



Review

# Sand Trapping Fences as a Nature-Based Solution for Coastal Protection: An International Review with a Focus on Installations in Germany

Christiane Eichmanns <sup>1,\*</sup>, Simone Lechthaler <sup>2</sup>, Wiebke Zander <sup>2</sup>, Mariana Vélez Pérez <sup>1</sup>, Holger Blum <sup>2</sup>, Frank Thorenz <sup>2</sup> and Holger Schüttrumpf <sup>1</sup>

<sup>1</sup> Institute of Hydraulic Engineering and Water Resources Management, RWTH Aachen University, 52074 Aachen, Germany; Mariana.Velez@rwth-aachen.de (M.V.P.); Schuettrumpf@iww.rwth-aachen.de (H.S.)

<sup>2</sup> Lower Saxony Water Management, Coastal Protection and Nature Conservation Agency, 26506 Norden, Germany; Lechthaler@iww.rwth-aachen.de (S.L.); Wiebke.Zander@nlwkn.niedersachsen.de (W.Z.); Holger.Blum@nlwkn.niedersachsen.de (H.B.); Frank.Thorenz@nlwkn.niedersachsen.de (F.T.)

\* Correspondence: Eichmanns@iww.rwth-aachen.de

**Abstract:** Sand trapping fences are a widely used nature-based solution to initiate dune toe growth along sandy shorelines for coastal protection. At present, the construction of sand trapping fences is based on empirical knowledge, since only a few scientific studies investigating their efficiency exist. However, the restoration and maintenance of beach-dune systems along the coast requires knowledge of the interaction between the beach-dune system and the sand trapping fences to provide guidance for coastal managers on how and where to install the fences. First, this review gives an overview of the typical aerodynamic and morphodynamic conditions around a single porous fence and the influence of various fence height and porosity values to understand the physical processes during dune establishment. Second, different approaches for evaluating the efficiency of sand trapping fences to trap sediment are described. This review then highlights significant differences between sand trapping fence configurations, nationally as well as internationally, regarding the arrangement, the materials used, and the height and porosity. In summary, it is crucial to enable an intensive exchange among the respective coastal authorities in order to create uniform or transferable guidelines taking local conditions into account, and thus work collaboratively on the idea of sand trapping fences as a nature-based solution in coastal areas worldwide.

**Keywords:** coastal dunes; aeolian sediment transport; sand trapping fence; nature-based solutions; coastal protection measures



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## 1. Introduction

Coastal dunes play a significant role in coastal protection along sandy coastlines worldwide, providing flood protection for the low-lying hinterland against storm surges. However, the majority of sandy coastlines are subject to erosion due to the energetic processes caused by waves, wind, and currents. This erosion is expected to accelerate due to anthropogenic climate change and the associated sea level rise [1–3]. Since coastal dunes are temporally and spatially highly dynamic systems, different flood protection levels will result over time, so the need to maintain coastal dunes for protection becomes even more important [4]. Considering that coastal dunes often contribute to various ecosystem services, such as recreation, tourism, and nature conservation, and approximately 33% of the world's population lives within 100 kilometers of a coast [5], the importance of restoring and maintaining coastal dunes is also highlighted [6,7]. However, the entire coastline is not protected by coastal dunes.

The need for multidisciplinary approaches to meet the challenges of coastal protection is urgent, due to increasing economic pressure on coastal areas. Where applicable,

nature-based solutions are an effective alternative for implementing coastal infrastructures compared to hard engineering structures such as revetments and breakwaters [8–10]. Over the past decades, sand nourishment, installing sand trapping fences, and planting vegetation have been established as effective measures to support the natural dynamics of coastal dunes [7,11–15]. Adding sand nourishment is very costly compared to installing sand trapping fences or planting vegetation. Natural components such as vegetation are generally preferable to structures, but as vegetation often needs some time to establish itself, sand trapping fences can be beneficial, especially in the initial stage. In order to enlarge the available sediment, sand nourishments may be required in addition to vegetation or sand trapping fences. For more information about sand nourishment, the reader is referred to Staudt et al. (2021) [14], and for information about the influence of vegetation on the accretion of sand or the growth of coastal dunes, the reader is referred to Keijsers et al. (2015) [2] or Charbonneau et al. (2021) [16].

Based on their functionality, sand fences can be categorized as wind or sand trapping fences [17–19]. The primary purpose of wind fences is to reduce wind velocity, prevent wind-induced erosion, and reduce the amount of windblown sand in arid and desert regions. Thus, wind fences can protect infrastructure from damage by sediment load or heavy wind [18,20–24]. By contrast, in coastal regions, sand trapping fences can support the rehabilitation of eroded areas in coastal dunes, strengthen coastal dune toes, prevent sand drifting, limit human access to (protected) coastal areas in recreational areas, or initiate coastal dune formation by selective sand deposition [17,25–29]. The positive effect of sand trapping fences results from the local reduction of wind velocity, leading to downwind sediment accumulation at the fences; thus, they function as a coastal protection tool by using aeolian sediment transport to initiate and advance dune stability [15,16]. However, installations of sand trapping fences within the foredune can also hinder sediment deposition behind the fence, and therefore hinder the vertical growth of natural dunes [30].

Numerous studies have considered the reduction of wind velocity by different types of wind fences [20,25,31]. However, these studies primarily considered vertical holed-plank fences [26,32], perforated plastic or metallic fences [18,33–35], and wire and gridded fences [20]. In particular, the purpose of installing sand trapping fences in coastal areas, e.g., for dune toe growth, is only considered in a few detailed studies [13,29,30,36,37]. Therefore, research on sand trapping fences in coastal areas is generally needed for initiating dune toe growth, so that coastal managers can find adequate locations for the fences along sandy coastlines and within the beach profile. Furthermore, uniform standardization can help to implement sand trapping fences as a coastal protection measure with more experience.

This review aims to provide better insight into the role of sand trapping fences in coastal dune development. This is of special interest, considering the extended use of such fences and the need for continuous maintenance to mitigate the effects of coastal erosion, particularly along sandy coastlines of barrier islands.

First, a review of the literature on the aerodynamics and morphodynamics of sand fences and their influencing factors is given, followed by different approaches to evaluate the efficiency of sand trapping fences. Subsequently, an overview of installed sand trapping fences worldwide and detailed information on handling them as part of coastal protection measures in Germany is given. To evaluate the current practice regarding sand trapping fences, an international review of available coastal management strategies, legal texts, guidelines, websites of coastal authorities, contractors, individual projects, project reports, and research publications (e.g., case studies) was conducted.

## 2. Methodology

In the following, the results from previously conducted field and wind tunnel experiments on sand fences are described. The results of experiments with wind fences can partially be transferred to sand trapping fences, because the structures are typically similar [17]. Therefore, a review of the literature on the aerodynamics and morphodynamics of sand fences and their influencing factors is given, followed by an overview of installed

sand trapping fences worldwide and detailed information on handling them as part of coastal protection measures in Germany.

A comprehensive review of the aerodynamics and morphodynamics of sand fences is given by Li and Sherman (2015) [17]. In contrast to that study, this review focuses on coastal sand trapping fences to initiate dune toe development based on more recent literature. Thus, an international and novel overview of sand trapping fences in coastal areas is given, showing the differences and the lack of standardization regarding their construction and use.

To evaluate current practices regarding sand trapping fences, an international review of available coastal management strategies, legal texts, guidelines, websites of coastal authorities, contractors, individual projects, project reports, and research publications (e.g., case studies) was conducted. It should be noted that many of the references used constitute non-peer-reviewed resources due to the lack of international publications on this subject. Figure 1 shows a flowchart of the document types used to gather the up-to-date information in this work.

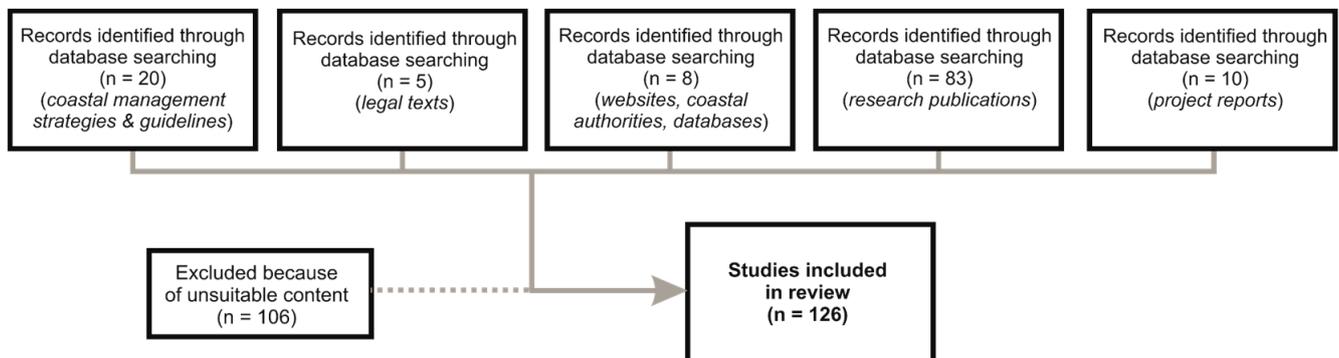


Figure 1. Flowchart for suitable studies used in this review.

### 3. General Aerodynamic and Morphodynamic Conditions around a Porous Fence

For the construction of coastal sand trapping fences, different materials can be applied. The construction materials include concrete, wood, plastic, jute, vegetation, and brushwood bundles [38–41]. Depending on the chosen material, the porosity of the fence can vary. Figure 2 shows examples of different sand trapping fences using brushwood bundles, vertical planks, and perforated plastic. In this work, we focus primarily on brushwood fences consisting of brushwood bundles as a nature-based solution (Figure 2a).



