Review

Forests for Coastal Resilience and Sea Level Rise Climate-Induced Adaptation - Part A

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Abstract: One-fifth of the world's population and critical infrastructures are near the coast and regions at high risk of sea level elevation. Climate change is expected to increase coastal extreme events, rising sea levels, and impact on ecosystem. This paper reviews coastal physical processes, wave and impacts, and the introduction of nature-based models for the mitigation of flooding, erosion, and recovery. Hard engineering like seawalls has been used to prevent, protect, and control water-based environmental forces with an extended impact on the land. A nature-based engineering solution, such as growing vegetation, is being adopted as a sustainable solution to help make existing technology live its design life and provide climate change adaptation and resilience for coastal and riverine communities. This paper presents applications of seaweed farms as an advanced nature-based mitigation approach. The result of the experiments conducted at RWTH Aachen University on wave damping of seaweed types and farming structures to validate the hypothesis will be presented in part B. A soft engineering approach to designing future vegetated protection systems using seaweed as a nature-based solution can help existing coastal infrastructure design life and protect against climate-induced SLR rise and adaptation, coastal risk mitigation, ecosystem restoration, and blue bio-economic development.

Keywords: Nature-based solution; seaweed; seagrass; platform; coastal protection

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1. Introduction

Extreme events, including tsunamis, flooding, erosion, and the subsequent cost of recovery in the EU and global coastal economic losses have increased substantially. Hurricane Nadine caused flooding and erosion along hundreds of miles of shoreline, and flooded, impacted communities and critical infrastructure. Climate change is expected to increase the number of coastal extreme events and rising sea levels could exacerbate the impact of extreme events [1]. Coastal water quality is declining due to microbial pathogens, fertilizers, pesticides, and heavy metal contamination resulting from the aftermath of coastal events that threatens the ecosystem and human health. The physical, biological, and chemical processes that impact human and ecosystem health in nearshore regions include disruptive economic activities involving recreation, tourism, human habitation, habitat, and ecosystem services, which are required to be sustained for future generations [2]. Addressing this research theme will result in an improved understanding of the physical processes during extreme events, leading to improved nature-based models of flooding, erosion, and recovery. The solution will require collaboration between scientists and engineers, nearshore communities, academicians, governments, and the coordinated development of nearshore coastal process observational and modeling research infrastructure to create novel nature-based solutions. This will lead to a new understanding and improved models of nearshore processes and green mitigation solutions. Collaborative transfer research involves stakeholders from knowledge institutes, communities, industry, and government along with the use utilization of resources like flume lab for testing and a scale-up to living lab sites that will provide the needed solutions to develop the best nature and soft engineering technology to protect future coasts.

This review focuses on technology to plant seaweed as a nature-based solution that leverages efforts, avoids redundancy, and moves science and engineering rapidly forward improving technology while still protecting the natural ecosystem. Moreover, this collaboration will enable the efficient transfer of results and predictive tools to stakeholders, supporting informed decisions that will improve diverse aspects of coastal management. Seaweed and seagrass green eco-engineering eco-technology and systems will be designed for future deployment and tested in selected troubled coasts to assess mitigation that a natural base and ecological approach can provide coastal protection and ensure environmental conservation. Nearshore processes research that intersects societal needs and scientific challenges have been organized into three broad themes, involving coupling and feedback between hydrodynamics, morpho-dynamics, and anthropogenic interactions, as well as between geological, meteorological, hydrological, and biological processes [3]. To develop the nature-based infrastructure that addresses current climate-induced coastal and nearshore challenges, the paper proposes the need to build a sustained integrated nature-based solution system. This system involves nearshore processes research to address the challenges of climate and ocean: Variability, Predictability, and Change via the development of novel nature-based infrastructure that will foster understanding and prediction through observations and modeling of long-term coastal change, flooding, and erosion from extreme storm events, and nearshore pollution and water quality evolution. Incorporating community participation and awareness will help foster and sustain the operation of the novel system and technology [4]. Besides the use of sea space for transportation and exploration of natural gas, farming the sea and the ocean for other nature-based products is a necessity. By cultivating seaweed and seagrass, the coast is protected from erosion, climate change is mitigated, and bioremediation is provided [5]. There are many species of seaweed and distinct species grow in different waters, so cultivation is important.

This paper explores the cultivation of macroalgae and seagrass that can provide ecosystem services including eco-hydraulic coastal protection and bioremediation for coastal cities and islands and circular use of the harvested plants for bio-based raw materials (i.e., bio-plastics and bio- textiles). [6],[7],[8].

This paper presents the applications of seagrass and seaweed farms as an advanced nature-based mitigation approach, which furthermore provides additional farming space, facilitating the increasing demand for seaweed and seagrass as a natural resource. Wave impact damping of seaweed types and farming structures by controlled laboratory experiments were conducted.

2. Extreme Events, Climate Stressors, and Nearshore Problems (Storms and Sea Level Rise, Waves, Storms Surge, Tsunamis, Marine Georisk)

The UN Atlas of the Oceans shows that over 40% of the world's population lives within 150 km of a coastline, and population growth and tourism are accelerating in coastal regions (inland and sea) [9]. Worldwide, almost 1 billion people live at elevations within 10 m of the present sea level. Long-term erosion threatens communities, infrastructure, ecosystems, and habitats, and extreme storms can cause billions of dollars in damage and degraded water quality which impacts the ecosystem and human health [10][11]. Nearshore processes involve the complex interactions between water, sediment, biota, and humans. Understanding the nearshore processes helps to predict and manage the vulnerable nearshore environment. This includes the causes of additional hazards leading to flooding inland. Coastal flooding and sea-level rise are expected to accelerate due to the warming climate [12], [13]. Over the last five decades, the observation of nearshore processes and different solutions applied have provided insight into improved methods. Societal needs are growing with increased coastal urbanization and threats of future climate change, and significant scientific challenges remain [14]. Climate change can further lead to an increase in coastal extreme events, sea level rise, and a reciprocal increase in the impact of extreme events [15], [1]. The challenges of today are an increase of pressure on biodiversity due to environmental pollution, climatic change, and coastal squeeze, while the growing population needs higher productivity and protection from disasters. The integrity of terrestrial and aquatic ecosystems and their capacity to deliver a wide range of essential services to people [16], [17] is expected to be undermined by the effects of unavoidable climate change emanating from nature's response [10].

