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Review Article

Shoreface nourishments: Research advances and future perspectives

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ABSTRACT

Shoreface nourishments have become a popular management option to mitigate coastal retreat for sites with abundant sand supplies. With shoreface nourishments, relatively large volumes of off-site sand are placed under water in typical water depths of 4–10 m. This part of the nearshore zone has a high bed level variability and contains a myriad of (rhythmic) morphological features. As a result, understanding and forecasting shoreface nourishment morphodynamics and impacts is challenging. Significant progress on this topic is needed in due time, especially in light of emerging climate-change effects. This review paper presents an overview of field, laboratory and numerical modeling studies on shoreface nourishment morphodynamics. We have identified 4 key knowledge gaps. First, the spreading of nourished sand through the coastal zone is poorly understood, and has not been quantified. Second, it is unclear how design variables such as size, placement location and grain-size affect the lifetime, spreading and impact of shoreface nourishments. Third, the cumulative effect of repeated shoreface nourishments (scale: 1–10 km, 1–10 years) on the coastal system as a whole (100+ km, 50+ years) is largely unknown. Fourth, numerical models cannot reliably predict the complete morphological development and impact of shoreface nourishments. To tackle these knowledge gaps we propose a research agenda to ensure the generation and valuation of scientifically robust and societally relevant knowledge.

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1. Introduction

The nearshore coastal zone, in particular sandy beaches and dunes, is important for flood risk management and holds high economic, recreational and natural values. An estimated 15 % of the world's sandy beaches have been retreating on average 1 m/year or more in the last decades (Luijendijk et al., 2018). Climate change, accelerated sea-level rise (SLR) in particular, is expected to further reduce beach width when beaches are backed by human infrastructure that restricts or inhibits retreat (Vousdoukas et al., 2020; Vitousek et al., 2023; Lansu et al., 2024).

Over time, sand nourishments have become a popular management option to mitigate coastal retreat for sites with abundant (offshore) sand supplies. With nourishments, off-site sand is added to the coastal system to replenish sediment budget deficits (Fig. 1). Hence, these are also referred to as sand replenishments or beach fills.

Nourishment can be preferred over hard engineering structures, such as seawalls and breakwaters, if sufficient sediment is available at offshore borrow areas. It is a natural and flexible human intervention that is less disruptive for natural sediment pathways and that positively influences the sediment budget. A negative sediment budget is generally the cause of coastal erosion and the resultant coastal retreat (de Schipper et al., 2020; Bridges et al., 2021). However, just as hard structures, nourishments generally do not eliminate the cause of coastal erosion. This means that nourishments must be repeated, possibly combined with hard structures.

There are different types of coastal nourishments. A distinction can be made between nourishments where sand is placed directly where it is needed, i.e. on the beach and dunes, and nourishments that aim for an indirect effect. In the latter case, the sand is supposed to be transported

Fig. 1. Implementation of shoreface nourishment by spraying a sand-water mixture from the bow of a dredging vessel. Image taken along the North-Holland coast, The Netherlands. © Rijkswaterstaat.

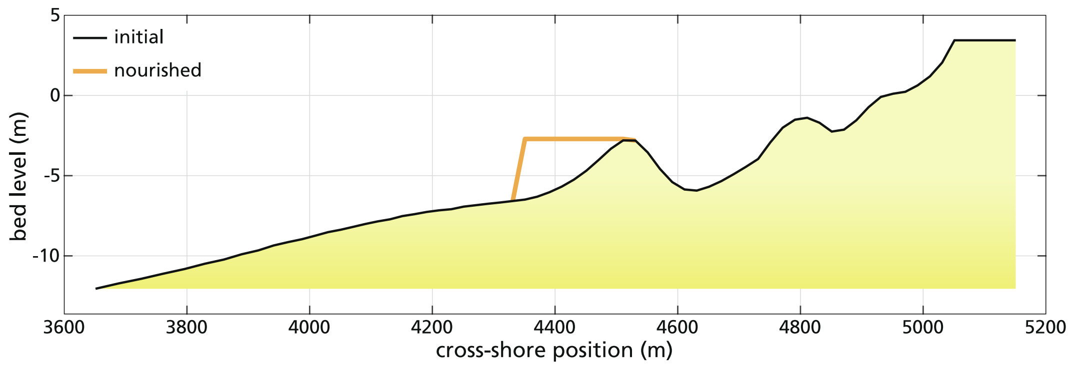

Fig. 2. Initial and nourished cross-shore profile representative for the Egmond coast, The Netherlands. Bed level given with respect to mean sea level. The shoreface nourishment is placed against the offshore flank of the outer bar in water depths of 4–7 m.

to the area of interest utilizing natural transport pathways. These nourishments may also be beneficial by reducing erosional processes and/or promote accretional processes, e.g. by means of additional wave energy dissipation. The most common "direct" type of nourishments is beach nourishment where sand is placed on the above-water (sub-aerial) beach, or just below mean sea-level. Beach nourishments have been carried out regularly since the early 1900s throughout the globe (see de Schipper et al. (2020) for a multidisciplinary overview). Later on, shoreface nourishments emerged. Shoreface nourishments are typically larger than beach nourishments and placed in water depths of 4–10 m (Fig. 2), which simplifies the construction as dredging vessels can navigate towards the location where the sand needs to be placed. The main advantages of shoreface nourishments, compared to beach nourishments, are that they are more cost-effective, have a longer lifetime and cause less disturbance on the beach (van der Spek and Elias, 2013). These shoreface nourishments are hypothesized to act as a feeder berm resulting in widening of the adjacent beach, and dissipate energy of the larger waves reducing the erosional processes (van Duin et al., 2004).

Shoreface nourishments are placed in the nearshore coastal zone, a zone which often has the highest variability in bed levels in the coastal zone (Ruessink and Kroon, 1994; Otto et al., 2021) as well as a myriad of (rhythmic) features (Coco and Murray, 2007). Unraveling and predicting this nearshore zone has been a challenge for decades (Ranasinghe, 2020; Sherwood et al., 2022) and understanding and forecasting human interventions is therefore not trivial.

Since the late 1990s, shoreface nourishment has been common practice in The Netherlands (Spanhoff and van de Graaff, 2007; Brand et al., 2022). Currently, the total volume of shoreface nourishments amounts to 5 million m^3 yearly, which is about 50 % of the total volume of nourished sand (Brand et al., 2022). Thanks to these and other types of nourishments, The Netherlands has dynamically conserved the coastline at its desired position over the past 30 years (Brand et al., 2022). Although less frequent, shoreface nourishments are also placed elsewhere in Europe, e.g. at the island of Sylt, Germany (Gijsman et al., 2018), the west coast of Denmark (see Hamm et al., 2002; Lodder and Sørensen, 2015), Belgium (Dan et al., 2019), France (Hanson et al., 2002) and Portugal (Pinto et al., 2022). These are generally aimed at improving coastal stability, improving coastal protection and increasing beach width (Hamm et al., 2002). In the USA shoreface nourishments are usually referred to as nearshore placements or nearshore nourishments. If the nourishment is constructed as a nearshore mound or bar, it is commonly called a nearshore berm. The placement of dredged sediment near the coast as a submerged mound or elongated bar is a common practice for the beneficial use of dredged sediment along the Pacific, Atlantic and Gulf coasts (Bain et al., 2021). As the fine material is washed out and transported offshore, nearshore nourishments allow for sediment with higher fine content than would typically be allowed for sub-aerial nourishments to be used (Brutsché et al., 2014). In the period 2001–2020, the US Army Corps of Engineers placed 140 million m^3 of sediment dredged from navigation channels in the nearshore during 792 projects (USACE, 2022). Shoreface nourishments have also been carried out in other countries, such as South Korea (Park et al., 2018) and Australia (Jackson and Corbett, 2023). Recent placements in Australia were designed to also improve surfing conditions in the short term.

Projected SLR (IPCC, 2022) requires re-thinking coastal nourishment strategies. This raises coastal policy and management questions, e.g. whether or not the nourishment volumes can be simply upscaled to deal with accelerated SLR. Is the transport capacity sufficient to bring nourished sand onshore? Should the time interval between consecutive nourishments be reduced or the volume per nourishment be increased? At the same time, there is an increasing need to know in more detail how nourished sand spreads to assess impact on habitats (ecological effects) and affects morphological state parameters like shoreline position, beach width and dune foot position. Both require a sound understanding and reliable prediction of the impact and evolution of nourishments. However, a comprehensive overview of advances in research on shoreface nourishment morphodynamics is currently lacking. This is a prerequisite to make significant progress, which is needed in due time, especially in light of the emerging climate-change effects.