Figure 2. Examples of different design types of sand trapping fences: (a) brushwood, (b) vertical plank, (c) perforated plastic. Photograph in (c) is published with permission from Peter Tigges [42].

In addition, the arrangement or design type can also be distinguished depending on the location of the installation and the selected functionality of the sand trapping fence. The fence configuration varies in terms of the number of rows placed (single, double, or more),

the orientation to the shoreline (alongshore, diagonal, or perpendicular), and the chosen design type (straight or zig-zag construction) [13,19,43,44]. Figure 3 shows frequently used configurations and design types of sand trapping fences in coastal areas. A combination of arrangements and/or design types is also common [44].

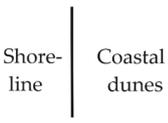
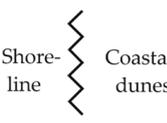
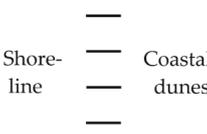
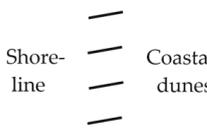
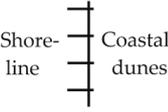
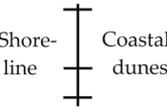
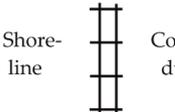
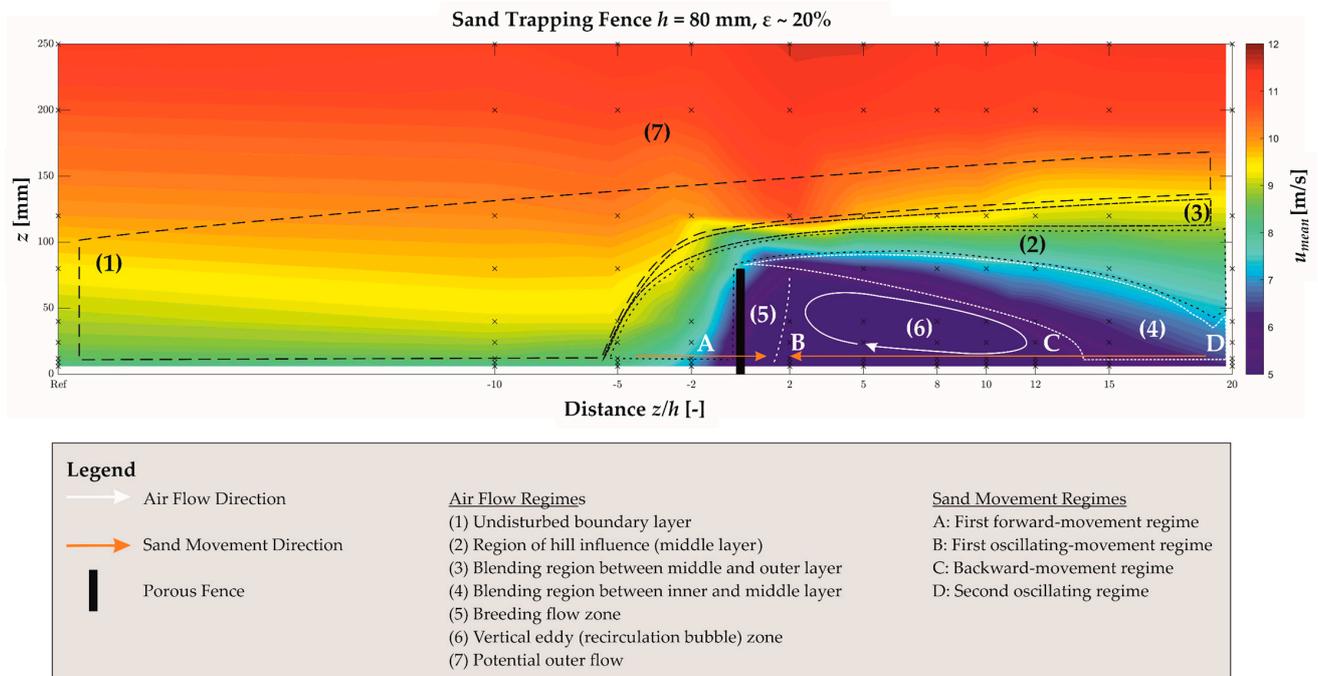
Orientation to the shoreline	Number of rows	
	Single	Double
Parallel	 <p>Straight</p>	 <p>Zig-Zag</p>
Perpendicular or oblique		
Parallel and perpendicular	 <p>Continuous</p>  <p>Discontinuous</p>	

Figure 3. Frequently installed configurations of coastal sand trapping fences (adapted from [44]).

The fence configurations have different advantages and disadvantages, which have to be considered when planning the structure. Straight fences require less construction material per shoreline length, which is why they are the most frequently used configuration. Moreover, straight fences are the most straightforward configuration; thus, they allow a faster building process and lower costs for installation and maintenance [19]. On the other hand, zig-zag fences present high sand-trapping efficiency, as their geometry allows sediment accumulation regardless of the wind direction. Therefore, zig-zag configurations are frequently used for new coastal dune formations. Increased sand-trapping efficiency can also be achieved for straight fences by placing perpendicular rows. This configuration is advantageous for coasts where the main wind direction is predominantly parallel to the coastline [19,25]. In addition, double- or multiple-row fences can be more effective in reducing the wind velocity and retaining windblown sand particles than single-row fences [35,43,45]. However, due to the limited data available, the analysis of airflow and sand movement was focused on single lines of porous fences.

The typical airflow conditions and sand movement regimes around a single porous fence from Plate (1971) [46], Judd et al. (1996), [47], and Dong et al. (2006) [48] were visually combined for the first time by Li and Sherman (2015) [17], based on the findings of Finney (1934, 1939) [49], Gloyne (1954) [50], Bodrov (1935) [51], Hallberg (1943) [52], Dyunin (1964) [53], Plate and Lin (1965) [54], Raine and Stevenson (1977) [55], Wilson (1985) [56], and Wilson et al. (1990) [57]. The description in Figure 4 is the simplest case regarding the aerodynamic and morphodynamic conditions, with the wind blowing perpendicularly toward the fence. To show the applicability of these airflow regimes, they were transferred to the results from laboratory wind tunnel experiments at the Institute of Hydraulic Engineering and Water Resources Management, Rheinisch Westfälische Hochschule Aachen University, Germany, and complemented by the sand movement zones. Figure 4 shows an exemplary wind profile in a wind tunnel around a modelled sand trapping fence ( $h = 80 \text{ mm}$ ,  $\epsilon \sim 20\%$ ) consisting of brushwood. The color map indicates the

mean wind velocity  $u_{mean}$  [m/s] in  $x$ -direction, the height  $z$  [mm] is plotted on the  $z$ -axis, and the relative distance ( $x/h$ ) with  $h$  [mm] as the fence height on the  $x$ -axis. However, it was impossible to distinguish between the different flow regimes, such as zones 1, 2, and 3. The vertical eddy zone (6), however, is very clearly visible directly behind the fence. Five sand movement zones can generally be identified, whereas only zones A–D are visible in Figure 4.



**Figure 4.** Typical regimes of airflow and sand movement over a single porous fence from laboratory experiments (adapted from [17,46,48]).

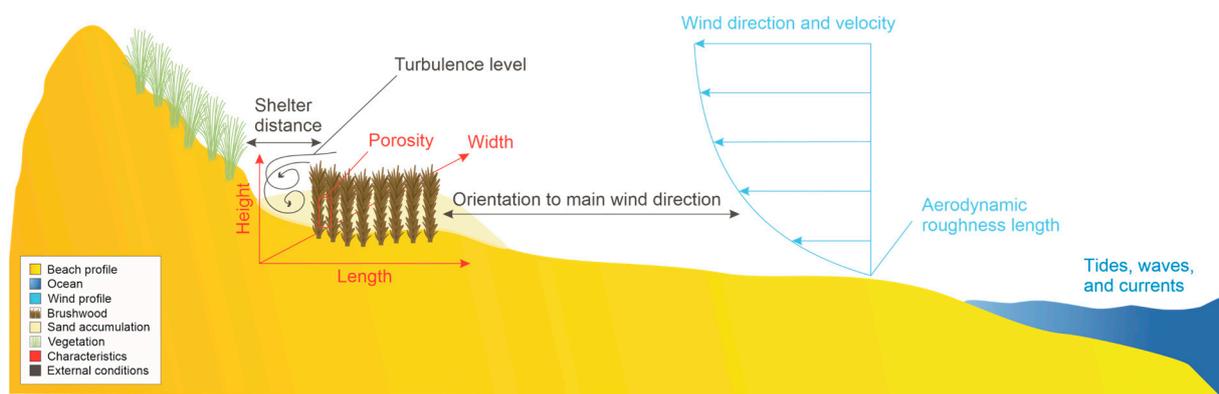
Regarding the flow direction, zone A is the first regime of downwind sand transport, zone B is the first regime of oscillating transport, zone C is the regime of upwind sand movement, zone D is the second regime of oscillating transport, and zone E is the last regime of downwind sand transport [17,20]. The oscillating transport regimes result from the chaotic recirculation of wind flow between downwind and upwind movements; e.g., flow directions converge in zone B, promoting sand deposition, while in zone D, flow divergence impedes sand deposition. The described particle movement regimes are typical of entirely or nearly closed fences. The complexity of particle movement regimes decreases as the fence porosity increases and height decreases. Some airflow regimes even disappear as the porosity increases [20,48]. However, depending on the fence geometry, local topography, sedimentology, and incoming wind conditions, the characteristics of the specified zones can vary considerably [17,20]. Referring to the typical airflow and sand movement regimes near a sand trapping fence defined by Li and Sherman (2015) [17], the outer layer zone, which is not influenced by the fence itself, is the undisturbed boundary layer. The middle layer is a secondary boundary layer characterized by flow separation across the top of the fence. The middle layer approaches a reattachment point behind the fence and is subsequently reflected upward [46]. Straight behind the fence, many individual air streams occur that are accelerated as they pass through the fence openings [47]. This so-called bleed flow (less frequently breed flow) interacts with the displaced flow running above the fence, forming the vertical eddy zone [18]. A further boundary layer develops downwind of the so-called reattachment point of the inner layer. Blending regions between the outer and middle layers and between the middle and inner layers are established due to the turbulent interactions between the boundary layers [46]. Immediately adjacent to the undisturbed boundary layer is the potential flow outside the fence-influenced zones.