Therefore, it is imperative to assess the risk and vulnerability of coastal hazards and biodiversity losses, including current and future typhoons, monsoons, tsunamis, and sea-level rise scenarios and associated impact and damage to critical infrastructure and analysis in terms of the damage that are detrimental to the economy and disruptive to the local community.

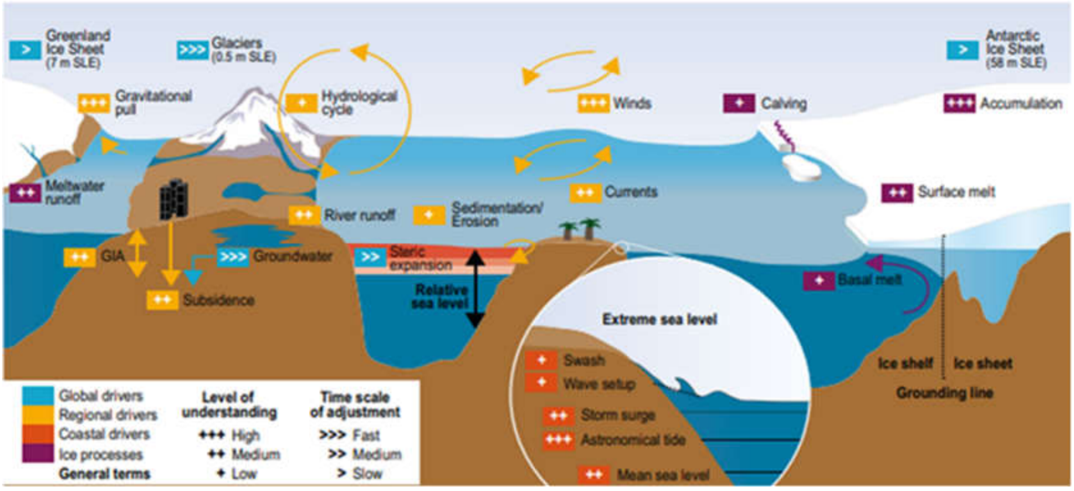

Figure 1. Climate-related challenges [18].

This is especially true in the context of global climate change and sea-level rise. To limit warming to 1.5° C and consequential sea level rise several intergovernmental organizations and governments have agreed to restrict global greenhouse gas (GHG) emissions [18]. Nonetheless, annual greenhouse gas (GHG) emissions are continuously rising [19]. Emanating climate change and coastal changes are an increased damage potential on critical infrastructure and detrimental effects on the bio-diversity, as well as socioeconomic effects and the disruption of local community activities. Some of the challenges facing today's society include risk and resilience of coastal communities, species biodiversity and inclusiveness, growing population, an increasing need for biomaterial, and damages that are detrimental to the economy and disruptive to the local community. On top of it all, estuarine and coastal waters are particularly susceptible to non-point/point source pollution conveyed by rivers and streams [20], [21]. Riverine transport is the primary mechanism for the direct impact of terrestrial human activities on the nearshore marine environment [22], [23]. Excess nutrients and sediments transported by rivers, among other pollutants, constitute a serious threat to the coastal and marine ecosystem [24],[25]. The discharge of wastewater, alterations of physiographic features, and alterations in the distribution and amount of freshwater inflow are critical parameters [26], [27]. Figure 1 shows, that the IPCC report warns about the increasing sea-level rise and threat to coastal ecosystems.

3. Threat of Climate Change, SLR, and threat to Sustainable Development

Recently time has seen environmental calamity and abnormal environmental behavior where the consensus of scientists has agreed to be linked to human activities. The connectivity and interdependency of the planetary system revealed uncertainty in the dynamics of air, water, and soil [28]. Especially the wave setup from the middle of the ocean involves a combination of temperature, and wind which in one way or another impose more energy on waves propagating inland. The impact of global warming includes rising sea levels, changing precipitation, and expansion of deserts in the subtropics. Increased temperature may also induce additional stress on society related to natural hazards including earthquakes and water extreme events. Climate change involves climate variability and the statistical distribution of weather over a long time. Human causal factors of climate change involve Green House Gas increases in the atmosphere (water vapor, carbon dioxide (CO2),

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methane, and nitrous oxide). Ozone GHG emissions have increased over the years, however, the accuracy of the increase is limited because of the environmental differences associated with all places. Makereadies [29], reported the potential of seaweed and seagrass carbon sequestration.

The causes of climate change are atmospheric composition including concentrations of greenhouse gases. The motion of tectonic plates results in changes in the relative location and amount of continental and oceanic crust on the earth's surface, which affect wind and ocean currents; variations in solar output; the orbital dynamics of the Earth-Moon system; the impact of large meteorites and volcanism including eruptions of impact volcanoes [30]. Changes in climate along shorter time scales are reported by remaining oral traditions, and climate proxies like ice cores, tree rings, sub-fossil pollen, boreholes, corals, lake and ocean sediments [31]. The escalating greenhouse gas emissions are the cause of the warming of the ocean, by which coral is bleached, ecosystems lost, extreme weather events fomented, and sea levels made to rise ever upwards. The heating of the ocean has also been causing glaciers to melt and snow cover to shrink, warm-adapted plant and animal species to migrate upslope, and a decrease of cold and snow-adapted species increasing the risk of their extinction. Also, the retreat of the cryosphere is expected to affect recreational activities, tourism, and cultural assets. Ocean warming reduces mixing between water layers, therefore reducing the supply of oxygen and nutrients for marine life.