This review paper fulfills this need. It describes the advances in research on shoreface nourishment morphodynamics and identifies future research needs based on field studies, laboratory experiments and numerical modeling. Since the first implementation of shoreface nourishments in the 1930s (Hall and Herron, 1950), nourishment performance and beach response have been examined through field observations. With nourishments becoming more and more commonplace, there is a wealth of data available at coastal agencies. These range from a few topographic surveys to more exhaustive studies, reports and practical guidance (e.g. Houthuys et al., 2014; Lodder and Sørensen, 2015; Gijsman et al., 2018; McFall et al., 2021; Brand et al., 2022). In the last decades, the insights obtained on morphological behavior and driving processes have been complemented by laboratory experiments, conducted in a controlled setting, and numerical modeling. We define shoreface nourishments as the sub-aqueous nearshore placement of sediment on wave-dominated coasts. This paper does not consider beach nourishments or large-scale nourishments, such as the Sand Motor (see e.g. Roest et al., 2021), in which also a large portion of sediment is placed on the beach. In addition, nourishments in tide-dominated systems (e.g. van Rhijn, 2019; van der Lugt et al., 2024) or in lakes (e.g. Ton, 2023) are not discussed.

The paper is organized as follows. Section 2 presents an overview of field measurements and laboratory experiments. These are the main sources for our knowledge on shoreface nourishment morphodynamics, discussed in Section 3. These physical processes are schematically represented in different types of numerical models, described in Section 4. In Section 5 we discuss the current knowledge base, leading to the conclusions and future perspectives in Section 6.

2. Overview of shoreface nourishment field campaigns and laboratory experiments

Due to the complex nature of nearshore morphodynamics, understanding and prediction of shoreface nourishment behavior rely heavily on experimental research in both field and laboratory conditions. This section presents an overview of different experimental studies and the range of conditions tested. The findings of these studies will be summarized in Section 3.

2.1. Field campaigns

Well-documented shoreface nourishment field experiments are of great value, but scarce. Such experiments include the interaction with the surrounding changing morphology and are not influenced by scaling effects. However, field experiments and observations are generally expensive and difficult to carry out. Furthermore, it is not possible to control (forcing) variables and keep these stationary. As a result, data from field measurements are generally less accurate and more difficult to interpret than those from laboratory experiments (van Rijn et al., 2013; Ferreira et al., 2023).

Field observations of nourishment projects are often based on bed level observations at varying spatial and temporal resolutions (e.g. van Duin et al., 2004; Brutsché et al., 2014; Pan et al., 2017), remote sensing of the water surface (e.g. Ojeda et al., 2008; Brutsché et al., 2019a) or both (Brutsché et al., 2019b). The bathymetric surveys are usually carried out before construction and afterwards, with an increasing measuring interval as the morphodynamics slow down over time (see e.g. Huisman et al., 2019; McFall et al., 2021). If present, long-term observations with regular bathymetric surveys from a coastal monitoring program (e.g. JARKUS, Rijkswaterstaat, 2024) provide additional data to examine nourishment evolution and their long-term morphological impact (e.g. Radermacher et al., 2018). Recently, satellite images are used to extract shorelines to determine the nearshore morphological response to a nourishment (McGill et al., 2022).

Field observations of transport processes at shoreface nourishments are scarce, since the placement and maintenance of instruments in the surfzone remain challenging. One of the first attempts was made following the 1985 nearshore nourishment at Gold Coast, Austria. This included dive observations using dyed sand to track sand transport (see Jackson and Corbett, 2023). Another rare shoreface nourishment field study is the NOURTEC campaign (Nourishment #22 in Table 2) providing a relatively long, 2.5 year, time-series of hydrodynamic forcing and estimates of suspended sediment transport at the nourishment body and further inshore (Hoekstra et al., 1996; Ruessink et al., 1998).

Concurrent observations of sediment composition and changes are rarely taken, but can provide additional evidence on the spreading of the added sediment. This is illustrated by Barnard et al. (2009) who used 191 bed samples and grain-size analysis to examine the dispersion of a nearshore dredge disposal and its surrounding area at Ocean Beach, San Francisco, California in 2005 (Nourishment #16 in Table 2). The NOURTEC experiment also acquired bed samples before and after construction to map the grain-size evolution (Guillén and Hoekstra, 1996).

2.2. Laboratory experiments

Shoreface nourishment laboratory experiments provide the opportunity to examine effects of different forcing mechanisms and topographic states in an isolated manner. Flow, sand transport and bed level changes can generally be measured with a high level of detail and accuracy. However, the main disadvantage is that laboratory experiments are, by definition, schematized models of only a part of the real physical system.

Table 1 presents an overview of existing shoreface nourishment laboratory experiments. These were carried out in two-dimensional wave flumes (only cross-shore processes) and three-dimensional wave basins that allow for flow circulation, including wave-driven alongshore currents in the oblique-incident wave experiments. Waves were the only forcing mechanism in the laboratory experiments; wind and tide were not considered. All waves were irregular (JONSWAP spectrum), except for in the D2019 study, where waves were monochromatic.

In Table 1, D_{50} is the median grain-size (the same for beach and nourishment, except for G2011), H_{s0} the offshore (significant) wave

Table 1
Overview of existing shoreface nourishment laboratory experiments. Ref = reference, Fac = facility, n = number of experiments.

Ref	Fac	n	D_{50}	H_{s0}	T_p	h_{nour}	H_{s0}/h_{nour}	Ω_D	$\Psi_{w,nour}$
			(mm)	(m)	(s)	(m)	(–)	(–)	(–)
H2010[a]	flume	32	0.32	0.03–0.07	0.9–1.4	0.02–0.15	0.2–3.5	0.6–1.6	2–128
W2010	flume	4	0.13	0.10, 0.17	2.3, 3.0	0.20, 0.25	0.4–0.9	3.3, 7.3	43–151
G2011[b]	flume	15	0.60–0.76	0.06–0.16	1.5–3.0	0.12–0.30	0.2–1.4	1.6–2.4	15–374
J2012[c]	basin	2	0.15	0.12	1.5	0.06, 0.12	1.0–2.0	6.1	104–225
B2016[c,d]	basin	4	0.15	0.17, 0.21	1.5, 3.5	0.06–0.28	0.6–2.8	4.7, 8.5	70–431
S2017a[c]	basin	1	0.15	0.16	1.5	0.10	1.8	6.7	289
S2017b[c,e]	basin	1	0.15	0.18	1.5	0.22	0.7	5.9	89
D2019[f]	basin	9	0.22	0.07–0.16	0.9–1.3	0.20	0.4–0.8	3.3–4.9	7–62
A2020[g]	flume	1	0.30	0.13	1.2	0.12	1.1	2.7	55
K2020[h]	flume	4	0.17	0.04–0.13	1.2–1.8	0.22	0.2–0.6	7.8–17.2	16–225
L2021	flume	2	0.23	0.05	2.0, 2.5	0.06, 0.12	0.4, 0.8	0.7, 0.8	13, 26
L2022	flume	6	0.23	0.16	1.6	0.07–0.22	0.7–2.3	3.3	60–224
L2023	flume	4	0.18	0.15	1.6	0.15, 0.20	0.8, 1.0	5.2	78, 110

H2010: Hwung et al. (2010), W2010: Walstra et al. (2010), G2011: Grasso et al. (2011), J2012: Johnson and Smith (2012), B2016: Bryant and McFall (2016), S2017a: Smith et al. (2017a), S2017b: Smith et al. (2017b), D2019: de Schipper et al. (2019), A2020: Atkinson and Baldock (2020), K2020: Kuang et al. (2020), L2021: Li et al. (2021), L2022: Li et al. (2022), L2023: Larsen et al. (2023).

[a] At least 32 different tests; artificial glass sand ($\rho_s = 2450$ kg/m^3); only bed-level measurements.
[b] The unnourished bed material had a different grain-size (0.41 mm); light-weight sediments ($\rho_s = 1190$ kg/m^3); waxing and waning of five wave conditions for three nourishment designs.
[c] Obliquely-incident waves (10°), pumps were used to match the wave-driven alongshore current.
[d] Concrete bed slope except for the mound.
[e] Also 1 case with the mound at the shoreline was tested.
[f] Monochromatic waves; 3 wave-alone cases, 2 current-alone cases and 4 wave-following current cases; horizontal bed except for the mound.
[g] Also 3 beach/berm nourishments were tested.
[h] Light-weight sediments ($\rho_s \approx 1425$ kg/m^3); also 4 nourishment tests with an offshore reef.

height, T_p the (spectral peak) wave period, and h_{nour} is the initial mean water depth above the nourishment. The Dean number:

$$\Omega_D = \frac{H_{s0}}{w_s T_p} \tag{1}$$

is an indicator of the beach state. Reflective beaches with predominantly bedload transport occur for $\Omega_D < 1$, and dissipative beaches with predominantly suspended load for $\Omega_D > 6$ (Wright and Short, 1984). If the sediment fall velocity w_s was not provided, it was computed using the formula of Soulsby (1997) using a kinematic viscosity $\nu = 1.3 \cdot 10^{-6}$ m^2/s (fresh water at 10^{o} Celsius) and gravity acceleration $g = 9.81$ m/s^2. The wave mobility number at the nourishment was computed in the following way:

$$\psi_{w,nour} = \frac{\hat{u}_{orb}^2}{\Delta_s g D_{50}} \tag{2}$$

with $\hat{u}_{orb}$ the orbital velocity amplitude at the depth of the nourishment according to linear wave theory (based on H_{s0} and T_p) and $\Delta_s = (\rho_s - \rho_w)/\rho_w$ the relative sediment density. We assumed a water density of $\rho_w = 1000$ kg/m^3 and a sediment density of $\rho_s = 2650$ kg/m^3 (quartz sand), unless the values were mentioned in the reference. $\psi_{w,nour}$ indicates the sediment mobility and bedform regime. Ripples are generally present for low wave mobility numbers. If the mobility number exceeds ≈ 200 the ripples are washed out, entering the flat-bed sheet-flow regime (O'Donoghue et al., 2006).