A slightly different model derived from wind tunnel experiments for describing typical airflow regimes was developed by Dong et al. (2007) [20], who identified two small vortex zones on the leeward and windward sides for fence porosity  $\leq 5\%$ . In addition, the authors found two sub-regions in the middle layer (upper and lower layer) with higher velocity gradients for the upper zone than the lower zone.

Similar in all published models are the formation of a new boundary layer at the top of the fence [17,46,48], large eddies behind the fence downwind [13,34,46,58], and the return of the boundary layer to equilibrium in the lee of the fence [20,46,48].

#### 4. Influencing Parameters of the Aerodynamic and Morphodynamic Conditions

The effects of a porous sand trapping fence on aeolian sediment transport are principally dependent on the following parameters: geometry (height, length, width, and two-dimensional porosity, defined as the ratio of open surface to total surface opening size, opening distribution), orientation of the fence relative to the main wind direction, aerodynamic roughness length of the wind profile, shelter distance, and turbulence level of incident or undisturbed flow [17,23,26,31], as shown in Figure 5. The aerodynamic roughness length is the height above the surface where the mean wind velocity profile is assumed to become zero on average and is thus a parameter for describing surface roughness.



**Figure 5.** Fence characteristics and wind conditions influencing aerodynamic and morphodynamic properties around a single porous sand trapping fence.

In the following, the results of previous investigations with varying fence height and porosity values are described for a single porous fence. These fence characteristics are most influential on the wind field and consequently the sand-trapping efficiency. However, it should be noted that the influence of the fence properties is highly dependent on the given boundary conditions of the sediment and the wind field. The following section gives a short overview; for detailed information, see Li and Sherman (2015) [17].

##### 4.1. Fence Height

Various experiments have been conducted to consider the influence of fence height. Yu et al. [31] conducted wind tunnel experiments on wire wind fences ( $h = 20, 50, 100$  mm) to investigate, among other things, the wind reduction coefficient  $R_{C_{x,z}}$  [–] of a porous fence, which is defined as follows [59]:

$$R_{C_{x,z}} = 1 - \frac{u_{x,z}}{u_{0x,z}} \quad (1)$$

where  $x$  [m] is the horizontal distance from the fence,  $z$  [m] is the height above the ground,  $u_{x,z}$  [m/s] is the horizontal wind velocity with an installed fence in the wind tunnel, and  $u_{0x,z}$  [m/s] is the horizontal wind velocity at the same position without any fence [31,35]. The results showed that, with increasing distance from the fence,  $R_{C_{x,z}}$  increased to the

maximum value and then decreased or stabilized again. The position at which  $R_{C_{x,z}}$  begins to decrease or stabilize is defined as the protection range. This protection range was substantially greater for higher fences than lower fences. Furthermore, numerous studies indicate that the length of the downwind protection range is proportional to the fence height [17].

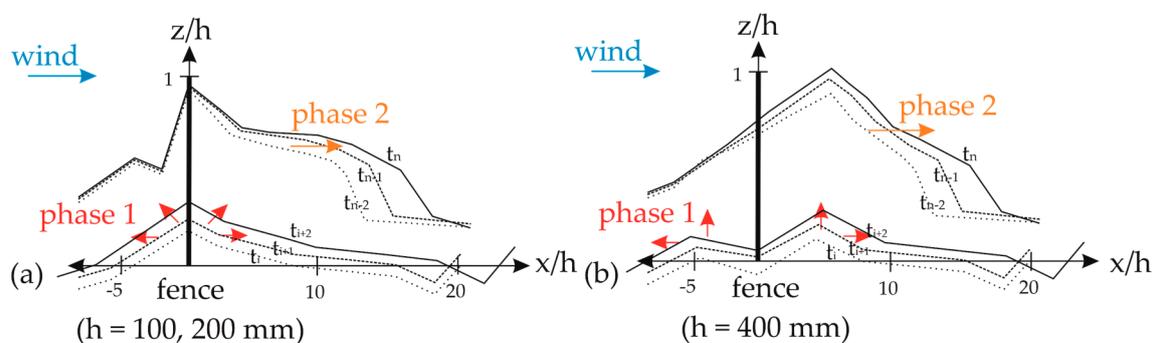
Ning et al. (2020) [26] conducted in-situ field experiments on holed-plank fences with three different heights: low ( $h = 100$  mm), medium ( $h = 200$  mm), and high ( $h = 400$  mm) to determine the dune development over time in the vicinity of the fences. The results indicated that two phases could typically be distinguished during the natural formation of coastal dunes after fences were installed. During the first phase, the dune grew horizontally and vertically until it reached approximately the fence height. During the second phase, the dune growth occurred almost exclusively horizontally in the main wind direction [26]. During the first phase, scouring occurred in front of the low and medium fences in the main wind direction. Consequently, sand dunes formed, reaching the fence height on the lee side.

In contrast, for the high fence, two sand dunes developed during the first phase, one in front of and one behind the fence, in the main wind direction. Between those dunes, a scouring area was present. The dune on the lee side of the fence developed faster and grew simultaneously with the front dune over time. Thus, during the first phase, dune cross-sectional area  $A$  [m<sup>2</sup>] increased proportionally to the product of dune height  $H$  [m] and fence height  $h$  [m]:

$$\frac{A}{h^2} = c \cdot \frac{H}{h} \tag{2}$$

with varying maximum dune height in the range between  $0.8$  and  $1.1 h$ . Due to strong shear stresses behind the fence at the top caused by the flow separation, further particle deposition is prevented above this height [10,26]. That coincides with the maximum dune height of about  $0.8 h$  determined by Hotta and Horikawa (1990) [22] in wind tunnel experiments, above which the fence successively lost its trapping function. Generally, the higher the fence, the greater the proportionality factor  $c$  [–].

Moreover, the investigations of Ning et al. (2020) [26] showed that sand-trapping is highest at the beginning of the first phase, drops significantly until the end of the first phase, and continues to drop slowly until the end of the second phase. The dune grows only horizontally during the second phase until a streamlined equilibrium is reached [29,60,61]. Overall, the high fence tended to show higher sand-trapping effectiveness than the medium and low fences. However, above a certain fence height, the efficiency to trap sand decreases [22,29]. Figure 6 shows a schematic sketch summarizing the two phases during dune establishment for (a) low and medium fences ( $h = 100, 200$  mm) and for (b) high fences ( $h = 400$  mm) based on the findings of Ning et al. (2020) [26].



**Figure 6.** Schematic sketch showing two phases during dune establishment for (a) low and medium fences ( $h = 100, 200$  mm) and (b) high fences ( $h = 400$  mm). Dune establishment is shown over time, starting at time  $t_i$  (shortly after starting experiment) until time  $t_n$  (end of experiment); times shown correspond to low, medium, and high fences, and arrows show dune growth directions (adapted from [26]).

Similar developments were observed on fences studied by Hotta and Horikawa (1990) [22] and Eichmanns and Schüttrumpf (2021) [29].

#### 4.2. Fence Porosity

In the vicinity of a fence, fence porosity  $\varepsilon$  [%] significantly influences the flow conditions. It determines the extent to which recirculating eddies form behind the fence in the main wind direction. For example, in wind tunnel experiments with varying fence porosity values of  $\varepsilon = 0\text{--}50\%$ , Perera (1981) [58] showed that recirculating eddies occurred only behind fences with porosity  $< 30\%$ , and that this zone became even smaller as the porosity increased and moved further downstream.

The results of wind tunnel experiments by Lee and Kim (1999) [34] demonstrated that by using perforated fences and circular openings ( $\varepsilon = 0, 20, 40, 65\%$ ) with porosity  $> 40\%$ , no recirculating zone occurred due to the strong bleed flow, see Figure 4. A fence with  $\varepsilon = 20\%$  showed the most substantial reduction in wind speed. In the case of  $\varepsilon < 20\%$ , the Reynolds stress and turbulent kinematic energy became very high on the top of the fence and near the reattachment point in the upper layer. A fence with porosity of 40% was more suitable to prevent wind erosion due to the lower turbulence fluctuations and favorable flow conditions [34].

