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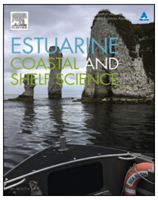

How natural foreshores offer flood protection during dike breaches: An explorative flume study

Kim van den Hoven [a,b,c,*], Jim van Belzen [b,d], Maarten G. Kleinhans [c], Dirk M.J. Schot [b], Joanne Merry [b], Jantsje M. van Loon-Steensma [e,f], Tjeerd J. Bouma [b,c]

[a] Water Systems and Global Change Group, Wageningen University & Research, Wageningen, the Netherlands
[b] NIOZ, Department of Estuarine and Delta Systems, Yerseke, the Netherlands
[c] Utrecht University, Department of Physical Geography, Utrecht, the Netherlands
[d] Wageningen Marine Research, Wageningen University & Research, Yerseke, the Netherlands
[e] Environmental Systems Analysis Group, Wageningen University & Research, Wageningen, the Netherlands
[f] Van Hall Larenstein University of Applied Sciences, Velp, the Netherlands

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ABSTRACT

In this paper we describe one aspect of nature-based flood protection by foreshores in hybrid flood defences and discuss how foreshore ecosystem restoration can contribute to flood protection. Flood protection consists of flood prevention, by grey, green or hybrid defences, and flood impact reduction, by spatial planning to limit damage and crisis management to limit exposure. Reduction of flood impact is increasingly important because no flood defence system can provide 100% safety, especially with climate change and sea level rise. In this study we aim to understand and visualize the effect of foreshore characteristics (i.e., width, elevation and erodibility) on flooding impact in the hinterland of hybrid flood defences. As it is difficult to research real dike breaches, we do an explorative flume study to analyse the impact of a mimicked dike breach in the hinterland. Our physical scale model showed the presence of a non-erodible foreshore reduces flood damage in the hinterland. With regards to foreshore characteristics, mainly foreshore elevation and erodibility are important, while differing foreshore width has little additional influence. Already a narrow foreshore reduced flood impact in the flume hinterland. Our findings strengthen the appeal to integrate Nature-based flood protection by foreshores in hybrid flood defences. Grey flood defences can be turned into hybrid flood defences even if there is limited space for foreshore ecosystem restoration, for instance by managed realignment.

1. Introduction

Low-lying regions along coasts and estuaries are prone to flooding. Therefore, at many locations worldwide inhabitants of such regions have protected themselves by flood defences (Fig. 1). These defences can be grey, such as dikes, dams, groynes, and breakwaters (CIRIA, 2013), or green such as dunes, saltmarshes, mangroves, and fluvial flood plains (e.g., Bridges et al., 2021; Hochard et al., 2021; Temmerman et al., 2013). Flood defences, both grey and green, are being challenged by climate change, sea level rise, soil subsidence, and increasing coastal populations (e.g., Nicholls et al., 2021; Oppenheimer et al., 2019). Following the increasing interest in Nature-based Solutions to combat the impact of these challenges (e.g., IFRC and WWF, 2022; Wendling et al., 2021), a lot of current research is exploring the feasibility and performance of Nature-based flood protection (e.g., Bouma et al., 2014; Morris et al., 2018; Salgado and Martinez, 2017; Temmerman et al., 2023). Nature-based solutions are often integrated with grey measures in so-called hybrid flood defences (e.g., Schoonees et al., 2019; Sutton-Grier et al., 2015), for instance a dike with adjacent foreshores (e.g., van Loon-Steensma et al., 2014).

A foreshore is the natural shore fronting a flood defence such as a tidal forest, marsh, tidal flat, or fluvial floodplain (Fig. 1). Foreshores, and in particular vegetated foreshores, provide many ecosystem services including biodiversity, carbon sequestration, pollution control, recreation, and flood risk reduction (e.g., Barbier et al., 2011). Moreover, under favourable conditions i.e., sufficient sediment supply, low hydrodynamic conditions and a favourable tidal range, coastal foreshores can keep pace with sea level rise and stabilize the shoreline (e.g., Allen,

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* Corresponding author. Water Systems and Global Change Group, Wageningen University & Research, Wageningen, the Netherlands.
E-mail address: kim.vandenhoven@wur.nl (K. van den Hoven).

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2000; Coleman et al., 2022). Foreshores are able to reduce flood risk by attenuating waves and reducing high water levels including storm surges (e.g., Gedan et al., 2011; Möller et al., 2014; Stark et al., 2015; Wamsley et al., 2010; Willemsen et al., 2020). According to Tiggeloven et al. (2022) and Fairchild et al. (2021) foreshores substantially reduce flood costs on the global scale. Furthermore, their ability to reduce hydrodynamic forcing on the adjacent grey flood defence results in adapted requirements of the dike crest height and revetment (van Loon-Steensma and Kok, 2016; van Wesenbeeck et al., 2022; van Zelst et al., 2021; Vuik et al., 2016). Combined flood protection by dikes and foreshores can be applied at for instance managed realignment sites (van den Hoven et al., 2022). All these studies show the benefits of foreshores for flood protection, especially with regards to flood prevention. Recently, the scientific flood protection focus is shifting from flood prevention by (engineered) defences towards integrated flood risk management with multiple layers (e.g., Klijn et al., 2022). In this study we also look at another layer of flood protection by investigating the flooding impact with foreshores integrated in hybrid flood defences.

Flood protection can be approached as a multi-layered system: a first layer of flood prevention by grey, green or hybrid defences, a second layer of limiting damage by spatial planning in the hinterland, and a third layer of limiting exposure during floods by crisis management including evacuation (Kok et al., 2017). In many West-European countries prevention has been the main flood risk strategy during the last decades (CIRIA, 2013). Flood risk is defined as the probability of flooding multiplied by the impact of flooding (Kok et al., 2017; Van Manen and Brinkhuis, 2005). The probability of flooding is determined by the *ex-ante* assessment of failure mechanisms like wave run-up, impact and overtopping, overflow, instability, and piping (CIRIA, 2013). The building and reinforcement of dikes, and the inclusion of foreshores for wave damping is meant to keep this probability low. However, dikes can never provide 100 % safety (CIRIA, 2013), there will remain a residual risk. Numerous historical and recent floods due to dike breaches underlines this. For instance, the Christmas flooding in 1717 and the 1953 North Sea flood (Zhu et al., 2020), the 2021 European summer floods (e.g., Ibebuchi, 2022), hurricane Katrina (e.g., Day et al., 2007), and regular coastal floods in Bangladesh (e.g., Islam et al., 2019). Therefore, there is increasing interest to improve flood protection by including the second and third safety layer of flood protection. These layers aim to limit flood impacts (Kok et al., 2017). Flood impacts include direct and indirect ecological, social, economic, physiological, political, and environmental flood consequences (Jonkman et al., 2008a; Merz et al., 2010). Direct impacts are amongst other, casualties (fatalities, injuries), physical damage to infrastructure and buildings, and environmental and cultural losses. Indirect impacts include societal disruption and damage outside the flooded area (for a more complete overview we refer to Jonkman et al., 2008a). Flood impact is affected by flood characteristics like inflow volume, flow velocity, rise rate, duration of inundation, water depth, extent of the flooded area, the debris and sediment in the floodwater (e.g., Jonkman et al., 2008a; Merz et al., 2010), and by exposure characteristics such as number of inhabitants, houses, infrastructure, and other assets located in flood-prone areas (UNDRR, n.d.). As the flood characteristics differ throughout the flooded hinterland, the flood damage differs accordingly resulting in three hazard zones: the breach zone (zone 1), the zone with rapid rising water (zone 2), and the remaining zone (zone 3) (Jonkman et al., 2008b). The main flood characteristic in the breach zone (i.e., hazard zone 1) is the flow velocity which can be up to 3–10 m/s (Jonkman et al., 2009). In zone 2 and 3 the main characteristics are water depth and rise rate (Jonkman et al., 2009). Hazardous water depths for people are 1.5m and deeper, so the critical water depth is 1.5 m (Jonkman et al., 2008b).

