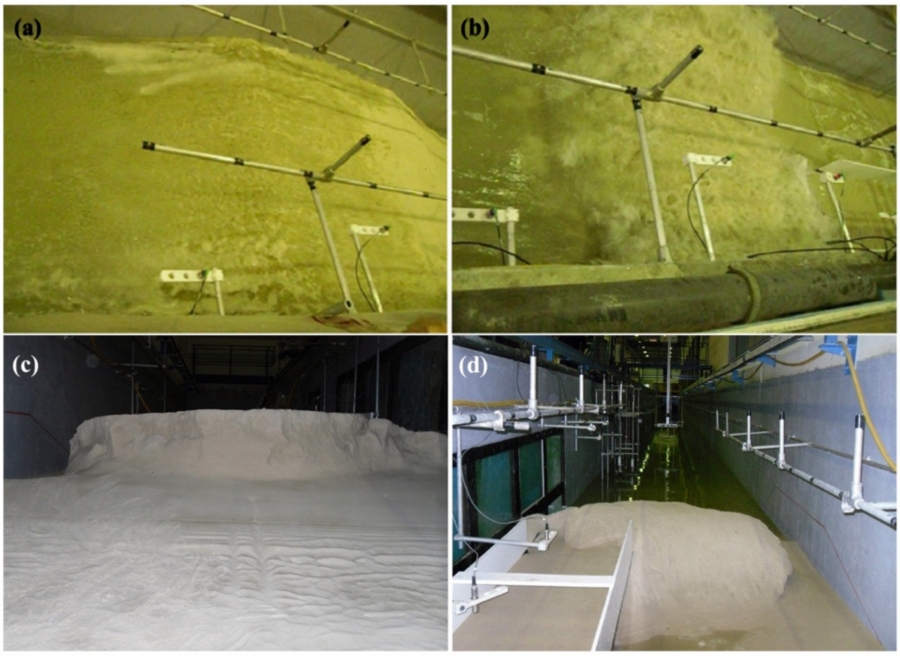

Figure 5. Observed overwash (**a**,**b**) and breaching (**c**,**d**) regimes. Hydralab-III BOB project at CIEM wave flume. Photo courtesy of Felice D'Alessandro.

4. Modeling Beach–Dune Profile Evolution

Modeling the evolution of beach–dune profiles has reached a verifiable level of maturity in recent decades thanks to well-defined equations, established numerical solutions, and high-quality laboratory and field data. Furthermore, remote sensing methods are useful tools for ecosystem monitoring, as they allow to capture a wide range of properties of vegetation [41–45].

Empirical models are primarily used to estimate the volume of erosion associated with a storm. An empirical model evaluates the dune profile before the storm and the erosion volume based on the profile after the storm. They offer advantages in that their simplicity makes them easy to apply, which is valuable in the early stages of a project when approximate estimates are needed [2]. In the early 1980s, based on extensive physical model experiments, Vellinga [46] presented an empirical model for predicting the dune erosion profile after a storm, taking into account storm surge levels, wave conditions, and sediment grain size characteristics. Larson and Kraus [47] proposed the semi-empirical model SBEACH based on equilibrium equations. Although the model of [47] does not fully resolve the hydrodynamics of the surf zone and the sediment transport processes, it overcomes some limitations of previous models and is able to reproduce bar formation. In [48], an analytical model for predicting the erosion and retreat of coastal dunes was developed based on a wave impact approach, where the dune profile evolution can be estimated by waves directly impacting the dune [49].

Process-based models describe the temporal and spatial evolution of the beach–dune profile based on numerical formulations of the prevailing physical processes. XBeach [50], CSHORE [51], and CROSMOR [52] are well-proven process-based models adopted to estimate the short-term evolution of beach–dune systems under storm conditions. XBeach solves the 2DH equations for wave propagation, current velocity, sediment transport, and bathymetry evolution, for time-varying hydrodynamic conditions. The model was developed to simulate the various effects of a storm as defined in [29]. In CSHORE, numerical integration of the depth-averaged energy, momentum, and continuity equations leads to predictions of wave height, water level, and wave-induced steady currents. The model accounts for wave-current interaction, wave-induced sediment transport, cross-shore bedload, and suspended sediment transport rates. CROSMOR simulates wave propagation, transformation, and refraction along the beach. Statistical parameters are calculated from the results of individual waves. The model accounts for wave-induced set-up, set-down, and breaking of associated long- and cross-shore currents. The depth-averaged return flow is derived from linear mass transport and water depth below the wave trough. The sediment transport rate (bedload and suspended sediment) is determined based on the calculated wave height, depth-averaged long- and cross-shore velocities, orbital velocities, friction factors, and sediment parameters. A detailed explanation of the structure and capabilities of these models is beyond the scope of this article. The interested reader is referred to [50–52].