Climate change is affecting people, ecosystems, and livelihoods, creating a need to put a system in place to keep warming to 1.5° C rather than 2° C. Most coastal ecosystems, including seagrass meadows and kelp forests, are at moderate to high risk at this temperature, since pre-industrial times, human activities have caused approximately 1.0° C of global warming, which has already caused consequences for people, nature, and livelihoods [32]. The ocean has taken up more than 90% of the excess heat in the climate system causing increases in ocean acidity. Oceans have taken up 20 to 30% of these emissions and continued uptake will exacerbate this. Marine heatwaves are harmful to warm-water corals, kelp forests, and the distribution of marine life. The projected ecosystem responses include losses of species' habitat and diversity and the degradation of ecosystem functions. Today warm-water corals are already at considerable risk. The heated water also evaporates from oceans into the atmosphere leading to heavy rainfall and flooding inland, alternatively, in other locations the heat has caused dry land, heatwaves, drought, and wildfires. In this mechanism, oceans control both the temperature and the humidity level, and weather [31], [33].

Sea-level rise is caused by ocean temperature, which is in turn caused by the emission of GHG, phenomenon with a reciprocal impact on marine life. The global mean sea level has been rising during the 20th century, creating a global mean sea level rise of around 15cm. The sea level is currently rising more than twice as fast, and if emissions are not sharply reduced, will further accelerate reaching up to 1.10m by 2100. Extreme sea-level events which now occur rarely during high tides and intense storms will become more common. Many low-lying coastal cities and small islands will be exposed to risks of flooding and land loss annually by 2050, especially without strong adaptation [18]. These events have led to an Intergovernmental Panel on Climate to provide the world with an objective scientific view of climate change and its political and economic impacts. The climate tipping point is the change from a stable state to an irreversible state. To mitigate the tipping points the United Nations Climate Change Conference (COP). Figure 2 shows that sea-level rise risk outpaces current technology.

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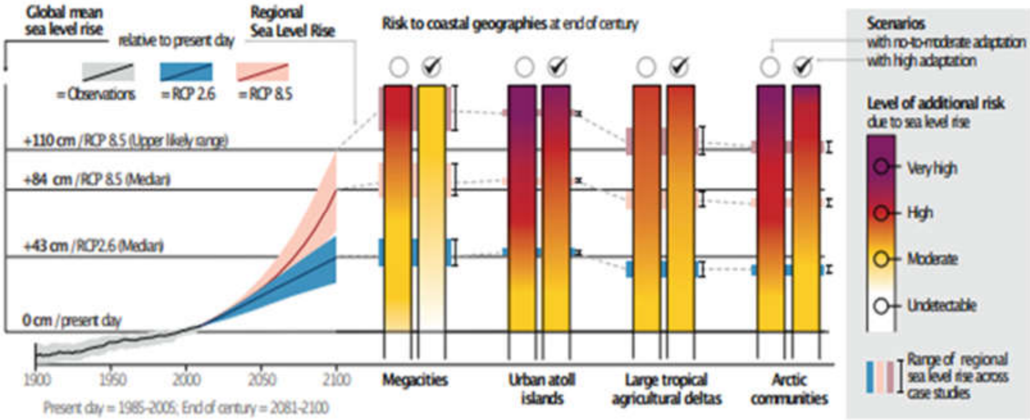

Figure 2: Projected sea-level rise (SLR) until 2300. The inset shows an assessment of the range of the projections for RCP2.6 and RCP8.5 up to 2100 (medium confidence) Sea Level Rise [18].

Natural variability has an impact and strong connectivity on the water cycle. Knowledge of uncertainty is essential to support the engineering design of climate change mitigation and adaptation actions to improve understanding and deduce efficient ways forward. Vegetated terrestrial systems such as forests sequester, capture and store carbon in their biomass and the soil beneath them [34]. A similar process occurs in the marine environment where vegetated marine systems, such as salt marshes, mangroves, and seagrass meadows, capture, and store carbon [35]. The blue-green future approach to adaptation is becoming popular, the ocean covers 70 percent of the planet, and its system provides a buffer against climate change, providing food, energy, medicine, and employment, along with the oxygen for every second breath we take. The world's ocean and cryosphere have been absorbing climate change for decades, and this has been causing high consequences to nature and society. Protecting, restoring ecosystems, and careful management of natural resources can reduce risks and provide multiple societal benefits.

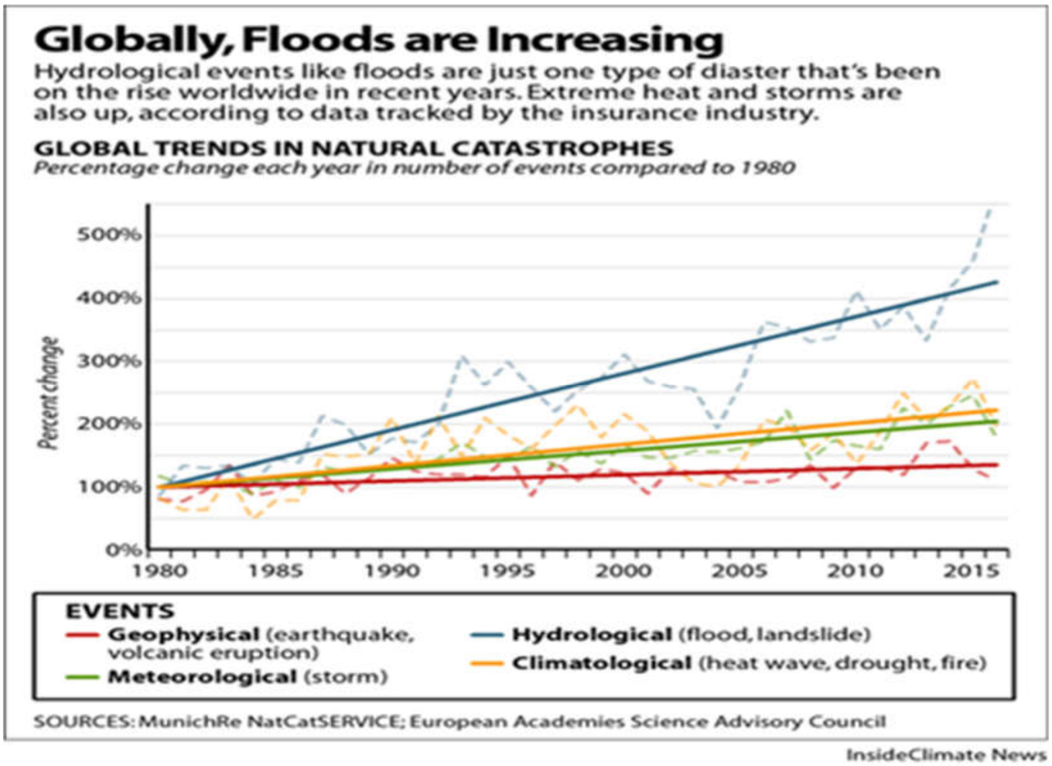

Figure 3. Global increase in natural hazards since 1980. Hydrological events, such as floods, are the disaster type with the most significant increase globally. Modified after MunichRE NatCatService (2019) [41].