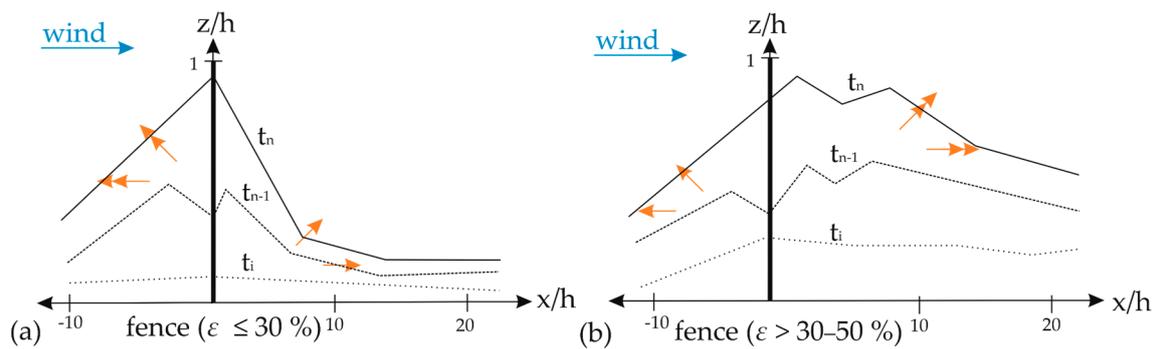
Dong et al. (2006) [48] obtained comparable results: with  $\varepsilon \geq 30\%$  (fence height  $h = 20, 40$  mm) or  $\varepsilon \geq 40\%$  ( $h = 80$  mm), no recirculating zone occurred due to a strong bleed flow, and only downwind sediment movement on the lee side of the fence took place. Dong et al. (2007) [20] also conducted wind tunnel experiments to measure the mean velocity fields behind wind fences with different porosity values. The results showed that a strong bleed flow led to an insufficient reduction of wind velocity. However, a robust backward flow facilitated turbulence and reduced the protection range. Therefore, an optimal porosity concerning the mean velocity field behind a fence of about  $\varepsilon = 20\text{--}30\%$  was determined, where the bleed flow and backward flow were balanced. This corresponds to the critical porosity above in which the bleed flow dominates.

The earlier studies concluded that the airflow becomes less complex and the number of flow regions decreases when the fence porosity increases. In particular, the recirculating zone disappears when a threshold porosity value is reached. Conversely, when the threshold porosity is exceeded, the bleed flow dominates. Furthermore, as porosity increases, the distance at which the airflow regions merge again into a single velocity profile decreases [20].

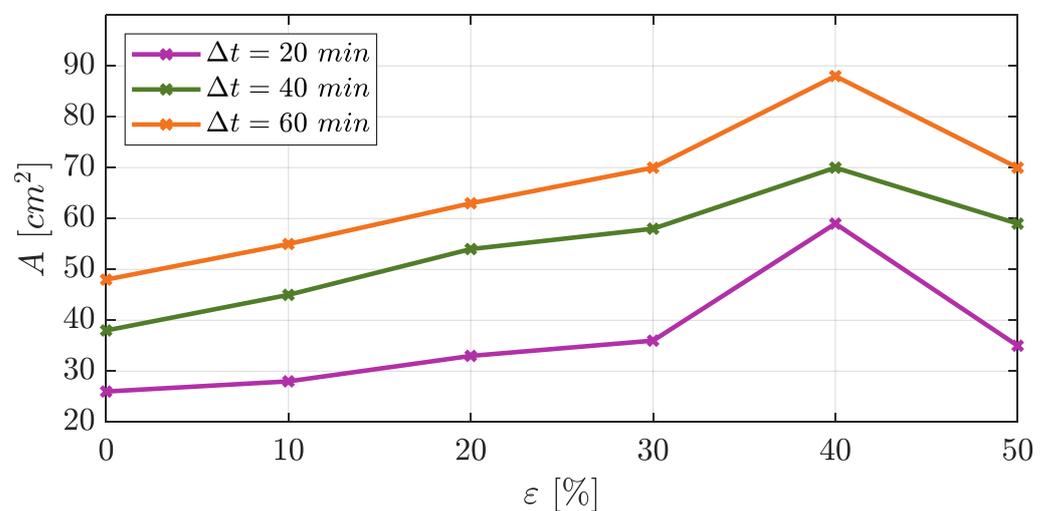
Porosity determines sand-trapping effectiveness and the location of deposition of transported sediments [26]. The threshold porosity of  $\varepsilon = 20\text{--}30\%$  determined by Dong et al. (2007) [20] is lower than that determined in the experiments of Perera (1981) [58], Lee and Kim (2015) [34], and Dong et al. (2006) [48], among others, with  $\varepsilon = 30\text{--}40\%$ . Porosity values of  $\varepsilon = 30\text{--}50\%$  are widely suggested as optimal for sand accretion [22,32,62,63].

The wind tunnel experiments of Hotta and Horikawa (1990) [22] on slat-type fences with porosity of  $\varepsilon = 0\text{--}50\%$  showed that for sand fences with  $\varepsilon \leq 30\%$ , the sediment was mainly deposited on the windward side of the fence, whereas with  $\varepsilon > 30\text{--}50\%$ , most sediment was deposited on the leeward side, see Figure 7. Generally, the sand was deposited at a high rate behind the fence with higher porosity.

The porosity at which sand was deposited most rapidly and in large volume was determined to be  $\varepsilon = 40\%$ , as shown in Figure 8, where the cross-sectional area of the dune,  $A$  [ $\text{cm}^2$ ], was highest at all times. Sand trapping fences with porosity of  $\varepsilon = 30$  and 50% trapped almost equivalent volumes of sand; however, the shape of the resulting dunes differed (see Hotta and Horikawa (1990) [22]).



**Figure 7.** Schematic sketch showing dune establishment for fences with porosity of (a)  $\epsilon \leq 30\%$ , and (b)  $\epsilon > 30\text{--}50\%$ . Dune establishment is shown over time, starting at timestep  $t_i$  (shortly after starting experiment) until  $t_n$  (end of experiment); timesteps shown correspond to fences with different porosity values. Arrows show areas with dune growth and their corresponding directions; double arrows show areas with comparatively stronger growth (adapted from [17,22]).



**Figure 8.** Sand-trapping efficiency expressed as cross-sectional area of dune for fences with different porosity values over time (adapted from [17,22]).

The compared results show that the efficiency of sand trapping fences is significantly controlled by the porosity and height of the fence.

### 5. Efficiency of Sand Trapping Fences to Trap Sediment

The authors are aware of two general approaches to estimate the trap efficiency of sand fences that have been published. These are discussed in the following. The first approach generally measures data of aeolian sediment fluxes over short time periods (1–20 min) as a basis for determining trap efficiency [13,35,64]. It describes trap efficiency as the ratio of windblown sediment flux with and without a fence. Among others, Chen et al. (2019) [64] and Wang et al. (2018) [35] used the following equation to describe trap efficiency  $E [-]$ :

$$E = \frac{q_{nz} - q_{hz}}{q_{nz}}, \tag{3}$$

where  $q_{nz}$  [kg/m<sup>2</sup>/s] is the windblown sediment flux at elevation  $z$  [m] in the absence of a fence and  $q_{hz}$  [kg/m<sup>2</sup>/s] is the flux in the presence of a fence [64]. The higher the efficiency, the more sediment is retained at the fence. Chen et al. (2019) [64] investigated hole plate-type sand fences, which were applied to control windblown sediment along the railways running through the windy Gobi Desert region, with varying hole diameters of  $\varnothing = 1.03, 2.06,$  and  $4.12$  cm, and the same porosity of  $\epsilon \sim 30\%$  in wind tunnel experiments.

The physical model tests ran for a maximum of 6 min for a wind velocity of  $u = 6$  m/s. They found that fences with a smaller hole diameter had higher sand-retaining efficiency. However, a too-small hole diameter reduced the sand retention significantly.

Wang et al. (2018) [35] conducted similar wind tunnel experiments with punch plate and wire mesh fences over a maximum time interval of 2 min with a wind velocity of  $u = 17$  m/s. They found that the sediment flux density was much lower on the leeward side of the fence than on the windward side, indicating that the fence was effective in keeping away windblown sand particles. During the experiments, the efficiency of the sand fence decreased with increasing wind velocity. Furthermore, Eichmanns and Schüttrumpf (2020) [13] conducted short-time in-situ field experiments on the barrier island Langeoog, Germany, from 19 to 24 May 2020 and measured the instantaneous sediment transport rates around a sand trapping fence consisting of brushwood with a porosity of  $\varepsilon \sim 37.5\%$  [29]. They found that during the field experiments, with wind velocity up to  $u_2 = 24.7$  m/s at a height of  $z = 2$  m, the sediment transport rates were significantly reduced behind the brushwood bundles: behind the first and second lines of brushwood, the reduction was 5–95% and 96–98%, respectively, compared to the incoming sediment grains. For the upper saltiphone, the rates were reduced by 13–44% (first brushwood line) and 72–91% (second brushwood line) [13]. It should be noted that this approach measures the average sediment transport as the sum over a short time interval; thus, it does not consider the temporal variability of sediment transport on a large spatial scale.