Climate change and related sea level rise are expected to increase the probability of future dike failure along coasts, estuaries, and rivers (Oppenheimer et al., 2019). Therefore, many explorative studies and reinforcement projects have commenced at multiple locations, including on hybrid flood protection by dikes and foreshores. So far, the research focus concerning hybrid flood defences has mainly been on flood prevention (first layer of flood protection, e.g., Kiesel et al., 2020; Marijnissen et al., 2020; Willemsen et al., 2020), and not on what happens once failure occurs (third layer). Slowly, the research focus broadens towards flood impact reduction. For instance, Narayan et al. (2017) showed that the presence of wetlands reduced flood damage and associated costs during hurricane Sandy. Recently, Zhu et al. (2020) raised that combining dikes and foreshores reduces both the probability of flooding and the impact. Analysis of historical data and initial modelling indicated that the presence of foreshores limits a dike breach (Zhu et al., 2020). Dike breach probability, size, and discharge were lower at dikes fronted with marshes compared with dikes without marshes (Zhu et al., 2020). Flume experiments by Marin-Diaz et al. (2022) and Schoutens et al. (2022) showed tidal marsh soils remain stable under the high flow velocities that can occur during a dike breach. Despite these examples, so far there has been little attention for the performance of hybrid flood defences during dike breaches and for their potential to reduce residual risk.

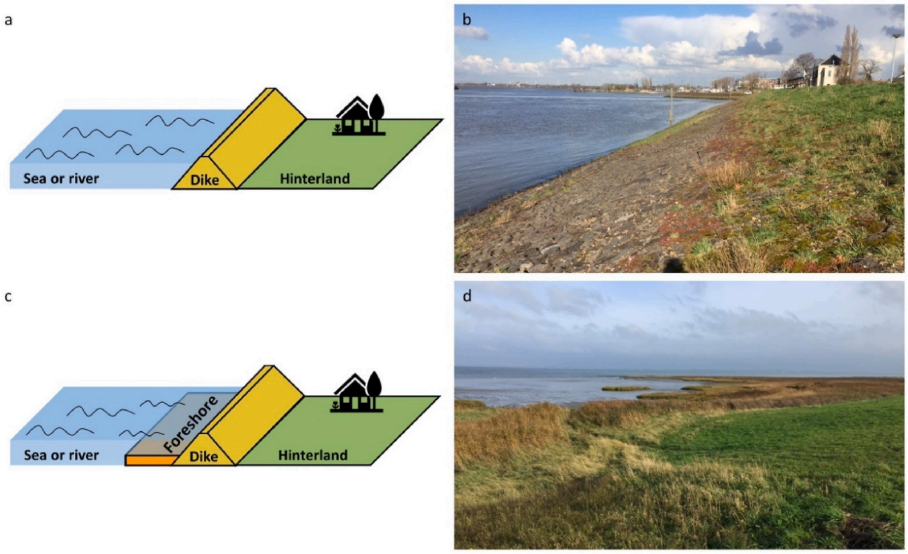

Fig. 1. Visualization of dikes without or with a foreshore. Dike with cover of stone and grass, without a foreshore, along the river Waal (b). Grass covered dike with foreshore at Scheldt Estuary (d). Photographs taken by K. van den Hoven.

Further research is required to better understand the safety effects foreshores may offer once a dike breaches (Morris et al., 2022). However, dike breaches are difficult to study in real life. One way to study dike breaches is by looking at historic breaches, as Zhu et al. (2020) did. Another way is by deliberately breaching an existing or experimental dike (e.g., Visser et al., 1995). For instance, one that is about to be realigned, as for example within the Living Lab Hedwige-Prosperpolder (e.g., van den Hoven et al., 2021). An alternative way is by modelling a dike breach event, either by computational modelling (e.g., Kamrath et al., 2006) or by setting up a physical scale model in a laboratory (e.g., Marra et al., 2014; Zhao, 2016).

In our study we scale a dike with a foreshore inside a flume. We focus on flow velocity, water depth, and rise rate because these characteristics are detrimental for direct physical flood damage and casualties in the three hazard zones. We aim to understand and visualize the effect of foreshore characteristics (i.e., foreshore width, elevation and erodibility) on flooding impact in the hinterland of hybrid flood defences. We hypothesize that the presence of a foreshore in front of a dike reduces flooding impact in the hinterland. We expect the foreshore to not only reduce the flow area of the breach but also increase friction in front of the dike and thereby reduce breach discharge and accompanied flow velocity. Strongest effects are assumed for highest elevated, widest, and least erodible foreshores. Our experimental results can be used to further explore the safety effects of foreshores as part of hybrid flood defences.

2. Methods

We developed a small-scale laboratory set-up to study the impact of flooding in a controlled environment (the flume). In this way we were able to scale a dike with different foreshore characteristics and study the effect of these characteristics on hinterland flooding in case the dike breaches. Experimental foreshores differed in elevation, width, and erodibility to mimic different states of real natural marshes. The dimensions of our scale model are based on conditions in the Netherlands and the dimensions of dike breaches during the 1953 flood disaster in the Netherlands (Zhu et al., 2020).