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Statistical analysis of flash flood events, for example, clearly shows an increasing trend regarding their reoccurrence intervals [36,41]; (Figure 1). Between 2012 and 2016 the number of yearly flash floods resulting from extreme weather events increased by 100%, a statistically robust increasing trend [37, 38]. The year 2020, for example, is only the second year in history, in which the common labeling system for hurricanes (containing 21 labels) is exceeded by the actual occurrences of 30 events [39,40]. Besides the frequency of storms and connected flash flood events, their impact on coastal areas is expected to increase with a rising sea level, not only regarding damages to critical infrastructure but also to ecological damages like salinization [41] [42]. Anthropogenic interferences can furthermore increase local risks if alterations of shorelines, river regulations, or extended land-use, can influence natural floodplains or the nearshore hydrodynamic behavior of waves [43, 44]. The demand for alternative approaches is rising. Figure 3a (right) shows the increase in coastal flooding and figure 3b (right) recognizes the increased risk of damage in coastal areas due to population growth, climate change, and the shortcomings of common mitigation measures [45, 46]. Nature-based approaches like tree belts and mangrove forests or the here proposed application of seaweed, can not only protect high-energy wave events and flash floods but also maintain local ecosystems by regulating the local biodiversity or providing fish habitats, for example [45] [46], [17]. Figure **4** shows our closeness to the ocean and treatment of coastal events.

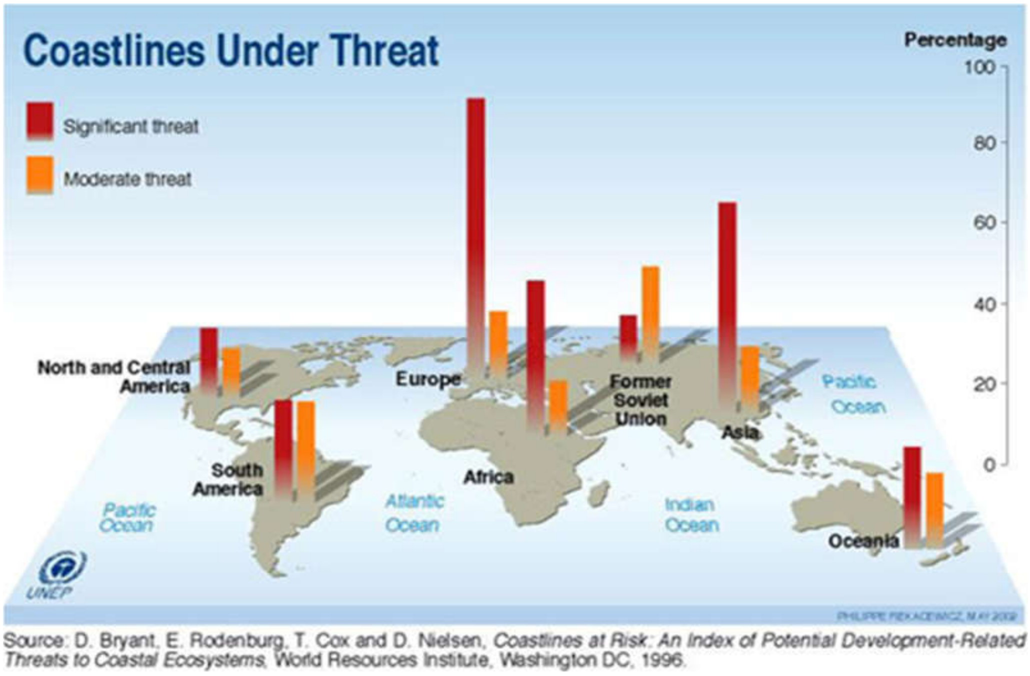

Figure 4. Level of threat to population and ecosystem near the coast.

4. Ecosystem and Biodiversity Degradation

Since 1970, humanity's ecological footprint is higher than the world's biocapacity, i.e., more environmental resources and services are in demand than can be regenerated by natural systems [47]. Regarding coastal ecosystems, large-scale losses of seagrass have been reported for decades, usually due to eutrophication or turbidity from industry, dredging, or catchment run-off, as well as natural disturbances [48]. For instance, worldwide seagrass loss between the mid-1980s and mid-1990s was estimated to be 12,000 km^2 [49]. This loss has led to numerous restoration programs [49],[50]. Traditional guidelines in restoration literature suggest that it is necessary to reverse habitat degradation, select transplantation habitats carefully, and optimize the transplantation techniques [51], [52]. Recently, the importance of ecosystem engineering for seagrass beds was studied and described [53],[54],[55], and, as a new guideline, these studies should be accounted for in restoration projects [56]. Other issues related to ecosystems and biodiversity are presented in Table 1.

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Table 1. Ecosystem issues.