The laboratory experiments listed in Table 1 are all scaled laboratory experiments with relatively small wave heights (< 0.21 m) and periods (< 3.5 s). The wave dynamics are correctly represented through Froude scaling with:

$$n_u = n_T = (n_L)^{0.5} = (n_H)^{0.5} = (n_h)^{0.5} \tag{3}$$

Table 2

Nourishment properties and calculated depth of closure values h_{inner} and h_{outer} for historical projects in the United States (USA) and The Netherlands (NL). V_{nour} = nourishment volume, A_{nour} = nourishment volume per alongshore unit of length, $h_{nour,0}$ = mean pre-construction nourishment depth below mean sea level, $D_{50,nour}$ = median nourishment sediment grain-size, Ref = reference. For some cases the nourishment volume is unknown. A_{nour} could not be computed for cases for which the alongshore nourishment length was not known.

#	Project site	Year	V_{nour} (10^3 m^3)	A_{nour} (m^3/m)	$h_{nour,0}$ (m)	$D_{50,nour}$ (mm)	h_{outer} (m)	h_{inner} (m)	Observed activity	Ref
1	Santa Barbara, CA, USA	1935	154	–	6.1	–	10.2	3.0	Stable	H1950
2	Atlantic City, NJ, USA	1935–1948	2700	–	5.8	–	8.1	5.9	Stable	H1950
3	Long Branch, NJ, USA	1948	460	407	11.6	0.34	4.9	5.5	Stable	H1950
4	New River Inlet, NC, USA	1976	27	178	2.1	0.49	4.3	5.8	Active	S1977
5	Dam Neck, VA, USA	1982	650	–	11	0.08	20.6	5.1	Stable	H1984
6	Fire Island, NY, USA	1987	323	–	4.9	–	13.9	8.2	Active	M1988
7	Sand Island, AL, USA	1987	352	192	5.8	0.22	7.0	6.6	Active	H1990
8	Silver Strand, CA, USA	1988	113	309	4.9	0.20	39.7	8.5	Active	J1990 A1991
9	Humboldt, CA, USA	1988–1989	–	–	15.8	0.23	76.2	15.2	Active	H1991
10	Humboldt, CA, USA	1988–1989	–	–	21.3	0.23	76.2	15.2	Active	H1991
11	South Padre Island, TX, USA	1989	125	102	7.9	–	23.0	8.4	Active	A1992
12	Perdido Key, FL, USA	1991	3000	800	6.0	0.30	5.9	8.3	Stable	O1994
13	Port Canaveral, FL, USA	1992	121	336	6.3	0.40	18.4	7.8	Active	B1994
14	Newport Beach, CA, USA	1992	980	–	5.5	0.09–0.22	22.2	5.1	Active	M1996
15	Brunswick, GA, USA	2003	–	–	6.0	–	13.4	6.1	Active	S2007
16	Ocean Beach, CA, USA	2005–2007	690	–	11.5	0.18	73.4	13.3	Active	B2009
17	Fort Myers, FL, USA	2009	175	109	1.8	0.17	2.3	3.2	Active	B2014
18	Chetco Inlet, OR, USA	1996–2013	277	638	6.4	8.4[a]	12.8	16.1	Active	G2019
19	Vilano Beach, FL, USA	2015	115	639	3.0	0.33	17.3	7.3	Active	B2019
20	Ogden Dunes, IN, USA	2016	107	–	5.5	0.15	5.6	7.5	Active	Y2020
21	Harvey Cedars, NJ, USA	2021	68	158	3.5	0.42	14.2	9.2	Active	M2022
22	Terschelling, NL	1993	2100	476	5.5	0.20	13.9	7.2	Active	K1994
23	Terheijde, NL	1997	900	517	6.5	0.25	12.1	7.2	Active	H2019
24	Katwijk, NL	1998	750	349	6.0	0.25	11.8	6.8	Active	H2019
25	Noordwijk, NL	1998	1300	414	6.0	0.40	10.3	7.2	Active	O2008
26	Egmond aan Zee, NL	1999	900[b]	376	6.5	0.23	13.2	7.3	Active	V2004
27	Scheveningen, NL	1999	1400	453	6.0	0.25	11.4	6.8	Active	H2019
28	Bergen, NL	2000	1000[b]	377	4.5	0.25	12.0	7.9	Active	H2019
29	Terheijde, NL	2001	3000[b]	569	7.0	0.25	11.8	7.4	Active	H2019
30	Camperduin, NL	2002	2000[b]	522	7.0	0.25	13.1	7.6	Active	H2019
31	Noordwijkerhout, NL	2002	2600	375	6.5	0.25	12.3	7.1	Active	H2019
32	Wassenaar, NL	2002	2500	412	6.5	0.25	12.0	7.1	Active	H2019
33	Callantsoog, NL	2003	2300	386	6.5	0.25	11.6	7.0	Active	H2019
34	Zandvoort, NL	2004	1400	278	6.0	0.25	13.1	7.6	Active	H2019
35	Bergen & Egmond, NL	2005	3100[b]	34	6.0	0.25	12.7	6.8	Active	H2019
36	Monster, NL	2005	1000[b]	198	5.5	0.25	12.8	7.4	Active	H2019
37	Bloemendaal, NL	2008	1000	531	6.0	0.25	11.9	6.7	Active	H2019
38	Zandvoort–Zuid, NL	2008	500[b]	191	5.5	0.25	12.1	6.9	Active	H2019
39	Hondsbossche & Pettemer Zeewering, NL	2009	5700[b]	423	8.0	0.25	12.8	7.3	Active	H2019
40	Julianadorp, NL	2009	1300	402	6.5	0.25	11.4	6.4	Active	H2019

H1950: Hall and Herron (1950), S1977: Schwartz and Musialowski (1977), H1984: Hands and DeLoach (1998), M1988: McLellan et al. (1988), H1990: Hands and Bradley (1990), H1991: Hands and Allison (1991), A1992: Aidala et al. (1992), J1990: Juhnke et al. (1990), A1991: Andrassy (1991), O1994: Otay (1994), B1994: Bodge (1994), M1996: Mesa (1996), S2007: Smith et al. (2007), B2009: Barnard et al. (2009), B2017: Brutsché et al. (2014), G2019: Gailani et al. (2019), B2019: Brutsché et al. (2019b), Y2020: Young et al. (2020), M2022: McGill et al. (2022), K1994: Kroon et al. (1994), H2019: Huisman et al. (2019), V2004: van Duin et al. (2004), O2008: Ojeda et al. (2008).

[a] Nourishment material from tidal inlet was predominately gravel.

[b] Measured volume in the first survey was considerably smaller than official nourishment volume (< 90 %).