The second approach quantifies the amount of accumulated sediment around the sand trapping fence and compares this to saturated aeolian sediment transport rates, calculated based on the (modified) Bagnold (1935/1954) model. The Bagnold model uses either the wind velocity  $u$  [m/s] or shear velocity  $u^*$  [m/s] at which the transport of dry sediment is initiated [18] as a variable to calculate sediment transport rates [65–67]. This approach was applied for time intervals of hours up to several months [26,29]. For example, Ning et al. (2020) [26] conducted in-situ field experiments with vertical slat fences on a sandy coastline in Ceará, Brazil, from 21 to 29 October 2014. The investigated fences had the same porosity of  $\varepsilon \sim 50\%$  but varied in height ( $h = 100, 200, 400$  mm) and slat width ( $d \sim 125, 250, 500$  mm). The trap efficiency  $E$  [–] is stated as follows:

$$E = \frac{Q_t}{Q_s} . \quad (4)$$

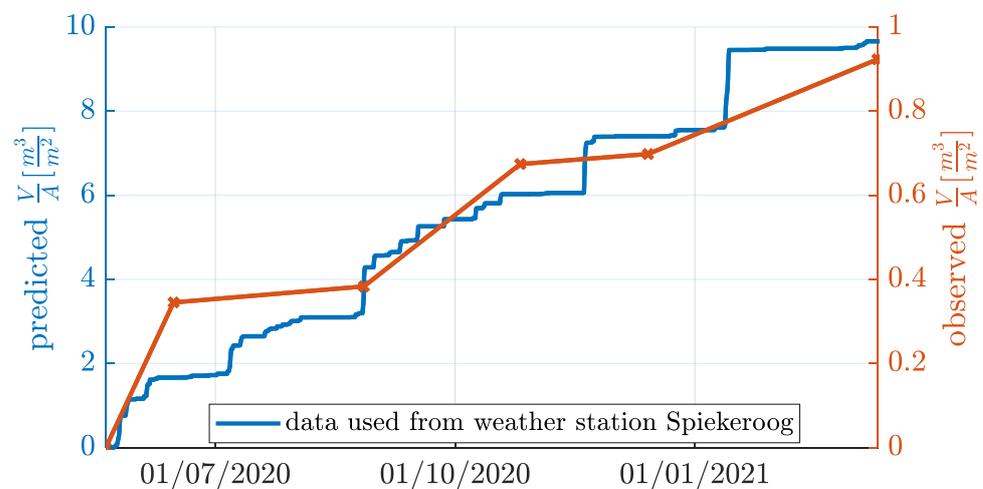
Trapped sediment  $Q_t$  [kg/m/s] is estimated as the product of the bulk density  $\gamma$  [kg/m<sup>3</sup>] of the sediment and the cross-sectional dune profile  $\Delta A$  [m<sup>2</sup>] around the sand fence over the measured time interval  $\Delta t$  [s] using the following equation:

$$Q_t = \frac{\gamma \cdot \Delta A}{\Delta t} . \quad (5)$$

During the field campaign, erosion pins were used to determine the cross-sectional dune profile at the centerline of each fence.  $Q_s$  [kg/m/s] is the total mass transport during exposure time, calculated based on the trapped sediment in the sediment traps. Thus, the collected sand needs to be weighed and divided by the inlet area and measurement duration. Ning et al. (2020) [26] found that during the first stage of development, the dune profiles developed proportional to the fence and dune height, and the trapping efficiency decreased significantly over time. During the second stage, the dune profiles mainly grew horizontally and the trapping efficiency decreased at a slower rate, see also Section 4.1. Eichmanns and Schüttrumpf (2021) [29] compared the trend in dune toe changes by integrating potential sediment transport rates calculated with hourly meteorological data on the timescale of months using the example of the barrier islands Langeoog and Norderney, Germany. The saturated aeolian sediment transport rate  $q_s$  [kg/m/hr] is calculated by a modified Bagnold model related to the third power of the wind velocity [67,68]:

$$q_s = \begin{cases} 3600 \cdot \alpha_B \cdot \sqrt{\frac{d_{50}}{d_{50,ref}}} \cdot \frac{\rho_a}{g} \cdot (u_*^3 - u_{*t}^3) & \text{for } u_* > u_{*t} \\ 0 & \text{for } u_* \leq u_{*t} \end{cases} \quad (6)$$

where the empirical constant  $\alpha_B$  [–] represents the Bagnold factor,  $d_{50}$  [ $\mu\text{m}$ ] is the mean particle size, and  $d_{50,ref}$  [ $\mu\text{m}$ ] is the reference diameter for dune sand [69]. Air density is defined by  $\rho_a$  [ $\text{kg}/\text{m}^3$ ] and gravitational acceleration by  $g$  [ $\text{m}/\text{s}^2$ ]. The shear velocity is assumed to be constant over an hourly interval. The sum of the potential transport rates calculated according to Equation (6) over the measured time series gives the total sediment transport. Depending on the angle of the prevailing wind direction relative to the coastline, total sediment transport can be divided into total cross-shore sediment transport  $Q_{cross-shore}$  [ $\text{m}^3/\text{m}$ ] and total longshore sediment transport  $Q_{longshore}$  [ $\text{m}^3/\text{m}$ ] [70,71]. Figure 9 shows the predicted and observed dune toe volume changes  $V/A$  [ $\text{m}^3/\text{m}^2$ ] with this described method for the results of Eichmanns and Schüttrumpf (2021) [29], who derived digital elevation models from repeated unmanned aerial vehicle surveys on the East Frisian island of Langeoog and Norderney. For the results shown in Figure 9, the cross-shore onshore aeolian sediment transport rates based on wind data from the Spiekeroog weather station were used to predict coastal dune toe growth on Langeoog. Other factors that influence dune toe volume changes, such as storm surges, were ruled out. The comparison between the analytical approach for predicting change trends in dune toe volume and the results of the conducted field surveys provides good results. However, the absolute values are overestimated. For a further discussion of these results as well as the prevailing boundary conditions, see Eichmanns and Schüttrumpf (2021) [29].



**Figure 9.** Predicted dune toe volume changes based on transportation equation using wind data from Spiekeroog weather station (blue line) and observed volume changes (orange line) for Langeoog study site (reproduced with permission from Eichmanns and Schüttrumpf (2021) [29]).

## 6. Sand Trapping Fences in Coastal Regions Worldwide and Germany

Sand trapping fences are part of coastal protection measures worldwide. However, there is no standardization regarding their technical construction methods. Table 1 gives an overview of sand trapping fences by specific examples from different countries. Legal and strategic frameworks are considered, including responsibilities, legal bases, and strategies, as well as fence characteristics with regard to their arrangement, geometry, and position along with the beach profile. It becomes clear that international information regarding this type of coastal protection is limited, and techniques and methods differ significantly. Mainly, data regarding porosity are limited, while the height of sand trapping fences is often mentioned. Completeness of describing sand trapping fences worldwide cannot be guaranteed.

**Table 1.** International overview showing examples of installed sand trapping fences.

Geography		Legal and Strategic Framework		Fence Characteristics			References
Country (Coastline)	Region	Responsibility and Legal Basis	Strategies for Coastal Protection	Materials	Arrangement/Geometry	Position in Beach Profile	
Germany (3624 km) 	North Sea	<ul style="list-style-type: none"> <li>States of Schleswig-Holstein and Lower Saxony</li> <li>Coastal authorities LKN-SH, MELUR-SH, and NLWKN</li> <li>Lower Saxony Dike law (NDG)</li> <li>National water law (LWG)</li> </ul>	<ul style="list-style-type: none"> <li>Long-term master plan of each coastal state</li> </ul>	<ul style="list-style-type: none"> <li>Brushwood fence (knob-thick or long, thick, straight birch twigs)</li> </ul>	<ul style="list-style-type: none"> <li>Height: <math>h \sim 1.0</math> m (buried <math>\sim 0.3</math> m, Sylt), orthogonally arranged (and parallel) to coastal dunes (SH)</li> <li><math>h \sim 1.8</math> m (buried <math>\sim 0.3</math> m, East Frisian Islands), <math>\epsilon = 10\text{--}75\%</math> (Norderney and Langeoog), orthogonally arranged and parallel to coastal dunes, distance between orthogonal elements: 10–20 m, deflectors (Lower Saxony)</li> </ul>	<ul style="list-style-type: none"> <li>Seaward side of dune, close to dune toe, depending on beach profile</li> </ul>	[13,72–75]
	Baltic Sea	<ul style="list-style-type: none"> <li>States of Mecklenburg-Vorpommern and Schleswig-Holstein</li> <li>Coastal authorities STALU MM and LKN-SH</li> </ul>					<ul style="list-style-type: none"> <li>Brushwood and/or woven reed</li> </ul>
Denmark (5316 km) 	North Sea	<ul style="list-style-type: none"> <li>Ministry of the Environment, Danish Coastal Authority</li> <li>Nature Protection Act</li> <li>Coastal Protection Act</li> </ul>	<ul style="list-style-type: none"> <li>Policy agreement renegotiated every 5 years</li> </ul>	<ul style="list-style-type: none"> <li>Brushwood</li> <li>Pine trees (Jutland)</li> <li>Wooden grills (Jutland)</li> </ul>	<ul style="list-style-type: none"> <li><math>h \sim 1.5\text{--}2.5</math> m (0.3–0.4 m buried, Jutland)</li> <li>Single straight row, rows perpendicular to prevailing wind direction, and/or parallel at an angle from dune toe (Jutland)</li> </ul>	<ul style="list-style-type: none"> <li>Seaward side of dune, close to dune toe</li> </ul>	[79–82]
Sweden (26,384 km) 	Baltic Sea	<ul style="list-style-type: none"> <li>Ministry of the Environment, Swedish Agency for Marine and Water Management</li> <li>County Administrative Boards Municipalities</li> <li>Executive Office: Environment and Health Office</li> </ul>	<ul style="list-style-type: none"> <li>Flood risk management plan</li> <li>Preliminary flood risk assessment</li> </ul>	<ul style="list-style-type: none"> <li>Wooden slats (40 mm wide, 40 mm gap) (Ängelholm)</li> </ul>	<ul style="list-style-type: none"> <li><math>h \sim 0.6\text{--}1.2</math> m (buried <math>\sim 1</math> m) (Ängelholm)</li> <li>Perpendicular and/or parallel to coastal dunes (Ängelholm)</li> <li>Multiple parallel rows possible (Ängelholm)</li> <li>Fence sections at least 30 m long with 10 m gaps (Ängelholm)</li> </ul>	<ul style="list-style-type: none"> <li>Parallel to shoreline</li> <li>0.5 m in front of dune toe (Ängelholm)</li> <li>For dune extension: 3–6 m in front of dune toe (Ängelholm)</li> </ul>	[83–85]
The Netherlands (1914 km) 	North Sea	<ul style="list-style-type: none"> <li>National policy</li> <li>Execution by national authority Rijkswaterstaat</li> </ul>	<ul style="list-style-type: none"> <li>Long-term national plan to maintain basal coastline</li> </ul>	<ul style="list-style-type: none"> <li>Brushwood fence (willow), often in combination with planting of <i>Marram grass</i> (Ameland)</li> <li>Reed stakes (sometimes placed in a grid) (Katwijk)</li> </ul>	<ul style="list-style-type: none"> <li><math>h \sim 1\text{--}2</math> m, perpendicular and/or oblique to foredune depending on prevailing wind direction</li> </ul>	<ul style="list-style-type: none"> <li>Seaward side of dune, close to dune toe</li> </ul>	[2,7,11,14,86–88]
Belgium (76 km) 	North Sea	<ul style="list-style-type: none"> <li>Flemish government, Agency for Maritime and Coastal Services</li> </ul>	<ul style="list-style-type: none"> <li>Long-term master plan to maintain coastline (since 2011)</li> </ul>	<ul style="list-style-type: none"> <li>Brushwood fence (Mariakerke and Koksijde)</li> </ul>	<ul style="list-style-type: none"> <li>Orthogonally arranged and parallel to coastal dunes (Mariakerke and Koksijde)</li> </ul>	<ul style="list-style-type: none"> <li>Seaward side of dune, close to dune toe</li> </ul>	[14,70]