2.1. Flume set-up

A dike breach event was physically scaled in a flume located at NIOZ Yerseke, The Netherlands. A scale overview is provided in the online Supplementary material. The geometrical scaling was approximately 1:1000 for the horizontal length and 1:100 for the vertical (Fig. 2ab). The flow velocity was scaled 1:10. This scale factor 10 is the square root of the vertical length scale 100, because the Froude similitude applied (Froude number$_{\text{experiment}}$ (1) = Froude number$_{\text{reality}}$ (1), Table S1 in Supplementary material). Inside the flume of 2.50 by 1.25 m, a sea, dike, and hinterland were created (Fig. 2). A farm was added in the hinterland to represent the assets and inhabitants in the flood prone area behind the dike. The flume had two settings for the seaside: Sea 1 and Sea 2. Two factors differed in Sea 2 when compared to Sea 1. First, the dike was in a different location in Sea 2 (40 cm more landward) which created a larger sea (flume sea capacity increased by 0.04 m^3). Second, water supply into the flume was adjusted to keep a similar constant sea level, resulting in larger initial discharge. In both Sea settings, the bottom of the flume at 0.00 m represented 2.0 m below mean sea level. During each run, the sea area had a constant sea level of approximately 0.09 m representing storm condition water levels of 7.0 m above mean sea level. Two water outlets on the left and right side of the flume avoided water depths above 0.10 m. This setup was aimed to focus on what happens landward of the breach (in the hinterland), so no waves were considered. The sea was filled with blue dyed water from higher placed water tanks outside the flume (Fig. 2ab). Water inflow through tubes created minor ripples on the water surface, which were attenuated by a grey mesh.

The grey part of a real hybrid flood defence was scaled and simplified into an experimental dike. The non-eroding dike was 0.11 m high (i.e., 13.0 m above mean sea level) and 1.25 m wide, spreading the entire flume width. In the middle of the dike, a breach of 0.05 m wide was created. This represented a real breach of 50 m wide, i.e., a scaling of 1:1000 (based on the averaged value of two adjacent dike breaches during the 1953 North Sea flood: one with vegetated foreshore (30 m wide) and one without foreshore (70 m wide) (Zhu et al., 2020)). For the 1953 flood dike breaches it has been shown that foreshore presence limits both breach depth and width (Zhu et al., 2020). In contrast, in our study the breach width was fixed for all foreshore settings, including for

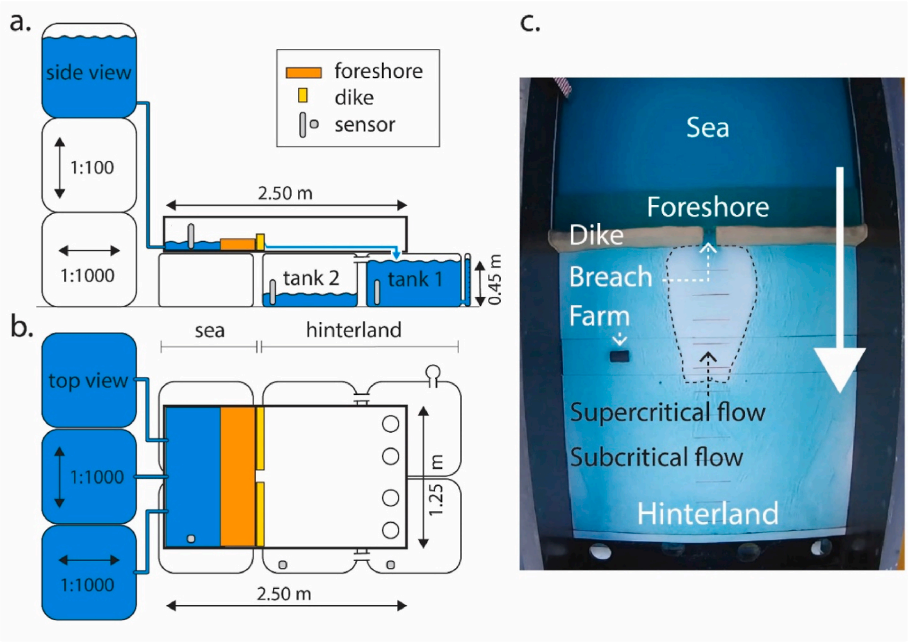

Fig. 2. Flume set-up. Side (a) and top (b) view, visualization approximately to scale. Flume scale indicated. Top view flume (c) during run 10. White arrow indicates water flow direction. Water was dyed blue, so supercritical flow in white area and subcritical flow in blue. A farm was added for visual scale indication. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

no foreshores. These assumptions allowed to focus on the influence of differences in foreshore elevation, width, and erodibility. The breach could be closed off to fill the sea at the start of each experimental run (Fig. S1 in Supplementary material).

When the experimental dike was breached, water flowed from the sea through the breach into the hinterland (Fig. S1 in Supplementary material). Water flow through the breach was critical. Immediately behind the breach, flow was supercritical (with a relatively high flow velocity). This is visualized by the white area (Fig. 2c), which represents the breach zone (hazard zone 1, Jonkman et al., 2008b). Further into the hinterland water flow was subcritical, indicated by the blue water (Fig. 2c). The experimental hinterland consisted of the hinterland part within the flume (with the bottom of the flume at 0.00 m representing a conservative level of 2.0 m below mean sea level) and four overflow tanks underneath the flume (tank set-1, tank set-2, Fig. 2ab). The area of one tank is 1.04 m^2 (A_{tank}). Water exited the flume through four holes in the bottom and dropped into tank 1-left and tank 1-right. These two overflow tanks communicated with tank 2-left and tank 2-right (Fig. 2ab). This resulted in an infinite large hinterland as the hinterland did not fill up (so, the water level is not increasing inside the flume hinterland as it would in e.g., a real finite-sized polder).

To simulate a flooding, one experimental run lasted for 12 min (Fig. 3). At the start of each run all water supply tanks were full, the flume and overflow tanks were empty of water, and the dike breach was closed (Fig. 2a). One run started by opening water tanks, so water could flow into the sea (phase two in Fig. 3). Once the sea was filled up and water level was constant, the dike was breached by pulling out the plug (Fig. 3). The dike breach initiated water flow into the hinterland (Fig. 2c and Fig. S1 in Supplementary material), which was measured first in overflow tank set-1 (Fig. 3). Once overflow tank set-1 was full, water reached overflow tank set-2 (Fig. 3). A run was terminated by closing of water supply, visualized by a draining sea and slowed water flow into the hinterland (Fig. 3).

2.2. Foreshore settings

As the flume was newly built, first all settings were tested in several pilot runs. Then, 24 experimental runs were conducted to focus on the foreshore characteristics. Run 01–15 were tested in flume setting Sea 1 and run 16–24 in Sea 2 (Table 1). First, we mimicked simply a grey flood defence, so a dike without a foreshore, to serve as control runs (run 01 and 16, Table 1). Then, we mimicked a hybrid flood defence in which the dike had a foreshore with different characteristics (run 02–15 and run 17–24, Table 1). We simulated each specific combination of settings only once. With regards to erodibility and elevation we assumed hypothetical extremes to focus on the relatively short term foreshore state during a dike breach.