Author	Issues
[57], [58, 122]	The current socio-political processes are delaying effective action
[59]	There are many solutions
[60]	the current scale of solution implementation does not match the pace of biodiversity loss
[61]	There are other existential threats tied to the expansion of enterprise development
[18]	Time delays between ecological deterioration and socio-economic, climate disruption impede recognition of the magnitude of the challenge
[62]	Disciplinary specialization and insularity encourage unfamiliarity with the complex adaptive systems
[63],[64]	The problems and their potential solutions are embedded
[65]	Widespread ignorance of human behavior
[17],[22]	Earth surface and ocean
[66],[67]	Kept and seagrass, corals,
[59],[68],[69]	Fish and terrestrial biodiversity
[70],[71],[72]	Terrestrial vegetation, wetland, rivers
[73],[74],[75],[76].	Vertebrate population, wild animals, endangered plants, threatened species
[77]	The ecosystem services of marine aquaculture:
.	valuing benefits to people and nature. Bioscience

5. Wave Propagation and Dynamic

The dynamic water-level characteristics in the nearshore include wave setup, runup, and overtopping of sandy beaches and natural or constructed barriers at different meteorological forcing (wind, air pressure) sea, and swell. Waves are periodic deformations of an air-sea and internal interface. When the wind blows over the vast expanses of open water, it transfers energy to the water's surface and creates water waves. The amount of energy imparted from wind to water is high and proportional to the fourth power of wind speed.

$$\text{frequency } f = 1 / \tau, \quad (1)$$
$$\text{angular frequency } \omega = 2 \pi / \tau, \quad (2)$$
$$\text{wave speed } c = \lambda / \tau, \quad (3)$$
$$\text{wave height } H = 2A \quad (4)$$
$$\text{wave steepness } \Delta = H / \lambda \quad (5)$$

Waves propagate at different periods τ, wavelength λ, and amplitude A. Three factors influence how big the waves are: the speed of the wind, the distance the wind travels over the water, which is called the "fetch," and the length of time the waves travel.

Efficient orbital motion cycles energy KE <=> PE

Considered "deep" until depth $< 1/2\ \lambda$

Wave Energy = Wind Speed x Wind Duration x Fetch Distance (6)

frequency (green), by generating force (yellow), and by restoring force (blue)

Phase velocity for surface gravity waves is defined as:

$$c = \sqrt{(g \tanh (k h) / k)} \quad (7)$$

Short waves depend on wavelength and dept, wavelength λ is larger than twice the water depth h. The deep and shallow water waves are independent of water depth but are determined by the ratio of water depth to wavelength.

$$c = \sqrt{(g/k)} \text{ (dispersive)} \quad (8)$$

Because of a tsunami's long wavelength, which can be hundreds of miles, a tsunami is barely noticeable in the deep ocean and is rarely more than three feet (one meter) high, however, when it enters shallow water close to land, most tsunamis slow down. Earthquakes generate tsunamis, which are shallow water or long waves. Tides (astronomical forcing) can be shallow water or long waves [78],[79]. Wave energy dynamic frequency range is presented in Figure 4.

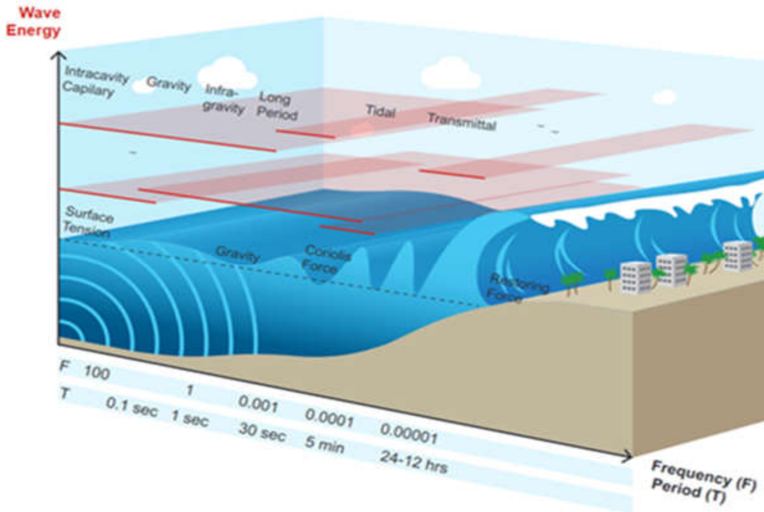

Figure 4: Wave Energy Dynamic.

6. Coastal Process and Wave Impact

The coastal process represents the feedback response to energy-driven waves to the shore. Wave setup propagation and run-up contribute to severe wave forces and damage potential along the coast. To ensure sustainable nearshore regions, predictive real-time water, and sediment-based pollutant modelling capabilities should be developed. This requires expanding our knowledge of the physics, chemistry, and biology of the nearshore wave dynamic and process. The resulting societal benefit needs to be more resilient coastal communities. The resulting benefits will come from implementing the best solutions including improved beach safety, healthier ecosystems, and improved mitigation and regulatory policies [80]. Assessment of long-term coastal evolution due to natural and anthropogenic processes includes global climate change impact on sea-level rise, change in storm patterns, and increase in coastal urbanization. It is essential to improve knowledge of long-term morphological, ecological, and societal processes and their interactions. Modeling and simulation based on assessing the requirements for improved coastal change will help deduce proactive solutions for resilient coasts, and better guidance for reducing coastal vulnerability [81].

Figure 5 shows the energy in the wave is stored between the top of the wave and a depth that is about one-half the wavelength. When the water depth decreases to about half the wavelength, then the wave becomes a shallow-water wave. As the water becomes shallower the wave rises and becomes higher, eventually, its potential energy is converted into kinetic energy, and we get a breaking wave. The wave's energy travels but the water does not. The water particles move in small circular motions as each wave passes by. The size of the circular motion decreases, as we get deeper below the wave, and dies out at a depth that is equal to half the wavelength [82]. Wind waves are propagating waves; during propagation, all points on the sea surface undergo periodic uplift and sinking and experience horizontal movement. A progressive wave is reflected at the barrier and

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produces a second wave of equal amplitude moving in the opposite direction. The two waves combine to produce a standing wave. Tide is standing waves in deep water; they involve oscillatory movement that does not create horizontal displacement [83].