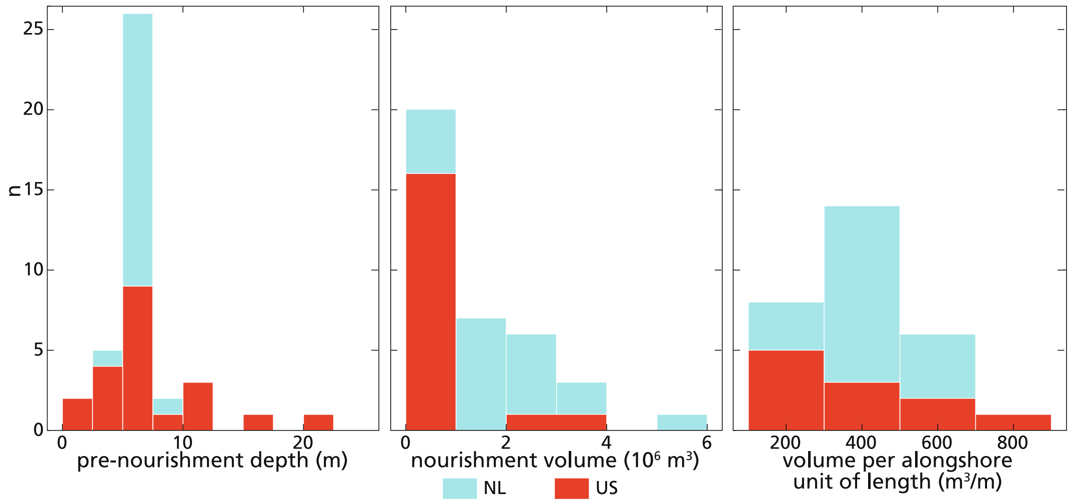

Fig. 3. Properties of historical shoreface nourishment projects in The Netherlands and the United States (see also Table 2): pre-nourishment depth (left, 40 cases), nourishment volume (middle, 37 cases) and volume per alongshore unit of length (right, 30 cases).

where n indicates the ratio between the parameter at prototype and laboratory scale, and u, T, L, H, h the orbital velocity, wave period, wave length, wave height and water depth, respectively (van Rijn et al., 2011). Due to the relatively small wave heights and short periods, Reynolds numbers in scaled laboratory experiments are typically one order of magnitude smaller than in the field. As a result, the near-bed wave boundary layer is less turbulent, which affects the velocity structure.

The laboratory experiments generally use sediment grains with similar size as in field conditions ($\approx 0.1 - 0.3$ mm). In other words, the sediment used is too coarse for the (Froude-scaled) wave conditions, which is reflected in the, generally, relatively low Dean numbers. This impacts the morphology, and beaches tend to steepen in model scale compared to field scale as described by Vellinga (1986) and recently discussed in detail by Bayle et al. (2021). It also means that the wave mobility numbers (and Shields numbers) are not similar between model and full scale, affecting the bedform regime, ripple dimensions and the ratio between bedload and suspended load. As a result, ripples are generally too large compared to the nourishment dimensions in these scaled experiments (Lee et al., 2023).

This was circumvented by Grasso et al. (2011) and Kuang et al. (2020) by using light-weight material. Another solution was to place the shoreface nourishments relatively high in the beach profile, expressed through the wave height/water depth ratio. $H_{s0}/h_{nour} > 0.4$ is very common, indicating the onset of wave breaking (van Rijn, 2013), whereas in field conditions wave breaking at the shoreface nourishment tends to occur only for infrequent, high-wave conditions. These scaling issues must be carefully considered when drawing general conclusions on shoreface nourishment morphodynamics from laboratory

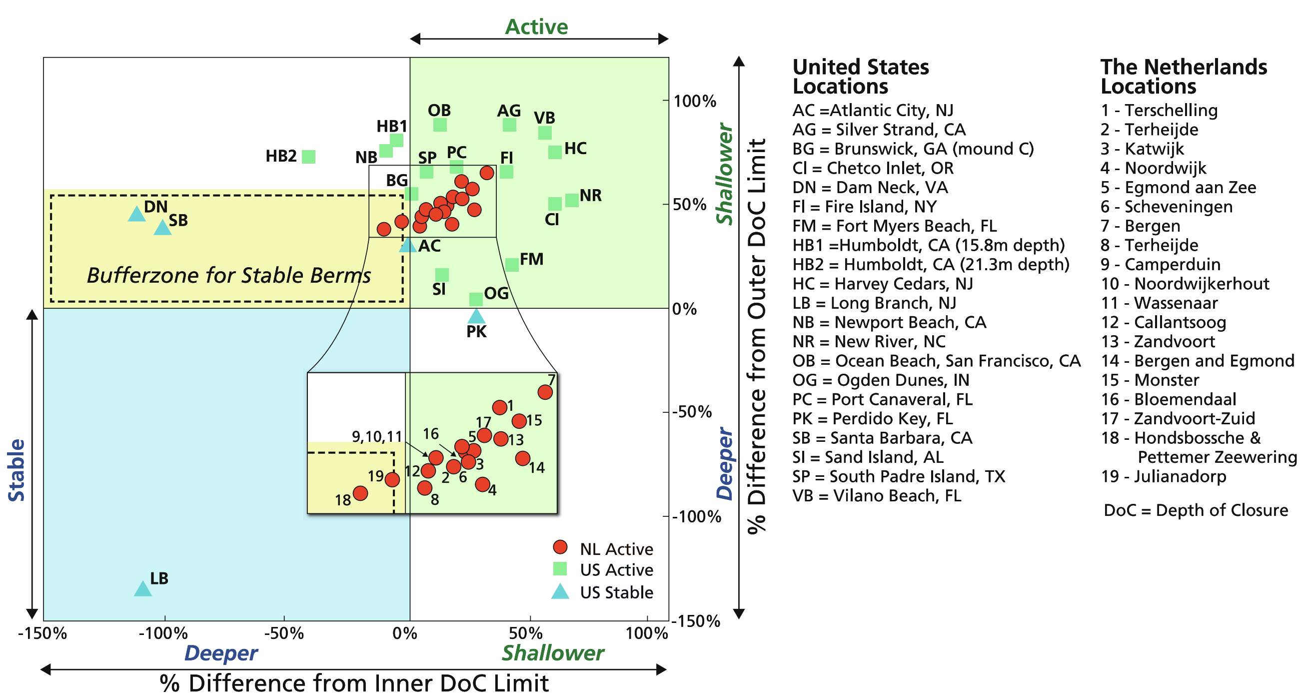

Fig. 4. Classification of historical shoreface nourishment projects into active and non-active nourishment bodies. Axes show the relative elevation in percentages of the nourishment with respect to the empirical depth of closure estimates at the sites (see also Table 2). Figure adapted from Hands and Allison (1991) and McFall et al. (2021) with permission from ASCE.

experiments only.

3. Shoreface nourishment morphodynamics

We start with a discussion of the morphodynamics of the nourishment body itself. The interaction with the surrounding (pre-existing) morphodynamics is discussed in Section 3.2, and the processes driving nourishment morphodynamics in Section 3.3.

3.1. Nourishment body morphodynamics

Shoreface nourishment designs vary widely from one project to the other. A geometric comparison between Dutch and US shoreface nourishments indicates that dimensions and locations within the nearshore vary (Table 2), with typical dimensions spanning volumes of 0–1 and 1–2 million m^3 (for the US and NL cases, respectively) and 300–500 m^3/m, and depths of 5.0–7.5 m (Fig. 3). US projects reported in literature show a much larger range in placement depths (1.8 to 21 m) compared to Dutch cases. Notably, US nourishment volumes are generally an order of magnitude smaller.

A first division in morphodynamic response after implementation can be made by classifying between active and non-active (stable) nourishments, indicating whether or not the nourishment body retains its original volume and placement area or not in the first period after implementation (Hands and Allison, 1991). There is no established threshold to delineate between active and stable nourishments. Here we use a threshold where a nourishment is assessed stable if ≈60 % of the volume is still present in the placement area after approximately two years.

A first estimate of active and non-active behavior can be obtained from the depth of the nourishment body with respect to the empirical inner and outer depth of closure (DoC). Hallermeier (1981) defined the inner DoC as the seaward limit of the littoral zone with intense bed activity caused by ‘extreme near-breaking waves and breaker-related currents’, and the outer DoC as the seaward edge of the shoal zone in which waves have neither strong nor negligible effects on the sand bed. This latter was called the depth of transport by Valiente et al. (2019). The inner DoC, h_{inner}, can be approximated as

$$h_{\text{inner}} = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right) \tag{4}$$

where H_e is the effective wave height exceeded only 12 h/year at the placement depth (transformed from the offshore) and T_e is the associated wave period. The outer DoC, h_{outer}, can be approximated as

$$h_{\text{outer}} = (\overline{H_s} - 0.3\sigma_s)\overline{T_s}\left(\frac{g}{5000D_{50}}\right)^{0.5} \tag{5}$$

where $\overline{H_s}$ is the annual mean significant wave height at the placement depth, $\overline{T_s}$ is the associated wave period, σ_s is the standard deviation of the significant wave height, and D_{50} is the median grain-size of the nourishment sand.

The DoC analysis to determine nourishment activity of Hands and Allison (1991) has been extended here to include a total of 21 historical projects in the USA (McFall et al., 2021), and 19 projects from The Netherlands (Table 2). The 19 projects from The Netherlands used wave hindcasts for five years post-project construction and the 17 projects from the US constructed after 1980 used current WIS (Wave Information Study) wave hindcasts from 1980 to 2023. The 4 US projects constructed prior to 1980 were calculated by Hands and Allison (1991) using 20 years of historical WIS hindcasts. The wave characteristics were transformed to the offshore depth threshold of half the linear wavelength and applied to Eqs. (4) and (5). The calculated DoC values were then normalized by the mean nourishment depth, $(h_{\text{inner}} - h_{\text{nour},0})/h_{\text{inner}}$ and $(h_{\text{outer}} - h_{\text{nour},0})/h_{\text{outer}}$, respectively (Fig. 4). Because the empirical equations for the inner and outer DoCs are based on different parameters, it is possible for the outer DoC to be calculated as shallower than the inner DoC, which occurred for 6 of the 40 projects.