Foreshore erodibility differed to mimic unstable marshes (erodible foreshores, run 02–09, Table 1) and stable marshes (non-erodible foreshores, run 10–15, 17–24, Table 1). Erodible foreshores were simulated using sand (D50 262.34 μm, D10 158.79 μm, and D90 435.34 μm). This grain size allowed for erosion with the flow velocity inside this flume. Non-erodible foreshores were simulated using TRESPA plates (partly covered with a thin clay layer for optimal visualization). The erodible foreshores had a higher roughness and lower cohesion when compared to the non-erodible foreshores. Foreshore elevation differed to mimic young saltmarshes, well below mean high water (low foreshores, run 02–05, 10–12, 18–20, Table 1) versus mature old marshes that reached the equilibrium elevation of around mean high water (high foreshores, run 06–09, 13–15, 21–24, Table 1). Low foreshores were represented with a height of 0.035 m (1.5 m above mean sea level) and high foreshores with 0.05 m (3.0 m above mean sea level) (based on AHN, n.d.). Foreshore width differed to mimic a range of marsh widths, which can vary due to extension and retreat (Allen, 2000). Experimental TRESPA foreshore widths of 0.15, 0.30, 0.45, and 0.60 m wide (Table 1) simulated marsh widths of 150, 300, 450 and 600 m wide (based on e.g., Dijkema et al., 2011).

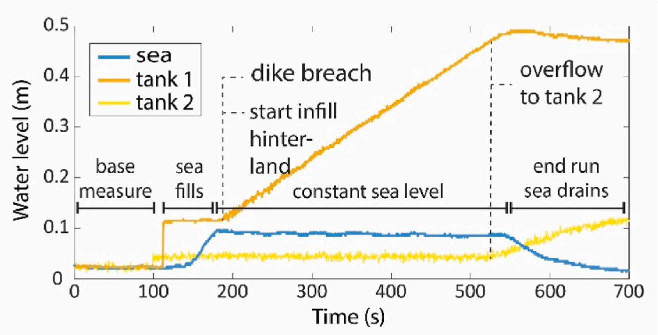

Fig. 3. Phases within one experimental run. With water level output from the three pressure sensors in run 01.

Table 1
Foreshore settings for the 24 runs. Including measured averaged sea level during breach flow.

Flume setting	Foreshore	Run	Elevation (m)	Width (m)	Sea level (m)
Sea 1	None	1	0.000	0.00	0.088
	Erodible	2	0.035	0.15	0.088
		3	0.035	0.30	0.086
		4	0.035	0.45	0.087
		5	0.035	0.60	0.092
		6	0.050	0.15	0.099[a]
		7	0.050	0.30	0.089
		8	0.050	0.45	0.087
		9	0.050	0.60	0.088
	Non-Erodible	10	0.035	0.15	0.092
		11	0.035	0.30	0.099*
		12	0.035	0.45	0.083
		13	0.050	0.15	0.085
		14	0.050	0.30	0.092
		15	0.050	0.45	0.094
Sea 2	None	16	0.000	0.00	0.090
	Non-Erodible	17	0.035	0.15	0.083
		18	0.035	0.30	0.083
		19	0.035	0.45	0.086
		20	0.035	0.60	0.086
		21	0.050	0.15	0.086
		22	0.050	0.30	0.081
		23	0.050	0.45	0.088
		24	0.050	0.60	0.104

[a] Visual observation and manual measurement indicated water level of approximately 0.09 m.

2.3. Data collection

To analyse the flooding impact area in the hinterland, visual data was collected. Five cameras were installed during run 01–15. Two cameras gave side views of the flume, in seaward and landward direction. Two cameras gave a top view of the flume. This allowed for observation of water flow into the hinterland area of the flume. One camera was directed at a transparent water level indicator. This indicator was connected to the non-transparent right overflow tank 1 (Fig. 2ab). Visual data was lacking for run 16–24 due to technical constraints with recording and data storing.

To analyse the water flow into the hinterland, water level data was collected. Three pressure sensors (sampling frequency 2 Hz) were placed inside the sea, left overflow tank 1, and left overflow tank 2 (locations in Fig. 2). Pressure sensor data was converted from mV to water depths (m), including a correction to subtract the air-pressure, to obtain the sea level and enable breach discharge calculations. A dry baseline measurement to obtain the air pressure was conducted at the start of each run (first phase in Fig. 3). Water level data was checked with manual depth measurements using rulers.

2.4. Data analysis

The effect of the different foreshore characteristics was compared only for the period of each run where sea level was constant and water level increased linearly inside the overflow tanks (Fig. 3). Start (t_0) and end (t_1) of this part were determined manually. Water depth inside the sea between t_0 and t_1 was averaged to obtain the mean sea level and was checked with manual depth measurements. This revealed that measured sea level in run 06 and 11 might be too high (manual measurements showed 0.09 m instead of 0.10 m, Table 1). Nevertheless, pressure sensor data was used for the analysis.

Water depth inside overflow tank$_1$ (H_{tank}) was used to calculate discharge into the hinterland (Q) and thus through the breach (Q_{breach}), based on the conservation of mass (Al-Hafidh et al., 2022).

$$Q = \frac{V}{T} \tag{1}$$

$$V = 2A_{tank}\left(H_{tank,t1} - H_{tank,t0}\right) \tag{2}$$

$$T = t_1 - t_0 \tag{3}$$

Water depth at the breach (h_{breach}) was obtained with sea level time series (H_{sea}) and foreshore elevation ($H_{foreshore}$). Due to erosion around the breach at all erodible foreshores, for run 02–09 $H_{foreshore}$ is set to 0 m. In Eq. (4).

$$h_{breach} = \overline{H_{sea(t0-t1)} - H_{foreshore}} \tag{4}$$

Water flow through the breach was critical, so Froude number = 1. Therefore, flow velocity through the breach (u_{breach}) was calculated using h_{breach} and gravitational acceleration ($g = 9.81\ m/s^2$).

$$u_{breach} = \sqrt{g \times h_{breach}} \tag{5}$$

Based on the broad crested weir formula (Zhao, 2016; Van Rijn, 1990), the discharge coefficient (Cd) was calculated. The Cd allows to check for specific foreshore influence on water flow through the breach. Higher Cd values indicate water flow through the breach is linearly lower. The Cd also depends on the breach shape and friction. Breach shape was fixed with breach width 0.05 m (b_{breach}) and similar for setting Sea 1 and Sea 2.

$$Cd = \frac{Q_{breach}}{\frac{2}{3}b_{breach}\left(\frac{2}{3}g\right)^{\frac{1}{2}}H_{breach}^{\frac{3}{2}}} \tag{6}$$

In addition, visual data was analysed for run 01–15. Four of the five cameras were used only for visual observations during the laboratory experiment. One of the top view cameras was used to analyse the supercritical flow area, visualized in white due to the blue dyed water (Fig. 2c). The size of this area (A) can be used as proxy for the breach zone (Jonkman et al., 2008b). A top view image was taken from the recorded videos for each run 60 s after breaching the dike (Fig. S2 in Supplementary material). The white area (i.e., corresponding to the breach zone) was measured in each image by counting the number of white pixels in an area of interest in the hinterland. Using Python, the images were converted to a panchromatic image. An image-specific threshold pixel value was chosen based on the values found at the transition from white to blue above which corresponded to supercritical flow conditions. Based on the markings at the bottom of the hinterland with known distance the pixel resolution was derived and hence pixel count was scaled to an area for each run.