7. Coastal System Breaking Wave and Impact

Coastal regions are vital to the national economy, security, and commerce. Recreation that imposes dynamic evolution due to natural and land stressors activities including dense population, can increase threats from sea-level rise, long-term erosion, extreme storms, and anthropogenic influences [85] [12]. Figure 5 shows the axis of wave breaking and related impact.

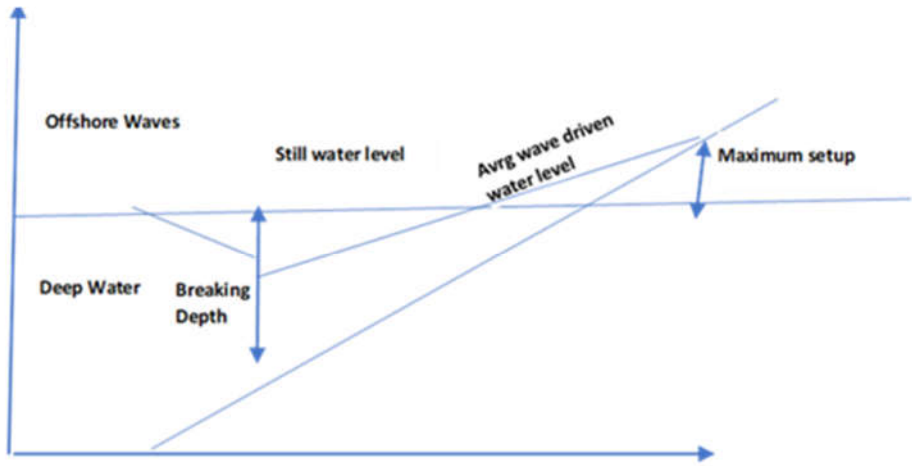

Figure 5. Wave breaking, and associated impact .

Wave action in sandy areas or Long Strand can lose up to 10 m of the dune in a single storm and have short-term damage because accretion can allow for soft sediments to be replenished. Rocky, hard soil areas are subject to long-term effects of coastal erosion [86]. Figure 6: Wave breaking Iribarren number [87].

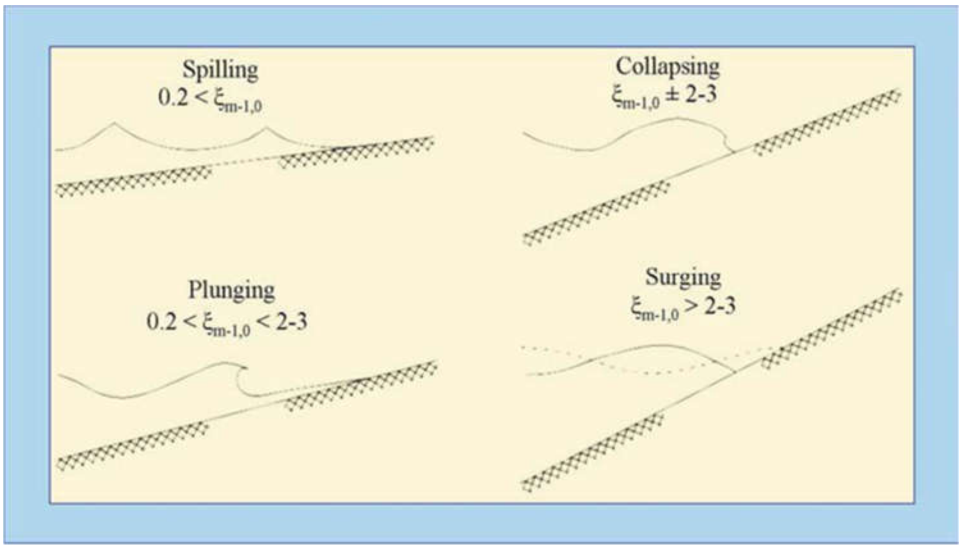

Figure 6. Wave breaking Iribarren number. [87],.

The setup is oscillating consisting of a steady and dynamic component inshore wave, conditions are influenced by shoaling and wave breaking. These processes are influenced by several parameters such as the sea steepness and the slope of the bathymetry. To take all the important parameters into account [87] provided a series of graphs, to determine the largest and the most significant wave heights (Hmax and Hs) for 1:10, 1:20, 1:30, and 1:100 sloping bathymetries [46]. The breaker parameter, surf similarity, or Iribarren number is defined as Jm–1,0 = tanA/ (Hm0/Lm–1,0) ½, where A is the slope of the front face of the structure, and Lm–1,0 is the deep-water wavelength gT2m–1,0/2π. The combination of structure slope and wave steepness gives a certain type of wave breaking.

Coastal problems can lead to the disruption of economic activities near the coast, this includes recreation, commerce, and safety. Many coasts have struggled over the year to live with the natural variability and associated hazard. The predictive system and physics of the coastal system have been used to define the dynamics of waves and wave-driven hydrodynamics on a sloping beach, as well as the response of an erodible bottom to those motions. Coastal research usually focuses on fluid dynamics or the sediment response to those motions, and important processes are the result of the dynamic wave energy propagating across the beach profile and topology [88].

The modeling of nature-based infrastructure includes improved process representation, better bio-physics model coupling, incorporation of data assimilation techniques, and testing of real-time models. Recently, we have witnessed failures of cliffs in the North Sea predominantly happening in the winter, because during that season the trees are not able to withdraw soil water, causing wetter ground conditions. The study found the dramatic effects of wetter and drier-than-average summers. In 2017, when 126 % of the typical rain amount was measured, a total of 65 failures happened. In contrast, the exceptional drought summer of 2018 (51 % of the average rain amount) resulted in only 11 cliff failure events during the following winter [89]. Figure 7 shows erosion impact in South China sea and the Northsea

Figure 7a. Erosion impact in Kuala Terengganu, Source: NST

Figure 7b. The sea moves in to claim the land between the man-made dwelling mounds, in the North Sea. by Helmholtz Association of German Research Centres. The chalk cliff of Jasmund at the coast of Rügen. [90]

8. Combining Coastal Protection and Biodiversity Restoration – Hard Coastal Structures vs. Nature-based Solutions

Hard coastal structures, such as sea dikes and seawalls, build a barrier between sea and land and thus protect the hinterland against flooding. Hard building materials, such as concrete or stone revetments, or grass covers provide surface protection of the coastal structures against the prevailing hydraulic loads: wave impacts, run-up, overtopping, and currents [91] [92]. Coastal dunes provide a similar flood protection function but are more prone to the loads from the sea because the building materials (sand, often vegetated) are less erosion resistant. They are regularly nourished before and after storm surges to restore the coastal protection function. Coastal dunes are considered a (managed) natural coastal protection solution. Sea dikes and seawalls are classified as "grey" infrastructure. In the course of incorporating nature-based solutions, grey infrastructure can be ecologically enhanced or integrated into a hybrid system, i.e., a combination of grey and natural structures [93]. However, there is little experience regarding the establishment and management of coastal ecosystems, and uncertainties concerning the constant, long-term coastal protection function that exists as shown in Figure 8 [94],[95].