Table 1. Cont.

Geography		Legal and Strategic Framework		Fence Characteristics			References
Country (Coastline)	Region	Responsibility and Legal Basis	Strategies for Coastal Protection	Materials	Arrangement/Geometry	Position in Beach Profile	
France (7330 km) 	North Sea	<ul style="list-style-type: none"> <li>Conservatoire du littoral (CDL)</li> </ul>	<ul style="list-style-type: none"> <li>Master plan of each shoreline council</li> <li>Master plan Flandre (Flanders)</li> </ul>	<ul style="list-style-type: none"> <li>Brushwood (local scrub)</li> <li>Wooden slats</li> </ul>	<ul style="list-style-type: none"> <li><math>h \sim 1.2</math> m (<math>\sim 0.1</math> m buried), distance <math>d \sim 3\text{--}7</math> m, <math>l \sim 3\text{--}4</math> m (Wissant Bay and Leffrinckoucke)</li> </ul>	<ul style="list-style-type: none"> <li>Perpendicular to shoreline, on seaward side, close to dune toe</li> <li>Upper tidal limit <math>z = +4\text{--}4.5</math> m above sea level (Wissant Bay)</li> <li>On seaward slope of incipient foredune <math>z = +5.5\text{--}7.5</math> m above sea level (Leffrinckoucke)</li> </ul>	[36,37,89]
	Mediterranean Sea	<ul style="list-style-type: none"> <li>Community Councils Perpignan Mediterranean Metropole Urban Community</li> </ul>	<ul style="list-style-type: none"> <li>Dossier de déclaration d'intérêt général pour la restauration du cordon dunaire entre le Bourdigou et la Têt Torreilles, Sainte-Marie la mer et Canet En-Roussillon</li> </ul>	<ul style="list-style-type: none"> <li>Wooden slats installed with small construction machine</li> </ul>	<ul style="list-style-type: none"> <li><math>h = 1\text{--}1.2</math> m (buried <math>\sim 0.1</math> m), tensioned and fixed to anchor piles placed at regular intervals of <math>d \sim 2\text{--}2.5</math> m, <math>\epsilon = 60\text{--}75\%</math> (from beach to coastal dune decreases), parallel to coastal dunes (coastline between Bourdigou and Têt Torreilles)</li> </ul>	<ul style="list-style-type: none"> <li>Depending on dune relief and coastal dunes, close to dune toe (coastline between Bourdigou and Têt)</li> </ul>	[90]
Portugal (2830 km) 	Atlantic Sea	<ul style="list-style-type: none"> <li>Portuguese government environmental agencies</li> <li>Hydrographic Regional Administration (Algarve)</li> </ul>	<ul style="list-style-type: none"> <li>Coastal Zone Spatial Plans (POOCs)</li> <li>Strategic Plan for Requalification and Valuation of the Coast (POLIS Littoral Ria Formosa)</li> </ul>	<ul style="list-style-type: none"> <li>Hole-plank fence (Ria Formosa and Algarve)</li> </ul>	<ul style="list-style-type: none"> <li><math>h \sim 1.3</math> m, parallel (double) rows with perpendicular rows (Ria Formosa and Algarve)</li> </ul>	<ul style="list-style-type: none"> <li>Seaward side of dune, close to dune toe</li> </ul>	[91–93]
Spain (7268 km) 	Mediterranean Sea-Cantabrian/Atlantic Sea	<ul style="list-style-type: none"> <li>Ministry of Environment of Spain, General Department of Coasts</li> </ul>	<ul style="list-style-type: none"> <li>Coastal dunes restoration manual</li> </ul>	<ul style="list-style-type: none"> <li>Brushwood (Spartina)</li> <li>Wicker, reed branches</li> <li>Wooden slats</li> <li>Synthetic fabrics (Cantabria, Valencia, Huelva)</li> </ul>	<ul style="list-style-type: none"> <li><math>h \sim 0.6\text{--}1.8</math> m</li> <li>Segment length: 1–2 m</li> <li>Arrangement of parallel rows depending on predominant wind direction (dune development)</li> <li>Parallel rows to coastal dunes (dune recovery) (Cantabria, Valencia, Huelva)</li> </ul>	<ul style="list-style-type: none"> <li>Close to embryo dunes</li> <li>On dune crest (to increase dune height)</li> </ul>	[94,95]
	Gran Canaria Island	<ul style="list-style-type: none"> <li>Gran Canaria Island Council</li> </ul>	<ul style="list-style-type: none"> <li>MASDUNAS program, Moquinií repopulation project</li> </ul>	<ul style="list-style-type: none"> <li>Wicker rods (Gran Canaria)</li> </ul>	<ul style="list-style-type: none"> <li>Sand collectors with semicircular rows</li> <li><math>h \sim 1.8</math> m (<math>\sim 0.7</math> m buried)</li> <li><math>d \sim 5\text{--}14</math> m (Gran Canaria)</li> </ul>	<ul style="list-style-type: none"> <li>Distributed over beach (Gran Canaria)</li> </ul>	[96]

Table 1. Cont.

Geography		Legal and Strategic Framework		Fence Characteristics			References
Country (Coastline)	Region	Responsibility and Legal Basis	Strategies for Coastal Protection	Materials	Arrangement/Geometry	Position in Beach Profile	
United Kingdom (England, Scotland) 	North Sea, Celtic Sea, Irish Sea, Atlantic Ocean	<ul style="list-style-type: none"> <li>Department for Environment Food and Rural Affairs</li> <li>Environmental Agency, Natural England</li> <li>Local councils</li> <li>Execution by local authorities, coastal groups</li> <li>Scottish Natural Heritage</li> <li>Scottish Environment Protection Agency</li> </ul>	<ul style="list-style-type: none"> <li>Coastal Concordat for England</li> <li>Shoreline management plans</li> <li>Joint DEFRA/EA Flood and Coastal Erosion Risk Management R&amp;D Program</li> <li>Flood and Water Management Act</li> <li>Localism Act</li> <li>Coastal Protection Act</li> <li>Flood and Environment Protection Act (FEPA)</li> <li>Town and Country Planning Act (TCPA)</li> <li>Shoreline Management Plans (SMPs)</li> <li>Potential application of shoreline management planning in Scotland</li> </ul>	<ul style="list-style-type: none"> <li>Brushwood (sea buckthorn)</li> <li>Forestry trimmings</li> <li>Wooden slats</li> <li>Chestnut paling</li> <li>Synthetic fabrics (Scotland, England)</li> </ul>	<ul style="list-style-type: none"> <li>Single and double rows</li> <li>Perpendicular and/or orthogonal rows to dominant wind direction</li> <li>Parallel to shore</li> <li>Chestnut paling: <math>\epsilon = 50\%</math></li> <li>Wooden slats: <math>w = 50</math> mm, <math>g = 50</math> mm, <math>\epsilon = 50\%</math></li> <li>To increase dune width, <math>h \sim 1</math> m above high water, <math>d \sim 4</math> m spacing</li> <li>To increase dune height, <math>h \sim 2</math> m above high water, <math>d \sim 10\text{--}15</math> m (Scotland, England)</li> </ul>	<ul style="list-style-type: none"> <li>Seaward side of dune, close to dune toe/eroded areas</li> </ul>	[14,97–103]
U.S.A. (133,312 km) 	Atlantic Ocean	<ul style="list-style-type: none"> <li>Federal Emergency Management Agency</li> </ul>	<ul style="list-style-type: none"> <li>State Shore Protection Master Plan, Hazard Mitigation Plan</li> <li>State Coastal Area Facilities Review Act (Voluntary) Coastal Zone Management Program to encourage and fund coastal protection</li> <li>Coastal Engineering Manual</li> </ul>	<ul style="list-style-type: none"> <li>Hole-plank</li> <li>3.8 cm wooden slats, spacing: 6–7 cm (New Jersey)</li> <li>Perforated plastic GeoJute (Santa Rosa Island)</li> </ul>	<ul style="list-style-type: none"> <li><math>\epsilon = 50\%</math> (Santa Rosa Island)</li> <li>Straight and zig-zag configuration, single and double rows, <math>h \sim 0.6\text{--}1.8</math> m (New Jersey)</li> <li>Rows normal to predominant wind direction and orthogonally arranged rows (New Jersey, Santa Rosa Island)</li> </ul>	<ul style="list-style-type: none"> <li>Seaward side of dune, close to dune toe/eroded areas</li> </ul>	[14,19,86,104, 105]
Australia (66,530 km) 	Pacific Ocean	<ul style="list-style-type: none"> <li>Department of Land and Water Conservation</li> <li>State Beach Protection Authority</li> <li>Local authorities</li> </ul>	<ul style="list-style-type: none"> <li>Coastal Dune Management Manual</li> <li>Integrated coastal zone management</li> </ul>	<ul style="list-style-type: none"> <li>Woven synthetic cloth, with wooden post every 4 m</li> <li>Driftwood</li> <li>Brushwood plain</li> <li>Wire fence</li> </ul>	<ul style="list-style-type: none"> <li><math>\epsilon = 40\%</math>, <math>h \sim 0.9</math> m</li> <li>Straight rows</li> <li>To build up width, series of parallel fences, <math>d \sim 2\text{--}5</math> m</li> <li>To build up dune height, additional fences</li> <li>Perpendicular to wind direction</li> </ul>	<ul style="list-style-type: none"> <li>Seaward side of dune, close to dune toe/eroded areas</li> </ul>	[14,106–108]