To visualize the possible effect of foreshores on flood impact in a real-world situation we used a hypothetical example. We took a hypothetical hinterland of 271 ha that we called ‘Modal Polder’. The size of Modal Polder was based on the average size of the diked hinterlands (i.e., polders) along the main estuaries and North Sea in the Dutch province of Zeeland (as in Weisscher et al., 2022, of these 233 polders the 25th and 75th percentiles are 34.3 and 270 ha). We assumed the dike at Modal Polder breached during a hypothetical flood. Similar to the experimental set-up, we assumed a fixed dike breach of 50 m wide and continuous water flow through the breach with a homogenous spread of water throughout Modal Polder, which is relatively low elevated at −2.0 m below sea level (to mimic an extreme situation with major soil subsidence). We note that in a real flood event, dike breach size is not necessarily fixed and water flow is also influenced by the tide and by water level and structures inside the hinterland.

3. Results

3.1. The effects of foreshore characteristics on breach hydrology in a scaled flume

The effects of foreshore characteristics on breach hydrology in the scaled flume were most apparent for the characteristic erodibility (Figs. 4 and 5). All erodible foreshores, which mimicked non-stable marshes, indeed eroded around the dike breach. This is visualized by sand inside the hinterland part of the flume (Fig. 4bc and Fig. S2 in Supplementary material). All hybrid flood defences with erodible foreshores had a similar water flow into the hinterland, irrespective of the foreshore characteristics elevation and width as the discharge coefficient was around 1 (Fig. 5e). The flow through the breach at these hybrid flood defences with erodible foreshores was directly comparable to the flow through a dike without a foreshore (i.e., a plain grey flood defence, Figs. 4 and 5). In contrast, all hybrid flood defences with non-erodible foreshores (i.e., stable marshes) reduced water flow into the hinterland when compared to the absence of a foreshore or the presence of an easily erodible foreshore (Figs. 4 and 5).

Foreshore erodibility (i.e., marsh stability) affected discharge and flow velocity through the dike breach. Breach discharge and flow velocity was highest in the erodible foreshore runs (2.21 L/s and 0.94 m/s on average for run 02–09), comparable to control run without a foreshore (2.14 L/s and 0.93 m/s, Figs. 4 and 5). Dike breach discharge decreased in all non-erodible runs (from 2.14 L/s to 1.33 L/s on average for Sea 1 and from 3.08 L/s to 1.94 L/s on average for Sea 2, Figs. 4 and 5). Flow velocity through the breach decreased likewise (from 0.93 m/s to 0.69 m/s on average for Sea 1 and from 0.94 m/s to 0.66 m/s on average for Sea 2, Fig. 5cd).

When focussing only on the non-erodible foreshore runs (i.e., hybrid flood defences with stable marshes, run 10–15 and 17–24), foreshore elevation had the main effect on breach hydrology (Fig. S3 in Supplementary Material). As expected, breach discharge, and accordingly flow velocity, were lowest for the high elevated foreshores that mimicked a mature old saltmarsh (1.11 L/s and 0.63 m/s on average for Sea 1 and 1.83 L/s and 0.62 m/s for Sea 2, Figs. 4 and 5ac). Non-erodible foreshores do show additional friction as the discharge coefficient is above 1 (Fig. 5), indicating non-erodible foreshores do more than simply decreasing the flow area of the breach. However, against expectation increasing foreshore width had no clear additional influence on breach hydrology in this experimental set-up, neither in Sea 1 nor Sea 2 (Fig. 5bd). The discharge coefficient also remained constant with increasing width or even decreased (Fig. 5e).

3.2. The effects of foreshore characteristics on flooding impact in the flume hinterland

The effect of foreshores characteristics on flooding impact in the flume hinterland was visualized in two ways. First, the presence of a foreshore affected the size of the breach zone (Fig. 4; Fig. 6a). The scaled zone was 0.186 m^2 for the dike without a foreshore (run 01). Each simulated hybrid flood defence with non-erodible foreshores (run

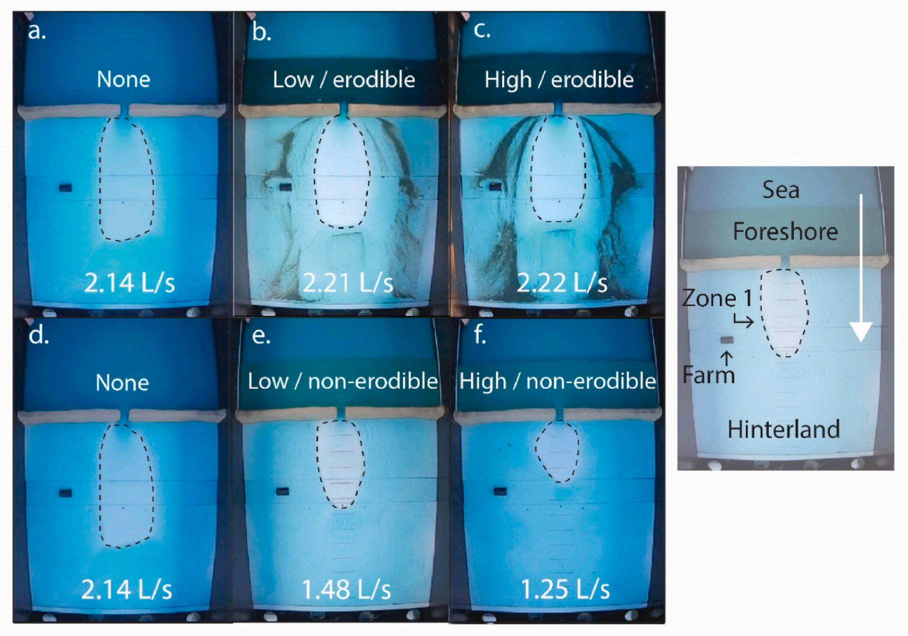

Fig. 4. Discharge through breach. Displayed in top view images and measured values (Q in L/s). Includes the control run without a foreshore (a,d) and the 30 cm wide foreshores (b,c,e,f) differing in erodibility and elevation (a–f: run # 01, 03, 07, 01, 11, 14). All images taken 60 s after breaching the dike. The breach zone is visualized by the supercritical flow area, which is white due to blue dyed water. Values and images of all runs in Supplementary material. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

10–15) showed a reduction of 0.052–0.135 m^2 when compared to the plain grey flood defence (Fig. 6a). Largest effect was again seen for the higher elevated foreshores that mimicked the old mature marshes. Even part of the erodible foreshores showed a reduction of 0.013–0.029 m^2 (Fig. 6a), this included most of the high elevated foreshores (run 06, 07, 09) and the widest low elevated foreshore (run 05).