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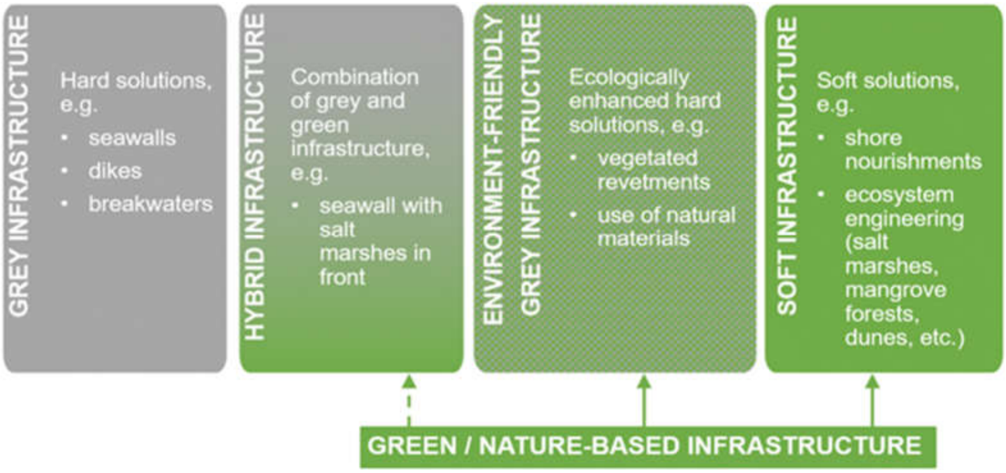

Figure 8. The concept of integrated coastal protection using green and hard engineering [95].

As the waves propagate towards the shore and encounter shallower water, the wavelength and hence, the wave speed decrease. However, the wave energy and height increase [96]. Friction between the water particles and the seabed results in energy loss. The presence of a vegetation meadow near the surface attenuates the wave energy and causes wave breaking. The presence of pockets of mud, large stands of seaweed, pile clusters, or submerged trees interferes with the wave orbital velocities, which causes an increase in turbulence and loss of energy. Previous studies to establish the effectiveness of coastal vegetation on wave attenuation include studies on internal wave attenuation by coastal kelp stands [97], wave damping as a result of local energy losses due to a cluster of cylinders, which represents a dense stand of giant kelp [98], flume observations of velocity and turbulence intensity profiles in eelgrass beds in a large seawater flume, and field investigations of water flow in a Spartina maritime salt-marsh in southern Portugal [99]. [100], investigated the processes of turbulence reduction and attenuation of orbital velocities in a Spartina anglica salt marsh in east England. 101], conducted laboratory experiments to measure wave attenuation resulting from synthetic emergent and nearly emergent wetland vegetation, under a range of wave conditions and plant stem densities. The effects of submergence ratio on wave attenuation, transmission, and energy dissipation over the model of seagrass *Posidonia Oceanica,* were investigated in a large-scale flume facility [102]. A meta-analysis performed by [103], shows average wave height reductions of 72% for salt marshes, and 70% for coral reefs, followed by average wave height reductions of 36% for seagrass, and 31% for mangroves. The wave-damping capacities of coastal ecosystems depend, amongst others, on the wave conditions (wave height and length) and the ecosystem properties (width, height, and density of the habitat). As average values for water depths and wave heights were used within the aforementioned study, further analyses for extreme events are required to consider design cases. Figure 11

Wave damping is highest when the plants occupy the entire water column. Seagrass grows shallow so that the relative height (ratio of vegetation height/water level) is quite low. It is expected that the wave-damping capacities of seagrass are low during extreme events with increased water levels and high waves. However, seagrass can also affect morphodynamics and thus contribute to coastal protection. Seagrasses are considered to increase sediment deposition by flow reduction, trap particles, and stabilize sediments [104],[105]. Kelp beds may reduce the longshore current and wave energy, in addition to creating onshore currents, which can promote the movement of sediment onshore [106].

Sea dikes, seawalls, coastal dunes, and associated coastal protection structures present the main coastal protection structures along the North Sea. With increasing design conditions due to climate change [107] and the aging of the infrastructure [108], a continuous costly adaptation of the structures is required. Recently, rising environmental awareness among the population has led to a reassessment of the common coastal protection approaches towards more nature-based solutions including hybrid solutions, i.e., a combination of natural and built infrastructure [93].

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Foreshore ecosystems provide ecosystem services with coastal protection functions, such as wave damping [103], and thus can reduce the wave loads on coastal structures and the maintenance required [109]. Risk and economic analyses for future climate scenarios reveal the necessity and costs for prospective coastal adaptations at the investigated site. The influence of the foreshore structures on the hydraulic loads at the coastal structure is investigated providing innovative design guidance for coastal structures regarding foreshore ecosystem services. Cost-benefit analyses can give important information on the cost-effectiveness of hybrid coastal protection systems and provides a planning tool for design processes.