Projects placed deeper than the outer DoC were found to be stable (Fig. 4, bottom half). All the examined nourishment bodies in The Netherlands were active; the mean nourishment depth ranged from 4.5 m to 8.0 m, and all projects were exposed to similar wave conditions as shown by the narrow-banded DoC values. On average, in The Netherlands, 68 % of the initial nourishment volume was found to remain after three years, and the average erosion rate of nourishment volume per alongshore length was found to be 34 m^3/m/yr (Huisman et al., 2019). The US projects ranged by an order of magnitude in nourishment depths (1.8 m to 21.3 m) and DoC values (2.3 m to 76.2 m).

Active shoreface nourishment bodies are reported to migrate onshore or that their center of mass remains nearly stationary over time, despite sediment loss from the placement area. A generic approach estimating this migration is currently lacking, such that cross-shore migration is often estimated based on experience with previous nourishments or natural subtidal bar cyclicity at the site (explored in more detail in Section 3.2.1). Although the vast majority of the scientific literature reports onshore shoreface nourishment migration, Steijn (2005) and Bruins (2016) report on a case study at Ameland, the Netherlands where offshore migration was found. Apart from this single case, there is little evidence that offshore migration is likely. Alongshore migration was observed at some sites (e.g. Grunnet and Ruessink, 2005; Lodder and Sørensen, 2015; Huisman et al., 2018), see also Section 3.3.2.

Cross-shore migration of the top of the nourishment may result in a skewing of the cross-shore profile of the nourishment (Pan et al., 2017), similar to the skewed shape of onshore migrating sandbars (e.g. Elgar et al., 2001). Both video imagery and repeated bed level measurements of the nearshore show that nourished sand typically disperses into the nearshore zone within 4–10 years after its placement (Brand et al., 2022). For nourishments that migrate, bed level measurements reveal a flattening and cross-shore widening of the nourishment body, indicative of the redistribution of sediment (de Sonneville and van der Spek, 2012). Similarly, the breaker zone over the nourishment, indicative of the shallower nourished area visible in imagery data, can be seen to widen and eventually fade over time in video imagery (see e.g. Ojeda et al., 2008; Ruessink et al., 2012). The lateral end sections of the nourishment are occasionally observed to move at a different cross-shore migration speed.

3.2. Impact on nearby morphology

As mentioned above, observations of the cross-shore migration of a nourishment body and its dispersion suggest a strong relation with local morphodynamics and the subtidal bar system in particular. Besides dispersal of the nourished sand, migration of the nourishment body may lead to its merging with a sandbar or the beach. More generally, nourishments have been observed to affect the natural morphodynamics of the entire bar-beach-dune system. Below, we give an overview of studies highlighting such interactions following the (repeated) placement of shoreface nourishments.

3.2.1. Nearshore sandbars

Nearshore sandbars, both in single- and multiple-bar systems, have been found to exhibit net offshore migration (NOM) at different open coast beaches worldwide, where a sandbar is formed near the low-tide shoreline, migrates in the offshore direction through the surf zone and eventually disappears as it migrates further offshore from the surfzone (Ruessink and Kroon, 1994; Shand et al., 1999; Ruessink et al., 2003; de Sonneville and van der Spek, 2012; Walstra et al., 2012; Cohn et al., 2014; Aleman et al., 2017). The entire NOM cycle has been found to last 1–15 years, where the water depth above the bar and the angle of wave incidence have been found to be important factors in the variation in NOM duration (Walstra et al., 2012). As the bar migrates offshore, the

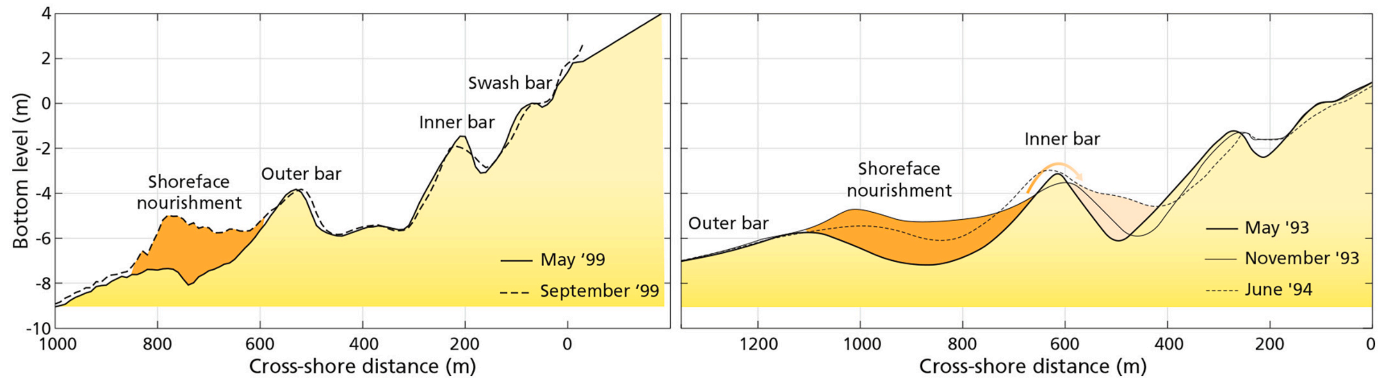

Fig. 5. Examples of placement locations of shoreface nourishments (orange area) in a barred system: (left) more typically against the seaward side of the outer bar (Egmond aan Zee, figure adapted from van Duin et al., 2004) and (right) in the bar trough (Terschelling, figure adapted from Grunnet and Ruessink, 2005). The light orange area in the right panel indicates sedimentation within 1 year as a result of nourished sand transported into the next landward trough (feeder effect) and, possibly, capturing of alongshore-directed sediment (lee-side effect).

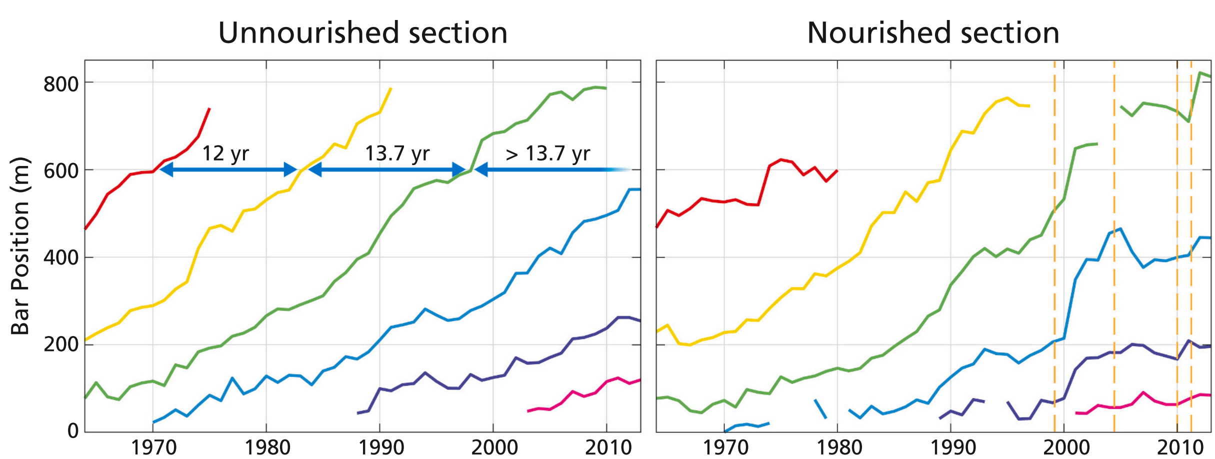

Fig. 6. Cross-shore bar crest positions (positive is in the offshore direction) for the period 1964–2013 at (left) an unnourished and (right) adjacent nourished stretch of the Dutch coast at Egmond aan Zee, The Netherlands (adapted from Haverkate (2020)). The colors indicate the temporal evolution of different bars. The vertical dashed lines indicate the timing of shoreface nourishments.

water depth above the bar increases and the bar grows in volume, until it moves beyond the surf zone, where migration ceases, and the bar volume decreases. Similar to the dispersal of nourishment bodies, the sand of such a decaying bar is gradually redistributed into the nearshore over a period of months to years (Ruessink and Terwindt, 2000), until the bar disappears.