Second, foreshores affected hinterland filling time (i.e., corresponding with rise rate) in our scale model. As breach discharge was reduced in the presence of non-erodible foreshores, it consequently took more time to reach a similar water level inside the flume hinterland (the overflow tanks, Fig. 2; Fig. 6b). Hinterland (overflow tank) filling time was increased by one third for low non-erodible foreshores that represented young marshes, and even doubled for high elevated non-erodible foreshores that mimicked mature old saltmarshes (Fig. 6b).

3.3. *From experimental to hypothetical real-situation flood characteristics*

The experimental flood characteristics for Sea 1 were upscaled to the hypothetical hinterland 'Modal Polder' (Table S4 in Supplementary material). The presence or absence of a foreshore in front of the dike makes a relevant difference during hypothetical flooding. In absence of a foreshore, breach flow velocity will be upscaled to 9.3 m/s, the breach zone (i.e., hazard zone 1) will have an area of 18.6 ha, and the water-level rise rate will be 2.94 m/h. The presence of an erodible foreshore has little influence on flow velocity and breach discharge, but a high elevated non-stable marsh can reduce the breach zone by up to 2.4 ha to a size of 16.2 ha. And a 600 m wide non-stable marsh shows a similar reduction (by 2.6 ha). The presence of a non-erodible foreshore will limit flow velocity through the breach to an average of 7.4 m/s for low elevated (young marsh) foreshores and 6.3 m/s for high elevated (mature marsh) foreshores. The breach zone will be reduced by 5.2–13.5 ha to 13.4–5.1 ha, with highest reduction for high elevated mature marshes. Rise rate will be on average 2.14 m/h (low elevated marshes) or 1.52 m/h (high elevated marshes). In absence of a foreshore, water depth inside Modal Polder will already reach the critical 1.5 m depth 30 min after dike breaching. In contrast, with a non-erodible foreshore it takes 42 min (low marshes) or 59 min (high marshes).

4. Discussion

4.1. *How foreshore characteristics affect flooding impact*

To add to the understanding of flood impact reduction by hybrid flood defences we scaled a dike breach event inside a flume. Our physical scale model showed the effect of foreshore characteristics on flooding impact in the hinterland. We hypothesized foreshores in front of a dike reduce flooding impact in the hinterland and assumed strongest effects for the highest elevated, widest, and least erodible foreshores. This hypothesis cannot be fully accepted or rejected since results differ for the three foreshore characteristics, especially for erodibility. Non-erodible foreshores that mimic stable salt marshes clearly reduced water flow through the dike breach (Fig. 4, Fig. 5, Fig. 6, Fig. S2 in Supplementary material). Our flume results hereby add to previous flume studies that included waves (e.g., Möller et al., 2014; Spencer et al., 2016). In our physical scale model the largest effect was measured with higher elevated foreshores that mimicked a mature old saltmarsh (Figs. 5 and 6). Although we also expected foreshore width to affect flooding (as found by e.g., Zhu et al., 2020), it had no clear additional influence in our model (Fig. 4, F. 5, Fig. 6). In accordance with Möller et al. (2014) and Vuik et al. (2016) this suggests that even the presence of a narrow stable foreshore can already reduce flooding impact. Vuik et al. (2016) indicate the importance of the foreshore's first tens of meters for wave energy attenuation. In addition, Garzon et al. (2019) show the importance of relatively narrow vegetated foreshores for flood protection. They measured wave attenuation by 200–400 m wide saltmarshes in storm conditions at Chesapeake Bay (Garzon et al., 2019).

We realize that our flume results do not correspond directly to real-world situations due to scaling issues in physical models (e.g., Weisscher et al., 2022a). In our flume, the hydrodynamic scale factor differs from the geometrical scale factor. The imposed length scale factors were 10^3 (horizontal) and 10^2 (vertical) while the velocity scale was 10^1 and discharge scale 10^6. With regards to foreshore erodibility, we assumed two hypothetical extremes in a nature-based flood protection