Table 1. Cont.

Geography		Legal and Strategic Framework		Fence Characteristics			References
Country (Coastline)	Region	Responsibility and Legal Basis	Strategies for Coastal Protection	Materials	Arrangement/Geometry	Position in Beach Profile	
Tasmania (3034 km) 	Tasmanian Sea	<ul style="list-style-type: none"> <li>Department of Land and Water Conservation</li> </ul>	<ul style="list-style-type: none"> <li>Tasmanian Coastal Works Manual</li> <li>Coastal dune management</li> </ul>	<ul style="list-style-type: none"> <li>Mesh (woven synthetic material), with wooden posts</li> </ul>	<ul style="list-style-type: none"> <li><math>h \sim 0.5\text{--}1.0</math> m, <math>\varepsilon = 60\%</math>, <math>d \sim 1\text{--}4</math> m</li> <li>Straight and curved placing</li> <li>Perpendicular to prevailing wind direction</li> </ul>	<ul style="list-style-type: none"> <li>Seaward side of dune, close to dune toe/eroded areas</li> </ul>	[106]
South Africa (3751 km) 	Indian and Atlantic Oceans	<ul style="list-style-type: none"> <li>Department of Environmental Affairs</li> <li>Coastal Management Act</li> </ul>	<ul style="list-style-type: none"> <li>Dune maintenance and management plans</li> </ul>	<ul style="list-style-type: none"> <li>Brushwood bundles (Cape Town)</li> </ul>	<ul style="list-style-type: none"> <li>Perpendicular to prevailing wind direction</li> </ul>	<ul style="list-style-type: none"> <li>Seaward side of dune, close to dune toe</li> </ul>	[109,110]

Detailed descriptions are given regarding sand trapping fences on the German coast, including the coastlines of the North Sea (see Section 6.1.1) and the Baltic Sea (see Section 6.1.2).

Table 1 shows legal and strategic frameworks for coastal protection measures in 13 countries with total coastline lengths between 76 and 66,000 km. The fences differ with regard to materials, arrangements, and geometries as well as the position within the beach profile. The materials include natural materials such as brushwood, wooden planks, chestnut palings, wicker rods, reed stakes, and pine trees, while synthetic fabrics are used rarely. Plastic pollution is increasingly recognized as a serious anthropogenic issue in coastal and marine ecosystems around the world. The unprecedented and continuously increasing plastic pollution in aquatic ecosystems has developed into a planetary boundary threat. People's awareness is shifting toward the use of ecologically degradable materials [111,112]. Although detailed information is missing from some countries, the height of these fences is generally between 0.6 and 2.5 m, the porosity is between 10 and 75%, and the arrangement is straight, zig-zag, or perpendicular in single or double rows, usually with a distance between orthogonally arranged lines of 1–20 m. Mostly, the fences are installed parallel to the main wind direction. The position on the beach profile is predominantly on the seaward side close to the dune toe, which can be considered as characteristic of coastal dunes internationally. Therefore, the summation is that sand trapping fences are a coastal protection measure along sandy coastlines used worldwide to stabilize coastal dunes. Since the parameters presented in Table 1 differ among countries or even within a single country, it becomes obvious that there is no uniform approach due to the lack of common coastal strategies or guidelines. With regard to international law regulating the installation of sand trapping fences to combine coastal protection and work on a joint basis, the difficulty is in the legal responsibility for coastal protection, which is distributed heterogeneously. Furthermore, due to different characteristics of coastal areas worldwide, e.g., topography, beach slope, wet and dry beach width, tidal ranges, wind direction, and wind velocity, such legal strategies need to cover these, too.

The following description of sand trapping fences used along the German coastline additionally illustrates the existing national differences, which is why an international standard would have to be preceded by national standardization.

### 6.1. Sand Trapping Fences at the German Coast

In Germany, coastal protection measures are organized by competing legislation; the federal government can regulate coastal protection statutorily, but leaves the responsibility for its execution to the federal states of Bremen, Hamburg, Lower Saxony, Mecklenburg-Vorpommern, and Schleswig-Holstein. They regulate coastal protection measures in individual laws and publish long-term strategies individually in master plans due to different socioeconomic, hydrodynamic, and topographic boundary conditions [113]. However, since coastal dunes are not present and thus do not play a relevant role in coastal protection measures in Bremen and Hamburg, only Schleswig-Holstein and Lower Saxony (North Sea Coast), along with Mecklenburg-Vorpommern (Baltic Coast), install sand trapping fences along their sandy coastlines. While the tidal range ( $T_R$ ) in some places at the North Sea reaches values of more than 4 m [114], the tidal range at the Baltic Sea rarely exceeds a maximum of 0.2 m [78,115]. Besides, the extent of expected storm surges differs strongly: according to the definition by the Federal Maritime and Hydrographic Agency of Germany, a severe storm surge is reached at the German Baltic Sea at a water level of 1.5 m above the mean water level (NHN = standard elevation zero) [116], whereas a water level of 2.5 m above mean high water (MHW) constitutes a severe storm surge at the German North Sea [116]. Because of these different conditions, the coastal protection strategies differ among the federal states and various localities, including different uses of sand trapping fences. The fences not only vary in terms of their characteristics, e.g., height, porosity, and relative position in the beach profile, but they may also be used for different purposes [6,74,78,117].

### 6.1.1. North Sea

In Lower Saxony, sand trapping fences are mainly used at the East Frisian Islands (Borkum, Juist, Norderney, Baltrum, Langeoog, Spiekeroog, Wangerooge). The coastal protection strategy of the East Frisian Islands, issued by the master plan of coastal protection management, aims to provide flood protection for flood-risk areas against storm surges and to secure the existence of these barrier islands [6,15,73,118]. The coastal dunes that need to be preserved to ensure the existence of the islands are so-called protection dunes; any utilization of these dunes other than as a protection measure is forbidden (§14 [119], §20a NDG [120]). Since the East Frisian Islands are part of the Wadden Sea National Park and the coastal dunes are a valuable ecosystem, they are statutorily protected biotopes (§30 Bundesnaturschutzgesetz [121], §28a Niedersächsisches Naturschutzgesetz [122]). Thus, any action that could damage these biotopes is forbidden [74]. For the preservation of coastal dunes, nature-based solutions, such as installing sand trapping fences and planting vegetation, are preferable to hard engineering structures [15,118]. Furthermore, plastic fibers are not used anymore for trapping sand, since they are not compatible with the ecological requirements of the Wadden Sea National Park.

The main objectives of these sand trapping fences are to strengthen the dune toe by facilitating sediment deposition and reconstruct eroded areas due to blowouts or storm surges. Furthermore, they prevent heavy sand drifting, e.g., on dike revetments or dune transitions, and guide tourists in recreation areas. Sand trapping fences are generally constructed in late spring after the storm surge season by the Lower Saxony Water Management, Coastal Protection, and Nature Conservation Agency (NLWKN). They are made of locally available brushwood positioned in one or two parallel lines and orthogonal lines oriented to the coastal dunes. By placing orthogonal brushwood lines between parallel brushwood lines, rectangular fields surrounded by brushwood are created to dampen wind blowout [13,29].

The number of brushwood bundles used can vary from two to five bundles per running meter. Brushwood lines with higher porosity arranged parallel to coastal dunes can allow sand accumulation closer to the dunes, whereas those with lower porosity allow significantly increased sand accumulation closer to the brushwood lines [29]. The distance between the orthogonally arranged brushwood lines varies between ~10 and ~20 m. The branches are buried about ~0.5 m in the ground and protrude about ~1.8 m [13]. The sand trapping fences are positioned close to the dune toe level, which is defined as  $z = +3$  m NHN [123].