The placement of shoreface nourishments has been observed to temporarily seize or slow down the NOM cycle, through stagnation, or partial reversal, of the offshore migration of one or more sandbars. In multiple bar systems, the response of each bar to the nourishment may be different, depending on the placement of the nourishment with respect to the bar morphology. Shoreface nourishments along the Dutch coast are generally placed against the seaward flank of outer bars (van Duin et al., 2004; Ojeda et al., 2008; Ruessink et al., 2012) (Fig. 5, left). From here, the nourishment either merges with the outer bar, creating a wider and/or shallower outer bar than would be observed in an

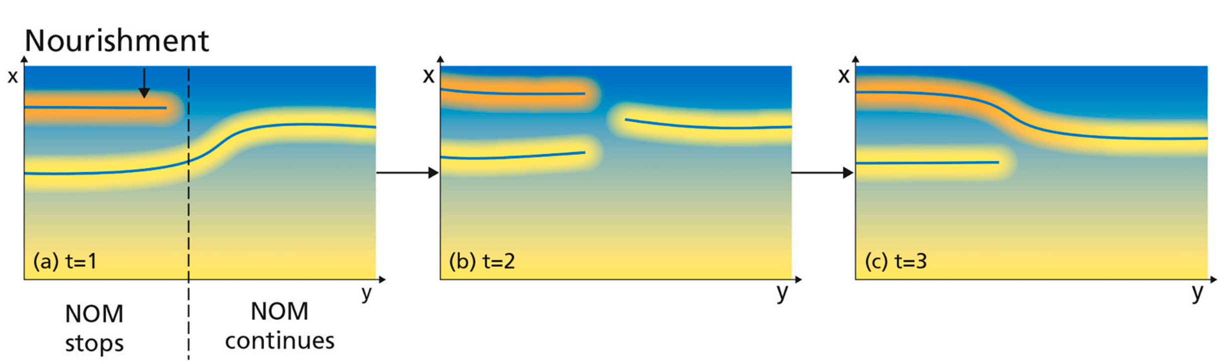

Fig. 7. Schematic overview of a bar switching example through time (t) induced by the placement of a shoreface nourishment seaward of the outer bar, with (a) the nourishment halting the outer bar NOM cycle, (b) a forking of the barline and (c) reattachment of the outer barline to the nourishment. x is the cross-shore direction (positive seaward), y is the alongshore direction. Adapted from Walstra et al. (2015).

unnourished situation (e.g., Fig. 2), or a trough may develop between the nourishment and offshore bar (van Duin et al., 2004; de Sonneville and van der Spek, 2012), in which case the nourishment acts as the new outermost bar (Fig. 5, left). Contrastingly, the NOURTEC nourishment at the Dutch barrier island of Terschelling, was placed in the trough landward of the outermost bar (Fig. 5, right). Here, the outer trough reappeared as the nourished sand moved into the next, more landward trough within the first year after placement (Grunnet and Ruessink, 2005).

Besides the effect on the outer-bar morphology, the placement of a shoreface nourishment has commonly been observed to temporarily stagnate the net offshore migration of the outer bar (e.g., Ojeda et al., 2008; Ruessink et al., 2012). This is typically followed by the stagnation of the inner-bar net offshore migration (e.g., Grunnet and Ruessink, 2005) or temporary onshore migration of the inner bars (van Duin et al., 2004). Once the nourishment has merged with the outer bar and is no longer detectable as a separate morphological entity in the cross-shore profile, the bars resume their offshore migration. This temporary arrest of the NOM cycle following the placement of single shoreface nourishment has been observed to last 4 to 7 years, but may last longer in case of repeated nourishment. The affected NOM behavior becomes more apparent through comparisons with adjacent unnourished sections, as done by Haverkate (2020) and Brand et al. (2022) for the coast at Egmond and Zee, the Netherlands. Time-series of the bar crest positions indicate the slowing down of the NOM in the nourished section, especially after the 2004/2005 nourishment (Fig. 6, right). Moreover, the long-term (≈ 40 years) dataset suggests an increase in the NOM-cycle duration in adjacent non-nourished sections (blue arrows in Fig. 6, left) since large-scale nourishment of the Dutch coast started in 1990.

For coasts with a nearly shore-normal or bimodal wave direction net alongshore bar migration is limited. Here, the morphological impact is restricted to the alongshore extent of the nourishment body. As a result, a discrepancy in cross-shore migration develops in alongshore adjacent areas, where the NOM cycle continues, affecting the alongshore variability of the bar through bar splitting and switching (Walstra et al. (2015); Fig. 7). This, together with the eventual merging of the nourishment with a bar, suggests that bar splitting and switching is a manifestation of nearshore sand redistribution. Such splitting and switching has also been observed at unnourished beaches (e.g. Shand, 2003), but appear more common at nourished beaches (Vermeer, 2021). Bar splitting and switching is likely to interact with alongshore sand transport processes.

For coasts with dominant oblique wave incidence, on the other hand, nourishment placement may temporarily stagnate the alongshore migration of the bar system, until the nourished sand is redistributed into the nearshore and the bar attains its pre-nourishment bar-trough morphology, after which the alongshore migration returns (Grunnet and Ruessink, 2005).

Besides impacting cross-shore bar behavior, nourishments have also been seen to affect the alongshore dimension of bar systems (Ojeda et al., 2011; Radermacher et al., 2018). Radermacher et al. (2018), for example, observed that crescentic patterns rarely developed at the Delfland coast before regular nourishment, but were common once the same stretch of coast was regularly nourished. Along with the crescentic patterns, the potential for rip channels to develop changes through time. Therefore, shoreface nourishments have the potential to affect rip channel development. Following the NOURTEC shoreface nourishment, Grunnet and Ruessink (2005) reported that the 3D bar behavior was enhanced for a period of 2–3 years, because the reduction in water depth caused an increase in wave dissipation and the formation of circulation cells. By tracking individual rip channels in the inner bar through time, Bergsma (2018) concluded that the placement of shoreface (and beach) nourishments at Egmond aan Zee reduced the alongshore migration rates and increased the alongshore spacing of rip currents, with respect to an adjacent stretch of unnourished coast.

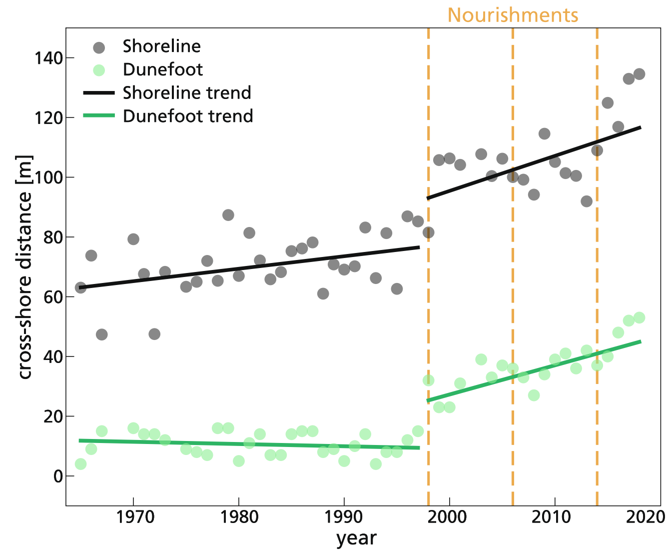

Fig. 8. Shoreline and dunefoot locations in the period 1965–2022 including three shoreface nourishments (vertical dashed lines). Observations from Katwijk aan Zee (The Netherlands). Note that both positions are affected by the nearby beach-dune nourishment constructed between 2013 and 2015. The positive cross-shore direction is seawards oriented. Shoreline position is the average position of the cross-shore position of the bed level between the NAP-1 m and NAP+1 m contour, the dunefoot is the NAP+3 m contour. NAP is the Dutch datum that is approximately equal to mean sea level.

Above observations illustrate how sand nourishment directly affects nearshore morphodynamics, but little is known about the implications of repeated, large-scale nourishment for the morphodynamics of an entire coastal system. Radermacher et al. (2018) observed that a combination of beach and shoreface nourishments along the Dutch Delfland coast led to a state switch from an unbarred coast to a barred coast. This relates to observations from Tătui et al. (2016), where alongshore variations in NOM cycle duration and average beach slope on adjacent sides of the Danube river mouth (Romania) were found to relate to alongshore differences in sediment supply. This suggests that the average number of bars within a cross-shore profile and their NOM cycle may depend on nearshore slope and sediment supply, in addition to, for example, wave climate. As such, repeated shoreface nourishments may indirectly affect the bar system and its NOM cycle through an increased sediment supply of the entire nearshore system.