Since collecting detailed information in the field during storm-induced surges and strong waves is a difficult and risky endeavor, physical model experiments in wave flumes remain fundamental to investigating wave-beach–dune interaction phenomena. Large-scale experiments on dune erosion under collision regimes have been conducted by [35,46,53–60]. Similar experiments have been performed in Germany [61] and in the USA [62]. Physical model tests carried out in the past have generally focused on the study of seaward profile evolution and morphodynamic processes under the given wave and water level conditions. Refs. [35,63] conducted large-scale experiments to investigate the key physical processes driving dune erosion during severe storm events. These experiments updated the results of [29] to include the effects of the wave period. Although accurate modeling of wave overwash processes is critical for predicting dune profile evolution and assessing inundation risk [64–67], observations of overtopping and overwash were not made in the earlier experiments. Despite the importance of beach–dune profile changes during overwash regimes, few small-scale [68–71] and large-scale [2,72–74] laboratory experiments have been conducted. On the other hand, laboratory studies of the same regimes proposed by [29] that also account for vegetation are extremely limited [75–77].

5. Adaptation of Beach-Dune Systems to Climate Change Impacts

Beach–dune systems are particularly vulnerable to the effects of climate change, especially erosion and flooding, because they are subject to multiple drivers that can occur on different time scales [78]. In addition, interdependence among climate drivers (e.g., storm surges and sea-level rise) can lead to extreme compound events [79]. There are several multivariate approaches to account for interdependencies among climate drivers. Copulas are widely used as an efficient tool to study the statistical behavior of dependent variables [64–67].

Sea level rise is generally considered the most important climate driver in coastal areas. This has led to improved projections. Among the key aspects of making accurate forecasts is understanding the long-term variability of sea level. Extensive studies have been conducted in the literature to explore sea-level fluctuations. The IPCC warns that under current trends, projected increases in mean sea level for the year 2100, relative to the time series of tide gauge records from 1986 to 2005, are 400, 470, 480, and 840 mm, for the RCP2.6, RCP4.5, RCP6.0, and RCP8.5 Representative Concentration Pathways scenarios, respectively. As a result, the global mean sea level has been rising over the past century and is projected to rise even faster in the 21st century.

In this context, sea-level rise and changes in storminess patterns could lead to a more frequent occurrence of high-water levels and wave storms which, in turn, could produce an amplification of coastal flood risk, especially in low-lying coastal landscapes. Therefore, the greater impact on beaches and dune systems will increase the important role of flood protection measures.

Restoration of beach–dune systems is increasingly seen as an effective measure for adapting and enhancing resilience to the adverse effects of climate change. The process of restoration consists of preventing degradation and supporting the recovery of a damaged or degraded ecosystem in terms of its health, integrity, and sustainability [80]. In recent decades, measures to mitigate the effects of climate change have been proposed, consisting of hard coastal structures or soft defenses to prevent beach and dune erosion. Although research on hard coastal structures (e.g., dikes and revetments) has continuously improved design approaches [81–85] and risk analysis techniques [64–67,86–97], significant changes in geomorphological processes and habits are inevitable.

Recent advances in coastal engineering and environmental science are being implemented to minimize the risk of flooding and improve coastal resilience [98–102]. Currently, experiments are being conducted with hybrid systems consisting of traditional structures covered with layers of sand in an attempt to mimic dunes. They combine the advantages of both hard and soft coastal protection solutions [4,5,103–108] and are therefore valuable in areas with limited space and allow for innovation in coastal design. Although such hybrid systems have the potential to become an alternative to conventional coastal protection systems, there are still many unknowns regarding the interaction between the soft and hard structural components and their effectiveness in mitigating storm surges and preventing flooding that requires focused research efforts to establish acceptable design guidelines.

In recent years, a growing number of approaches have emerged as important nature-based solutions [2,3,109,110]. Indeed, coastal protection measures based on natural approaches have gained prominence since they were included in several European directives [111–113] as possible disaster risk reduction strategies. For example, dune restoration projects combine coastal habitat recovery, vegetation replanting, and beach nourishments with sustainable and soft solutions inspired and supported by nature. They are particularly suitable where the application of traditional engineering methods might conflict with the intrinsic value of the ecosystem and its biodiversity, such as in coastal natural areas or reserves.

Nature-based solutions emphasize the role that plants play in the geomorphology of coastal dunes, as has been recognized for more than a hundred years [114–116]. According to [117], coastal dunes and their associated vegetation communities act as barriers to storm surges and prevent or reduce flooding and coastal erosion. Vegetated dune systems also play an important role in promoting a positive coastal sediment budget. Various studies describe how plants can contribute to beach recovery after storms, as vegetation retains sediment transported by wind [117–119].

In many cases, these approaches have been implemented as demonstration projects in protected areas. For example, Figure 6 shows the results of an innovative and environmentally friendly technique for the consolidation of coastal dunes studied in recent field experiments conducted by the authors on the Adriatic coast in Salento (southern Italy) [2].