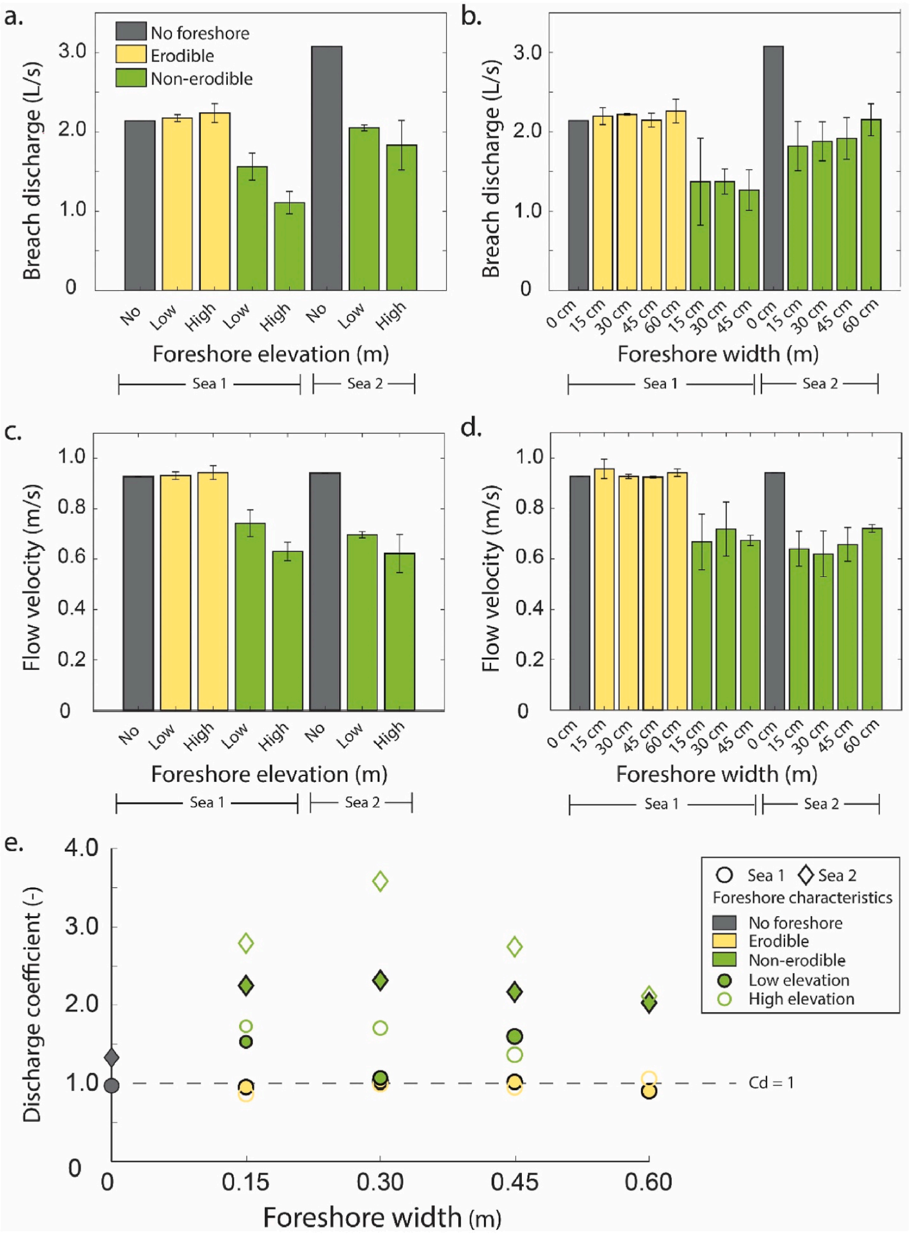

Fig. 5. The effect of foreshore characteristics on breach hydrology. Averaged breach discharge (Q) (a,b) and flow velocity (u) (c,d), presented per group of foreshore characteristics for settings Sea 1 and Sea 2. Note that Q for Sea 2 are higher due to a larger sea area inside the flume. Results are grouped by foreshore elevation (a,c) and by foreshore width (b.d). Error bars indicate standard deviation. (e) Discharge coefficient (Cd) for each run. Cd = 1 shows no additional foreshore effect. Values in Supplementary material.

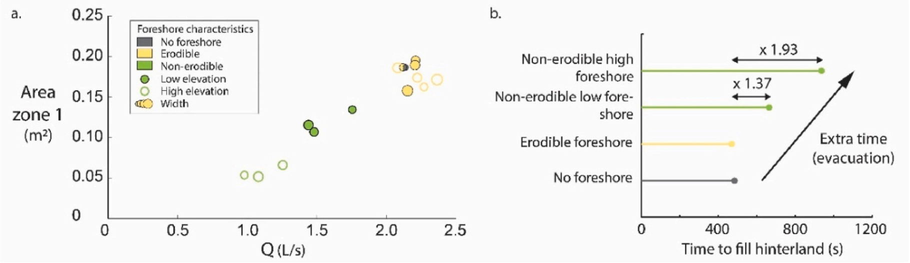

Fig. 6. Flood impact in the mimicked hinterland. (a) Size of the proxy for the breach zone (Area zone 1 in m2) plotted against breach discharge (Q in L/s) for run 01–15. Different foreshore widths indicated by dot size. (b) Hinterland filling time (time to fill first overflow tank-set), based on the constant breach discharge as calculated for the linear phase in each run. Averaged values per group for run 01–15. Values in Supplementary material.

perspective: stable (non-erodible) or unstable (erodible) foreshores. Real-world foreshores can have more diverse erodibility states due to amongst others different sediment types and varying vegetation species or states (e.g., Brooks et al., 2023; Schoutens et al., 2019). Marin-Diaz et al. (2022) tested the erodibility of diverse real-world marsh states. In contrast to our unstable sandy foreshores, they found sandy established marshes remained stable under water flows of up to 2.3 m/s. Assumptions in the physical set-up of the model thus prevent direct application to a real situation. For further research we recommend simulating more states per foreshore characteristic, especially for erodibility. Various material types that differ in roughness can mimic the diverse natural and heterogenous foreshores. The number of replicates per setting can then also be increased. Nevertheless, our small-scale set-up gave a first impression of foreshore characteristics during a simulated dike breach event and results give an indication of the order of magnitude by which flood impact will be reduced due to the presence of non-erodible foreshores. An example of non-erodible foreshores in the real-world can be found along the Scheldt Estuary. Van den Berg et al. (*in prep.*) and Schoutens et al., (2022) tested these high elevated foreshores with reed vegetation under high flow conditions. They both reported none to very minor erosion (order of millimetres) with flow velocities of up to 1.75 m/s (Schoutens et al., 2022) and 1.5 m/s (Van den Berg et al., in prep.).

Our hypothetical hinterland 'Modal Polder' showed the possible effect of a foreshore on flood impact in a real-world situation. Lower flood characteristic values are related to reduced flood impact in the three flood hazard zones. In real-world hinterlands, this means reduced physical damage and lower casualty numbers (e.g., Jonkman et al., 2008b). Our experimental results suggest that the presence of a stable marsh in a hybrid flood defence can reduce flood impact in the flood hazard zones. The breach zone (i.e., hazard zone 1) not only has lower flow velocities, but it is also reduced in size. For the hypothetical flooding of Modal Polder this means that a smaller area of Modal Polder would have severe physical flood damage. Hazard zone 2 and 3 are mainly affected by a slower rise in water level. This increases the time to reach the critical water depth of 1.5 m (Jonkman et al., 2008b). Jonkman et al. (2008b) showed casualties are lower with timely evacuation and our results suggest a foreshore, especially a stable and high elevated marsh, can provide valuable extra time for evacuation. In Modal Polder the presence of a high elevated marsh doubled the time to reach the critical water depth. The associated rise rate of 1.52 m/h gives a realistic indication as rise rate can indeed be over 1 m/h in real polders (e.g., Pieterse et al., 2009). Although our Modal Polder was based on average polder size, the flood characteristics of course vary with larger or smaller polders. So, we note flood characterises also depend on polder size.

4.2. New avenues for hybrid flood defences

Due to sea-level rise and socio-economic developments, an increasing number of people are exposed to coastal flood risk (Neumann et al., 2015). Vousdoukas et al. (2020) demonstrated the benefits of increasing flood protection and associated costs for future flood damage reduction. While Vousdoukas et al. (2020) focus on grey defences, they do imply that dikes are not the only way to go. Several studies have explored the flood prevention service of foreshores such as mangroves and saltmarshes (see review by Temmerman et al., 2023). Field observations (e.g., Willemsen et al., 2020), lab studies (e.g., Hu et al., 2014), and modelling (e.g., Hewageegana et al., 2022) quantify the effect of foreshores on hydraulic loads and subsequently on flood risk reduction. For instance, the foreshore's ability to dissipate wave energy (e.g., Phan et al., 2019) and attenuate storm surges (e.g., Wamsley et al., 2010). Moreover, Narayan et al. (2016) and Van Zelst et al. (2021) found that flood protection costs will reduce when considering the presence of foreshores. Vuik et al. (2019) calculated dike reinforcements can be more expensive than foreshore creation in front of dikes. In combination with a dike, foreshores may contribute to a wide and robust green dike, as mentioned by Vellinga (2008), resulting in less flood damage. Our current flume study adds to the shift towards integrated flood risk management (e.g., Klijn et al., 2022) with increased understanding of flood impact reduction by foreshores as part of hybrid flood defences (section 4.1 and Fig. 4, Fig. 5, Fig. 6).