Climate change calls for sustainable adaptation strategies for coastal protection. Using nature-based solutions presents an innovative measure that integrates the three pillars of sustainability (society, economy, ecology) into coastal engineering [45]. At this, foreshore ecosystems provide ecosystem services that not only lead to ecological but also socio-economic effects by strengthening existing coastal protection and thus reducing flood risk [110]. Yet, the use of foreshore ecosystems for coastal protection is limited to small-scale projects. With the current project, the basics for the design and upscaling of foreshore seagrass, seaweed, and an offshore aquaculture platform shall be obtained to promote the large-scale implementation of nature-based solutions for coastal adaptation with positive effects on the environment and humankind.

The coastal protection function and effects of foreshore seagrass, seaweed, and an offshore aquaculture platform on hydrodynamics and thus on the design and maintenance of coastal structures are investigated in physical, numerical, and in situ experiments with natural and artificial structures. The results are the input for the elaboration of design guidance for hybrid coastal structures. Wave damping capacities of the foreshore ecosystems and the effect on the hydraulic loads at the structure are analysed and processed to provide planning instructions for engineers. The tasks are completed with common design manuals [46] and in consultation with the site, authorities to ensure practical handling and implementation. Figure 9 shows the concept of integrated hard and soft engineering for coastal protection.

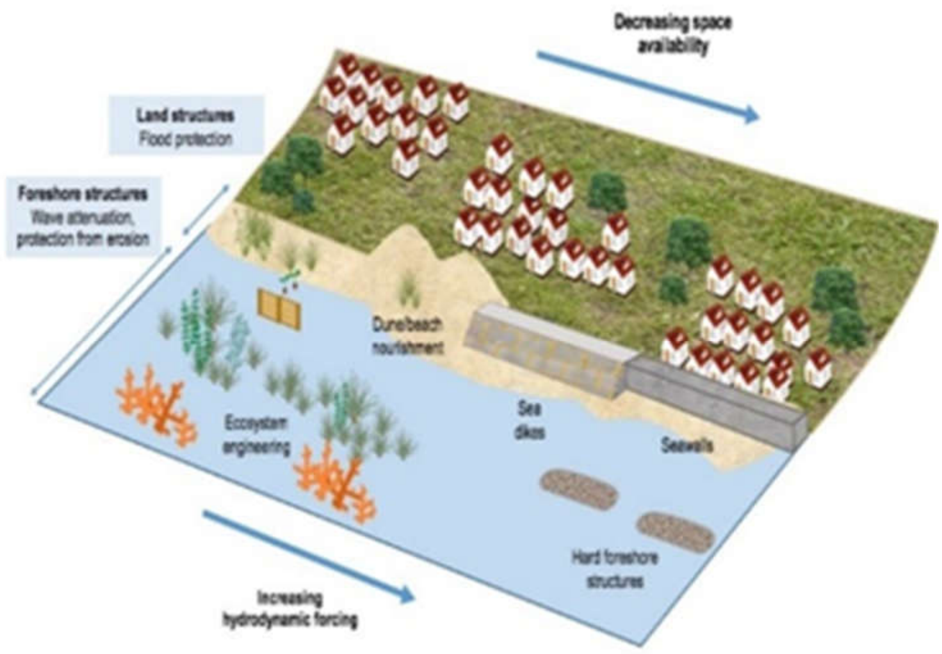

Figure 9. Implementation plan of integrated hard and soft engineering for coastal protection. [93].

Attenuation of the hydraulic loads on the coastal structure from foreshore ecosystems reduces the stress on the infrastructure and thus reduces maintenance requirements and prolongs lifetime. In cooperation with the accountable site authorities, the effects on maintenance efforts and the lifetime of the structure are quantified. Furthermore, under consideration of the coastal protection function of the investigated foreshore structures, the costs for future adaptation of the coastal structure are determined and compared to the costs without ecosystem-based foreshore engineering using cost-benefit analyses. The findings provide a new decision-making tool for planning processes and facilitate the wider use of nature-based solutions under consideration of socio-economic factors.

Coastal engineers are facing new challenges when it comes to nature-based solutions for coastal protection as design guidance is still missing and knowledge gaps exist [95]. The long-term, continuous coastal protection function of ecosystems and the effects on adjacent infrastructure are largely unexplored. The review provides a new understanding of the interaction of ecosystem engineers, the environment, and coastal structures. It provides coastal engineers with quantifiable information on the coastal protection services of the investigated foreshore ecosystems as a base for the design process of coastal structures and a decision-making tool for future planning processes.

Seaweed is a water plant with many applications. Growing seaweed can provide a natural way for adaptation that can help curb the increasing sea level rise and associated risk. Seaweed aquaculture can also help reduce the emissions from agriculture, by improving soil quality feeding to reduce methane emissions [96], [97],). Seaweed aquaculture helps climate change adaptation by damping wave energy to protect shorelines, and by elevating pH and supplying oxygen to the waters, thereby locally reducing the effects of ocean acidification and de-oxygenation. Seaweed aquaculture faces challenges of the site, suitable areas, engineering systems that can withstand offshore conditions, and increasing market demand for seaweed products [98], [99]. The ongoing climate change and extensive anthropogenic interferences in the ecosystems of coastal areas will further amplify the risk and damage of high-energy wave events, e.g., due to sea-level rise and increased frequency of extreme weather events like cyclones.

9. Conclusion and Recommendation

The use of natural vegetation for coastal protection continues to develop in coastal and risk communities. Thus, there are only a few experiments and minimal data that have been accomplished in this area, especially in the use of seaweed for wave damping and coastal adaptation. This paper provides a review of the state of the art and presented experimental results for the need to design a future vegetated protection system using seaweed. This adds value to the spectrum of the ecosystem and coastal infrastructure protection and adaptation. The use of vegetated soft engineering can help existing coastal infrastructure to meet its design life and prepare the system against climate-induced SLR rise. Seaweed growth has the potential to provide a solution to major contemporary challenges facing the coast. The natural ecosystem and critical infrastructure on land face threats from climate change SLR-induced events. Growing seaweed can help open up new space for farming to meet the growing need for bio-based food and non-food material. Incorporation of holistic risk and comprehensive modelling and robust design is important for the sustainable function of vegetated floating structures aimed at dampening waves and providing adaptation for coastal structure and biodiversity.

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