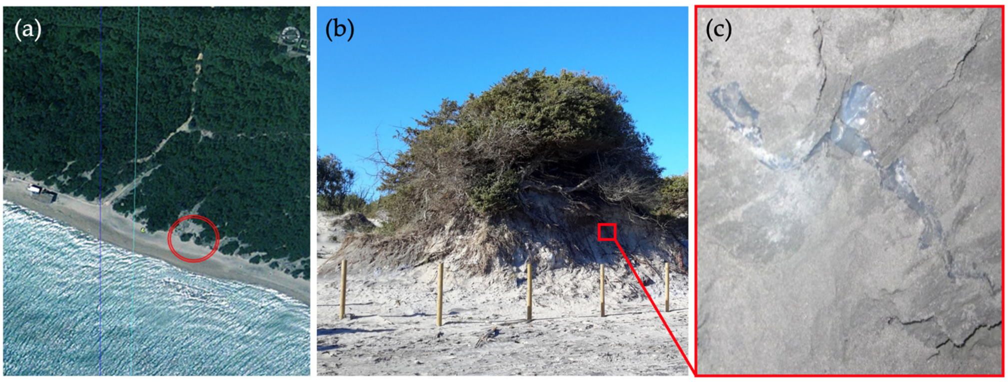

Figure 6. Aerial view of the intervention site (**a**), visual observation of the restored dune six months after the intervention (**b**), and detail of the consolidated dune face (**c**). Photo courtesy of Giuseppe Roberto Tomasicchio.

In addition to reducing wind speed and the deposition of drifting sand, which can be achieved through vegetation and/or conventional techniques (e.g., dune fencing), an alternative solution to reducing the near-surface wind impact and the effects of frequent minor storms is to strengthen the dune face. Specifically, injecting a mineral colloidal silica-based grout into the most exposed side of the dune, which is native material, allows the mechanical strength of the non-cohesive sediment to be increased. The colloidal silica-based grout is a non-toxic, transparent mineral suspension of nanometric particles of silica (SiO_2), which looks like "liquid sand" and resembles the material found in nature. It has a low viscosity that allows it to easily penetrate very fine sand and silty soil. The advantage over traditional dune remediation solutions is that the proposed intervention does not impact the environment and does not increase the footprint of the dune, thus avoiding further obstacles. This aspect can be particularly important when the rehabilitation intervention is carried out on a stretch of beach that is valuable for tourism and recreation [2].

The reliability of this solution has been verified by laboratory experiments conducted in the 2D wave flume of the EUMER laboratory of the University of Salento (Italy) [3]. The observations have shown that the mineral colloidal silica increases the mechanical strength of non-cohesive sediments reducing the volume of dune erosion and improving the resistance and longevity of the beach–dune system.

Although various nature-based solutions can be found on many coasts around the world, in-depth studies of efficiency, vulnerabilities, and natural dynamics are still lacking. To overcome these knowledge gaps, scientific insight from systematic research is urgently needed to identify measures that combine spatial and statistical analysis, remote sensing, field monitoring techniques, and numerical modeling to create a novel understanding of nature-based coastal adaptation to erosion and flooding risks in low-density coastal areas.

6. Conclusions

Although there is much relevant research in the field of beach–dune system morphodynamics, the problem remains challenging for coastal and environmental sciences. Therefore, it is critical to improve the knowledge, tools, and expertise needed to develop new and sustainable ways to mitigate the negative impacts of climate change.

This overview provides the basis for a general summary of recommendations for further research and practice.

- It should be recognized that the most severe climate-related impacts are caused by the interaction of multiple hazards. A systematic research program is overdue, and more comprehensive multidimensional approaches to risk are needed. Such approaches must account for the non-stationarity of risk components and allow for the quantification of uncertainty. In addition, new methods and tools are needed to evaluate the multivariate analysis of extremes.
- A major challenge is the development and implementation of nature-based adaptation measures, whose behavior needs to be better understood. Improved understanding and application of this knowledge, as well as the implementation of innovative monitoring systems, will be a critical component of coastal adaptation planning, likely reducing the need for expensive engineering options at some sites and providing a complementary tool for hybrid engineering design.
- More research on the interaction between the swash and soil mechanics in the dune face seems critical to better understand dune erosion during storm surges.

Furthermore, research efforts should be made to:

- Better use remote sensing technologies to measure indicators of wind erosion potential.
- Integrate wind erosion models with other models, including those for driving forces (e.g., hydrodynamics) and controls (e.g., plant growth).
- Develop databases for numerical models to expand their applications.

With such complex issues, greater collaboration and synchronization across multiple research areas are needed to provide multidisciplinary and comprehensive studies and approaches. At the same time, it is crucial to propose methods for assessing the value of ecosystem services to promote investment in coastal environmental protection and improve the efficiency of natural resource use.

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