3.2.2. *Nearshore response*

Shoreface nourishments have been shown to be successful in augmenting the volume of sand landward of their placement on longer timescales. However, there are few field observations that show a direct link between the deformation of an individual shoreface nourishment and the concurrent shoreline change in the year(s) after nourishment. Shoreface nourishments are placed offshore and their effect on the beach is lagging behind and dampened. Natural variability in shoreline positions (e.g. through shoreline features such as sand waves or cusps and storm response) obscure the signal of the nourishment response. This is illustrated by a recent comparative study concluding that only 1 out of 27 analyzed nearshore berm nourishments resulted in a significant increase of the sub-aerial beach in the years after (Brutsché et al., 2014). The low efficiency is underlined by van Rijn (2011), stating that the ratio of initial nourishment volume and sediment increase in the beach zone (−1 to +3 m above mean sea level) due to an individual nearshore berm nourishment is about 2 % to 5 % after 3–5 years. Decadal shoreline data reveals a clearer picture of the shoreline position, where a changing trend (i.e. an increase in the slope of the linear trend line) can be observed in data of beaches that are frequently nourished when compared to the unnourished time periods (e.g. van Koningsveld and

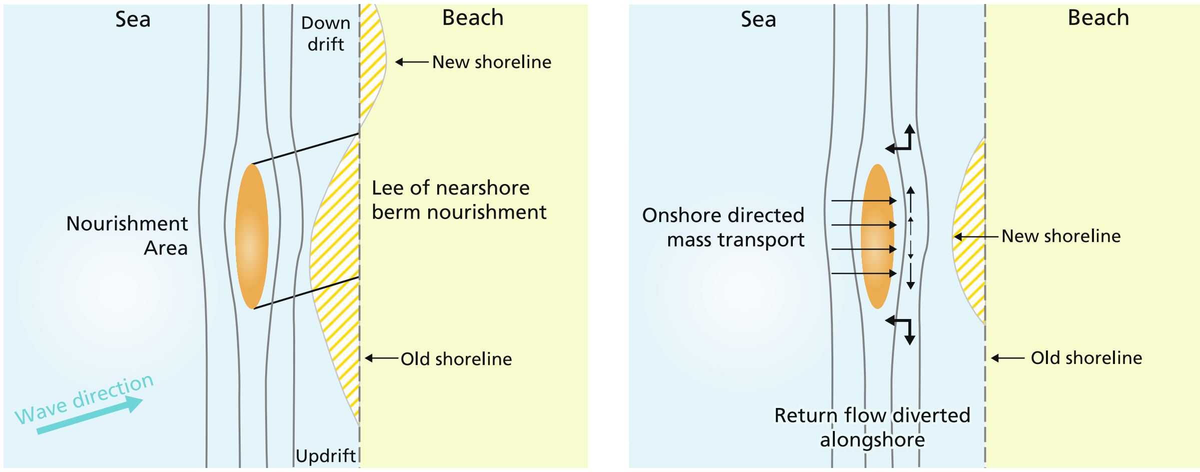

Fig. 9. Schematic figure of the lee-side effect (left) and feeder effect (right) on the nearshore sediment volume. Figure adapted from Onnink (2020), based on van Duin et al. (2004).

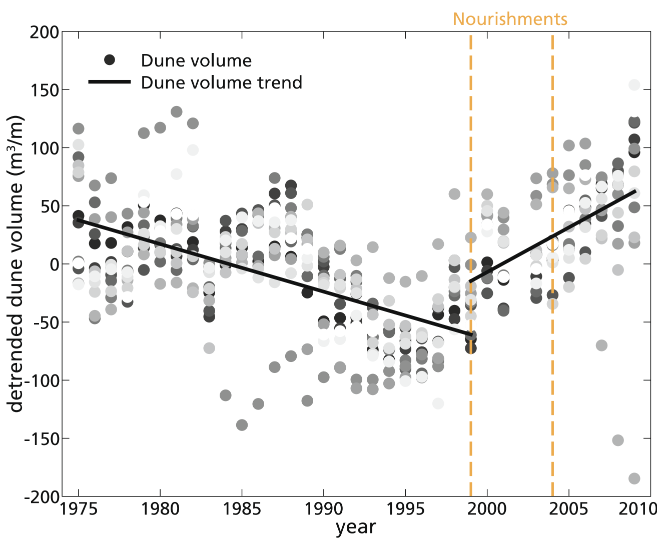

Fig. 10. Dune volume change in the period 1975 to 2009 along a 3-km stretch of coast between Egmond and Bergen (the Netherlands). The gray dots represent values for 13 locations alongshore with a 250-m spacing, where lighter (darker) tints represent locations more to the south (north). Linear regression lines are fitted through all points for the period before and after the first shoreface nourishment (vertical dashed line) in 1999, after temporally detrending the dune volumes from Arens (2010) for each alongshore location.

Mulder, 2004; Löhr, 2024), Fig. 8.

It is postulated that the (shoreline) accretion behind a shoreface nourishment is related to two different mechanisms: the lee-side and feeder effect (Fig. 9). The lee-side effect (also known as reef or breaker bar effect) relates to increased wave dissipation over the nourishment, which influences both cross-shore and alongshore sediment transport, resulting in updrift sedimentation and downdrift erosion (Fig. 9, left). As shoreline signals are often small or absent, a volumetric metric is usually chosen, such as the sediment volume landward of the nourishment (e.g. Hoekstra et al., 1996) or the sediment volume within the so-called MKL zone (cross-shore profile between ≈ 3 m above and 5 m below mean sea level, see e.g. Brand et al., 2022). When observations reveal a volumetric response in the cross-shore profile near the shoreline that is larger than the change in the nourishment body, this is seen as a sign of the lee-side effect (e.g. Hoekstra et al., 1996). The feeder effect refers to the ability of the nourishment to adjust the cross-shore redistribution of sediment (e.g. Grunnet et al., 2004) and results in accretion behind the nourishment body (see Section 3.3 for more details).

3.2.3. Dunes

Observations of the increased volume of the dune after the implementation of a single shoreface nourishment is often troubled by natural variability and other natural interventions. On decadal scale however, nourished sections have been observed to gain sediment volume in the first dunerow (Fig. 10). Furthermore, sections of coast with more nourishments display larger gains in dune volume, as found by Arens (2010) in a study examining both beach and shoreface nourishments. The response of shoreline and increase in sediment in the subtidal zone may impact the sub-aerial beach and dunes through two mechanisms. First, an increase in beach width and change in the intertidal zone may result in an increase in aeolian sediment transport towards the dune, through the fetch effect and change in sediment supply, respectively (e.g. Wijnberg et al., 2021). Second, the increase in sediment volume lower in the profile reduces storm impact on the (embryonic) dunes. These combined effects can yield a seaward migration of the dunefoot (Fig. 8, green symbols).

The sediment composition of the nourishment and in particular the shell content can be of importance for the year to year variations in sediment transport on the subaerial beach. Observations at beach nourishments have revealed that sediment transport may be largest in the first year and reduced in the years thereafter as the beach surface becomes armored with shell fractions (van der Wal, 2004; Hoonhout and De Vries, 2017).

Some attempts have been made to directly link the origin of accreted material at a nourished beach with the added material. Ground-penetrating radar data in combination with bed level surveys can for instance be used to establish the origin of sedimentary elements within the beach-foredune area. Bakker et al. (2012) examined the beach at Bergen aan Zee, The Netherlands over the period 1990–2008. This site was heavily nourished, including beach, shoreface and dune face (‘embankments’) nourishments, resulting in a net accretion of approximately 200 m^3/m. The accreted foredune and beach consist of nourishment embankments (20 %), wind-blown units derived from nourished sand (70 %), and progradational beach deposits (10 %). Bakker et al. conclude that almost all sand nourished before 2000 has been washed away, related to the 1999 storm surges. The relative longevity of post-2000 nourishments was attributed to the combination of the shoreface nourishments in 2000 and 2005, and favorable meteorological conditions.

3.3. Processes driving nourishment morphodynamics

Processes responsible for shoreface nourishment morphodynamics are similar (to a certain extent) to those driving nearshore bar dynamics. Over time, the nourished sand becomes part of the natural/bar system as the nourishment disperses. Shoreface nourishments morphodynamics are a manifestation of migration of the nourishment body (i.e. advection) and diffusion of its shape (decay or dispersion of sediments). The dynamics are determined by the nourishment body itself (height, cross-shore width and length), the depth at which it is placed, the median grain-size of the sediment used and the hydrodynamic forcing. The current section examines the different processes individually. These are further discussed in Section 5.2.

3.3.1. Hydrodynamic drivers

Waves are the main driver for nourishment dynamics. As waves propagate from deep water onto beaches, their surface form and orbital water motion deform from sinusoidal to higher but shorter wave crests and longer but less deep wave troughs. This is referred to as wave or orbital velocity skewness (see Ruessink et al., 2012). Further onshore, waves increasingly pitch forward, with a steep front face and a gentle rear face; the so-called saw-tooth waves. This is referred to as wave asymmetry or acceleration (time-derivative of orbital velocity) skewness (Hoefel and Elgar, 2003). Due to the non-linear relation between sand transport and orbital velocity/bed shear stress both wave skewness and asymmetry generally promote net sand transport in the direction of wave advance (onshore), see van der A et al. (2013). This is thought to contribute to the previously mentioned feeder effect (Section 3.2.2).