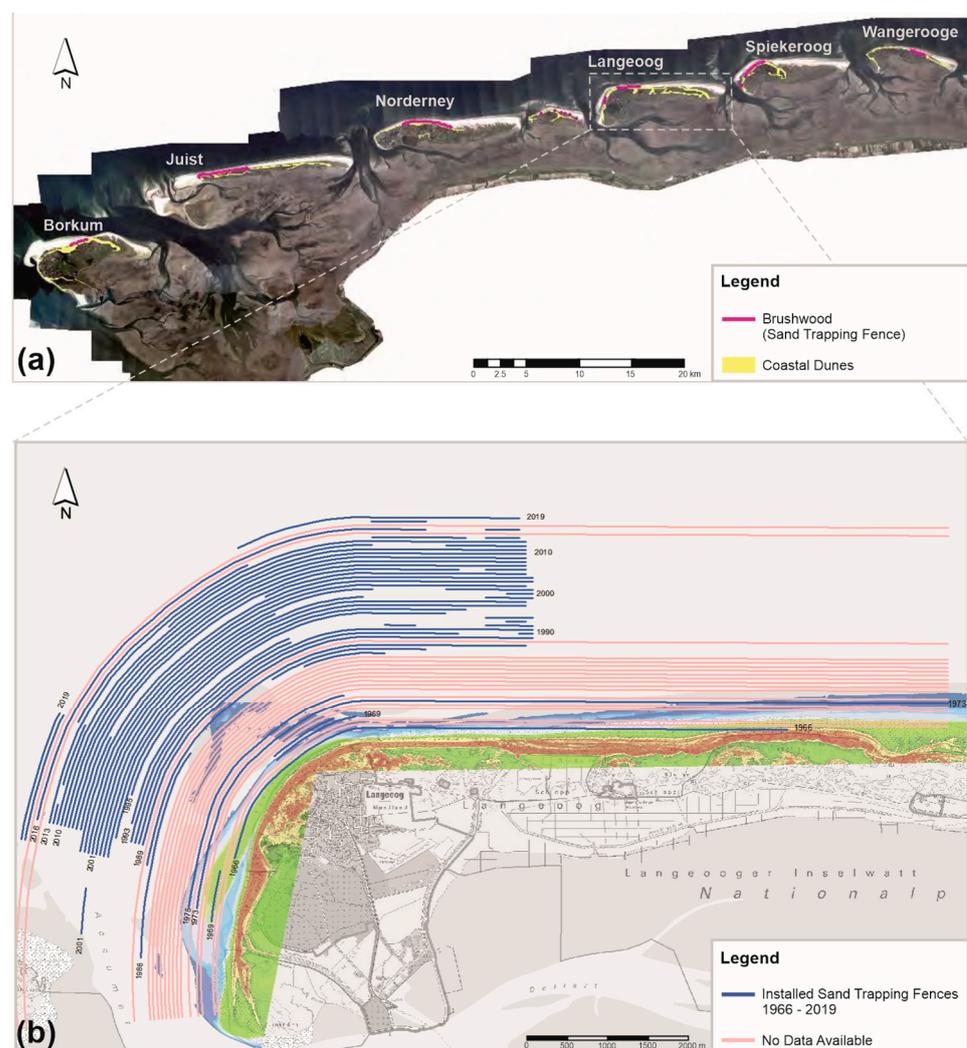
Currently, there are sand trapping fences on the East Frisian Islands with a total length of about 20 km in areas exposed to the North Sea, see Figure 10a. The fences are located mainly on the northwestern part of the islands, where generally the highest wind and wave impact occurs, thus protecting the coastline near the village of Langeoog, which is subject to erosion [124]. Figure 10b shows the locations of sand trapping fences at Langeoog Island from 1966 to 2019.

In Schleswig-Holstein, sand trapping fences are also an integral part of coastal protection [72,73,125]. The Agency for Coastal Protection, National Parks, and Ocean Protection Schleswig-Holstein (LKN-SH) is responsible for installing and maintaining the fences to prevent sediment from blowing over the coastal dunes into the hinterland. This way, the drifting of sediment in the hinterland is avoided, and the sediment is kept on the coastline, where it is needed for wave dampening. Additionally, sand trapping fences are used for the reconstruction of blowouts in the coastal dunes. Blowouts are sandy saucer-, cup-, or trough-shaped depressions in a sand dune ecosystem caused by the erosion of sediments by oblique wind at a low to moderate angle [72,117,126].

The following section is primarily based on data from the North Frisian island Sylt, the only island with sufficient information on sand trapping fences available [72,73,125]. In contrast to the ~1.8 m protruding branches of the sand trapping fences on the East Frisian Islands, the fences on the islands of Sylt, Föhr, and Amrum are generally made of branches of deciduous trees that are buried about ~0.3 m in the ground and typically protrude

about ~1 m above the ground. Variations due to beach width, elevation level, and the predicted amount of aeolian sediment transport can occur due to a lack of standardization and guidelines [72,73]. Mostly one or two parallel and many perpendicular brushwood lines oriented toward the main wind direction are installed on the seaward side close to the dune toe. The distance between individual brushwood lines differs by four to six times the fence height on the island of Sylt [72]. According to rough estimations of the LKN-SH, sand volume of approximately 8 m<sup>3</sup> per meter of coastline per year can be trapped between two parallel brushwood lines ( $h \sim 0.8$  m) on the island Sylt. With the combination of sand trapping fences and *Marram grass*, a sand volume of ~330,000 m<sup>3</sup> per year is stabilized on Sylt, where 240,000 m<sup>3</sup> per year is trapped by fences and 90,000 m<sup>3</sup> per year by vegetation [73].

In general, the installation of sand trapping fences in Lower Saxony and Schleswig-Holstein is accompanied by planting *Marram grass* and adding sand nourishment. In Germany, the average shore (face) nourishment volume is 1.9 million m<sup>3</sup>/a [14,72,73].



**Figure 10.** (a) Schematic overview of locations with installed sand trapping fences on East Frisian Islands, and (b) installations from 1966 to 2019 at Langeoog Island (UTM ETRS89 with German Geoid height GCG 2016).

### 6.1.2. Baltic Sea

In Germany, the Baltic Sea borders the states of Mecklenburg-Vorpommern and Schleswig-Holstein, where sand trapping fences are an element of coastal protection. The measurements for the former are addressed within the master plan of coastal protection

management for Mecklenburg-Vorpommern under the responsibility of the State Agency for Agriculture and Environment (StALU-MM) [78].

In Mecklenburg-Vorpommern, the overarching objective of all work being done in the coastal zone is to ensure the existence and performance of the coastal dunes. To stabilize the dune toe, enhance coastal dune growth, and increase dune height, sand trapping fences consisting of woven reed ( $h \sim 0.5\text{--}1.5$  m, estimated based on field studies and photographs) are installed on the seaward side, orthogonally arranged to the dunes or in a chessboard pattern. There may also be a surrounding fence made of thicker branches. Notably, sand drifting into the hinterland is a common issue. To prevent sand drifting, especially toward protected areas (such as tourist buildings), low brushwood fences are installed [77]. The strategies at the Mecklenburg-Vorpommern coastline show the necessity for coastal protection to gain long-term stability and erosion control, and allow the possibility of improving dune growth by using sand trapping fences in combination with vegetation.

Along the Baltic coastline of Schleswig-Holstein, the aeolian sediment transport is generally low. Therefore, protection elements such as sand trapping fences are usually not applied there; one exception is, e.g., the bay of Kiel. In order to prevent sand drifting from coastal dunes onto vegetated dike embankments, sand trapping fences were installed and vegetation was planted [76].

The detailed description of sand trapping fences along the German coast shows that there are already large differences within one country, highlighting the lack of uniform specifications regarding installation techniques and characteristics of sand trapping fences. A national strategy based on the current knowledge base would be preferable.

## 7. Conclusions

In summary, the data comparison of this review shows that there are no uniform approaches or international standardized guidelines for installing sand trapping fences. However, some national authorities have published local guidelines for the use of sand trapping fences as a nature-based solution. Nevertheless, there are significant differences between the arrangements and the materials used for these fences. At present, the design of sand trapping fences in coastal areas, i.e., the arrangement of individual lines, number of rows, material, porosity, position relative to the dune profile, and geometry (height, width, length), is based on empirical knowledge. However, these design parameters are highly relevant for coastal managers to decide how and where to install sand trapping fences along sandy coastlines.

More research on sand trapping fences in coastal areas is needed due to the complexity of incoming wind flow conditions interacting with the fences themselves and influencing the adjacent flow, newly formed coastal dunes, and aeolian sediment transport processes. Furthermore, there is a lack of open access data on in-situ fences over long-term periods to investigate the influence of sand trapping fences on the initiation of dune toe development.

It is still a great challenge to standardize the guidelines, since many regional differences, such as topography, tidal range, beach profile, and prevailing wind conditions, exist at different coastlines. For a uniform assessment of the effectiveness of sand trapping fences worldwide, long-term measurements of changes in topography, beach slope, wet and dry beach width, tidal range, wind direction, and wind velocity are needed along extensive coastlines.

Therefore, it is necessary to enable an intensive exchange of responsibility among coastal areas in order to create uniform or transferable guidelines and work collaboratively on the issue of coastal protection worldwide.

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