Like Möller et al. (2014) and Vuik et al. (2016) we found in our scale model that even the presence of a narrow natural foreshore does already affect flood characteristics (Fig. 4) and may thus reduce the impact of floods during extreme events. We therefore argue to explicitly include foreshores in flood protection infrastructure and plea for further research on flood risk reduction by hybrid flood defences. For further research we recommend to study hybrid flood defences such as dikes with foreshores on a larger scale. For example, a 1:2 to 1:3 scale will reduce kinematic scaling issues (e.g., Van den Berg et al., in prep.). A next step is a real scale, which can be achieved in a large laboratory set-up (such as by Van Wesenbeeck et al. (2022) and Spencer et al. (2016)) or by using a real dike that has no primary flood defence function. Planned breaches, such as at managed realignments (e.g., van den Hoven et al., 2021), can also be closely monitored. Furthermore, we recommend benefitting from the unfortunate event of an accidental dike breach by monitoring and measuring breach and foreshore characteristics.

As foreshores are globally declining (e.g., Allen, 2000; Crosby et al., 2016; Schuerch et al., 2018), it is important to conserve or restore them from a flood risk perspective. Recently, Stoorvogel et al. (in prep.) found restored foreshores are very stable under high flow velocities as occur during dike breaches. They measured only a few centimetres of erosion after 3 h of 4.3 m/s water flow. Schuerch et al. (2018) indicate that a shift towards nature-based adaptations can further assist foreshore persistence. Conservation and restoration of foreshores from a flood risk perspective may also result in a variety of co-benefits for biodiversity, landscape quality, recreation, or carbon sequestration (Barbier et al., 2011). In the Netherlands, saltmarshes will indeed be integrated in the design of reinforced grey defences along some Wadden Sea stretches (e.g., Koehoal-Lauwersmeer, HWBP, 2022), leading to less extensive requirements for the obliged reinforcement and several co-benefits for the protected Wadden Sea landscape. Foreshore co-benefits may support the implementation process because they are in line with policy objectives regarding nature (e.g., the EU Green Deal, European Commission, 2021) and because they add socio-economic value (Barbier et al., 2011). The latter make natural foreshores an interesting flood protection strategy for developing countries. Apart from reducing flood risk, foreshores also reduce vulnerability by providing ecosystem services that improve socio-economic values and capacities (Barbier et al., 2011). Often, these developing countries have no, or not sufficient grey flood defences in place. So, conservation or restoration of foreshores will have a substantial contribution to flood protection in developing countries (Tiggeloven, 2022).

4.3. Where ecosystem restoration can create space for hybrid flood defences

To turn a grey flood defence into a hybrid flood defence, one needs space for the foreshore. Foreshores might already be present near the grey defence. However, if foreshores are absent or degrading, foreshore development can be enhanced by ecosystem restoration. Space for foreshore restoration can be found seaward or landward of the existing dike. We recommend to locally explore the best options and consider other land uses and ecosystem services.

Seaward of the dike there are several possibilities for foreshore restoration. In temperate regions, tidal and freshwater marshes can develop under favourable conditions (e.g., Baptist et al., 2021; Van Loon-Steensma, 2015). In tropical regions, mangroves can establish in front of dikes (e.g., Xie et al., 2022). In a more riverine tidal environment, willow tree forests can be restored to attenuate waves (e.g., van Wesenbeeck et al., 2022).

There is not always sufficient space seaward of a dike to create a hybrid flood defence as it might displace key intertidal ecosystems or other services. In that case, space for foreshore restoration can be created landward of the dike. One option is to do so by managed realignment (Esteves, 2014). While many realignments have been implemented to restore intertidal habitats, challenges remain to implement managed realignments for flood risk reduction (Schuerch et al., 2022; Van den Hoven et al., 2022). An alternative to managed realignment is setting up transitional polders between double dikes (De Mesel et al., 2013; Marijnissen et al., 2021; Van Belzen et al., 2021; Weisscher et al., 2022). A transitional polder can be seen as a temporary realignment, as the aim is to elevate land level by letting water in and accrete sediment. Once land level is elevated the seaward dike can be closed off so the area can again be used, e.g., for agriculture (e.g., Van Belzen et al., 2021). In the meantime, the double dike system creates space for foreshore development and additional functions such as aquaculture (Marijnissen et al., 2021).

5. Conclusion

In this study we aimed to understand and visualize the effect of foreshore characteristics on dike breach impact in hybrid flood defences. As it is difficult to research real dike breaches, we did an explorative flume study and analysed the effect of mimicked dike breaches in the hinterland. Our physical scale model showed the presence of a non-erodible foreshore reduces flood damage in the hinterland, no matter the size (width) of the foreshore. Even narrow foreshores reduce the area of the breach zone and thereby the severeness of physical flood damage. Non-erodible foreshores such as stable marshes can half the water rise rate and thus the water depth inside a hinterland. This means there is up to twice as much time to warn and evacuate inhabitants and take measures.

Our findings on flood impact reduction by non-erodible foreshores strengthen the appeal to apply Nature-based flood protection by foreshores. Conservation and restoration of natural foreshores will reduce flood risk by reducing both hydraulic loads and the impacts of flood (our paper) and add socio-economic values that may decrease vulnerability as well. Reduction of flood impact is increasingly important because no flood defence system can ever provide 100% safety. Grey flood defences can be turned into hybrid flood defences if there is space for foreshores. Foreshore development can be enhanced by restoration of marsh ecosystems both seaward and landward of the dike, at for instance managed realignments. Thus, ecosystem restoration can assist in turning grey flood defences into hybrid flood defences.

CRediT authorship contribution statement

Kim van den Hoven: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jim van Belzen:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Maarten G. Kleinhans:** Writing – review & editing, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Dirk M.J. Schot:** Writing – review & editing, Methodology, Data curation. **Joanne Merry:** Writing – review & editing, Data curation. **Jantsje M. van Loon-Steensma:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition. **Tjeerd J. Bouma:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data belonging to this publication is available open access at Zenodo with doi 10.5281/zenodo.7353903

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Appendix A. Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.ecss.2023.108560.

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