These short waves (2−25 s) induce long, infragravity (IG) waves (25−250 s) due to wave groupiness and associated radiation stress gradients (bound long waves). IG waves may also be generated by a time-varying break point in case of irregular waves (Bertin et al., 2018). In the shoaling and surfzone the IG wave amplitudes are small compared to short waves. The phase difference between the IG waves and the short wave envelope can result in net cross-shore sediment transport. An out-of-phase coupling is typically seen seaward of the breakpoint leading to a small net transport in the offshore direction (Ruessink et al., 1998; Aagaard and Greenwood, 2008). Further landward, the phase relation is more complicated (de Bakker et al., 2016).

Short waves also drive wave-averaged currents. Outside the surf zone (non-breaking waves), these are generally small (Ruessink et al., 1998). There is typically a near-bed offshore-directed current to compensate for the onshore-directed mass flux higher up the water column (Stokes drift) (Reniers et al., 2004). In the wave bottom boundary layer, very close to the bed (< 0.05 m), there is generally a small onshore-directed current; the Longuet-Higgins (1953) wave streaming. For breaking waves there is a relatively strong seaward wave-averaged current near the seabed (undertow) due to radiation stress gradients (van der Werf et al., 2017). Wave breaking also injects turbulence into the water column which enhances mixing of momentum and sediment, especially in the case of plunging breakers (Aagaard and Jensen, 2013). This leads to relatively large offshore-directed net sand transport in the vicinity of the breakpoint.

The presence of a shoreface nourishment can lead to horizontal circulations with an onshore current at the middle section of the nourishment that feeds offshore currents at the lateral sides (van Duin et al., 2004; Huisman et al., 2019), see Fig. 9, right panel. Analogous to the generation of rip currents, wave breaking is relatively stronger on top of the nourishment, compared to the deeper sections directly next to it. This results in more set-up, and the water level gradients drive the horizontal circulation. Nourishments with shorter alongshore length typically experience higher losses (Huisman et al., 2019), which has been attributed to a larger relative importance of the lateral end sections and the horizontal flow circulation patterns.

Tidal and wind-driven currents are generally of second-order importance (Grunnet et al., 2004; Chen and Dodd, 2019). There are indications that the vertical tide results in more onshore migration and skewing of shoreface nourishments, as the waves during low tide situation have a larger impact than during high tide (Chen and Dodd, 2019).

3.3.2. Cross-shore and alongshore processes

The majority of the volume losses in the placement area are in most cases attributed to cross-shore transport (e.g. Huisman et al., 2019; Bain et al., 2021). The dominant importance of cross-shore processes is analogous to breaker bar dynamics (Ruessink and Kuriyama, 2008). It is enhanced for shoreface nourishments with an alongshore extent much larger than the cross-shore extent, which is typically the case in The Netherlands (Brand et al., 2022).

Alongshore effects include the generation of an alongshore current and sand transport in the surf zone in case of obliquely-incident waves. These are likely enhanced by the presence of a shoreface nourishment (decreased water depth), leading to alongshore transport gradients providing a mechanism for alongshore nourishment migration. Relatively speaking, shorter nourishments experience a larger impact of the alongshore transport, which mainly acts at the lateral ends (Huisman et al., 2019). At locations where alongshore migration or alongshore variability in the nourishment body is observed, asymmetry of tidal flows (e.g. due to a nearby inlet) or unidirectional waves (e.g. due to blocking of waves due to structures or an ebb tidal delta) and associated large alongshore sand transport are hypothesized to play a role (Lodder and Sørensen, 2015; Bruins, 2016; Dan et al., 2019).

Next to the angle of wave incidence, the relative importance of cross-shore and alongshore sand transport processes is largely controlled by the placement depth. In relatively shallow water, onshore from the breaker bar (inner surfzone), alongshore currents and sediment transport are relatively large and nourishments decay fast (Johnson and Smith, 2012; Bryant and McFall, 2016; Huisman et al., 2019; Bain et al., 2021).

According to Walstra et al. (2012), the breaker bar amplitude response is particularly sensitive to the water depth above the bar crest and the angle of wave incidence. These variables largely control the amount of waves breaking on the bar and the strength and cross-shore distribution of the associated alongshore current. If the alongshore current has its maximum landward of the bar crest, it induces additional stirring of sediment on the landward bar slope and trough. The enhanced sediment concentration in the trough region shifts the cross-shore transport peak landward of the bar crest, forcing bar amplitude growth during offshore migration. For increased water depth above the crest, wave breaking becomes less frequent, reducing the influence of the alongshore current on sediment stirring. Therefore, the resulting dominance of the cross-shore current results in a sediment transport peak at, or just seaward of, the bar crest causing bar amplitude decay. It is likely that a shoreface nourishment is affected in a similar fashion by the water depth and wave angle, although this has not been confirmed in the literature.

The lee-side effect relates to increased wave dissipation over the nourishment, which influences both cross-shore and alongshore sediment transport. The smaller waves near the shoreline generate less stirring of the sediment and a decrease of the wave-induced return flow, reducing offshore-directed transport. An extreme example is the wave dissipation and beach erosion reduction due to a 14.3 million m^3 nearshore mound at Haeundae Beach, Korea during the 2016 Typhoon Chaba (wave heights up to 13 m) (Park et al., 2018). Alongshore currents are also reduced by the calmer wave climate behind the shoreface nourishment area, as a result of which alongshore transport decreases, resulting in updrift sedimentation and downdrift erosion (see van Duin et al., 2004; Pinto et al., 2022). The feeder effect refers to the ability of the nourishment in supplying its nourished sediment directly to the beach by the cross-shore redistribution of the sediment due to non-linear wave effects and horizontal circulations (see also Section 3.3).

Larsen et al. (2023) concluded that sand placed on the offshore side of the bar or on the bar crest is more efficient in protecting the shoreline than a bar trough nourishment. The bar nourishment caused waves to break earlier compared to the trough nourishments, and at the same time probably resulted in reduced undertow strength in the inner surf zone. This conclusion should not be generalized, as the nourishment only acted as a sheltering mechanism, i.e. there was no significant feeder effect. It is noted that this conclusion of Larsen et al. (2023) is based on relatively small-scale cross-shore only laboratory experiments (see Table 1).

The lee-side effect has mostly been attributed to nourishments placed at larger depth for which the nourishment body itself is active during storm conditions only (e.g. Zwamborn et al., 1970). The feeder function is hypothesized to fit shallower placed nourishments (e.g. Onnink, 2020; Mendes et al., 2021). The feeder effect of a nourishment may take place in different ways from a morphodynamic point of view; from a gradual (small flux) onshore movement of grains (Jackson and Corbett, 2023) to the migration of the entire nourishment crest in the direction of the wave propagation similar to SPAW bar features. SPAW, Shoreward Propagating Accretionary Wave, is a bar-like feature shed from the nearshore bar that travels onshore as an intact form (Wijnberg and Holman, 2007).

3.3.3. Process controlling migration and dispersion of the nourishment body

Both laboratory and field studies have made attempts to link processes and design elements (e.g. nourishment position and crest level) to migration and dispersion rates. Although a generic relationship has not been presented yet, the different studies reveal an important connection between migration and dispersion of the nourished sands and the aforementioned processes.

The net offshore bar migration on the time-scale of years (NOM) is the result of gradual onshore movement during calm periods and an episodic strong offshore movement during storms (see e.g. van Enckevort and Ruessink, 2003; Walstra, 2016). This is mainly attributed to the dominant onshore wave-related transport during calm conditions, and offshore-directed transport during storms, related to wave breaking and undertow. This balance between onshore- and offshore-directed transport components is subtle as a result of which shoreface nourishment bodies are observed to migrate or remain nearly stationary over time (see also Section 3.1). The data (e.g. Ojeda et al., 2008) and model (e.g. van Duin et al., 2004; Huisman et al., 2019) studies that focused on shoreface nourishments placed seaward from the outer bar generally indicate a net onshore shoreface nourishment migration, due to the dominant effect of wave skewness and cell-circulation patterns. Huisman et al. (2019) found that the onshore feeding from shoreface nourishments especially occurred during storm conditions ($H_{s0} \geq 3$ m). This could be linked to wave breaking needed to generate the horizontal circulation cells with onshore-directed currents at the nourishments. According to the modeling study of Chen and Dodd (2021) the onshore-directed wave streaming contributes significantly to net sand transport under non-breaking waves, contributing to onshore nourishment migration.

Eventually, in case of high(er) waves and/or fine sand, undertow is postulated to dominate the sediment transport direction causing the nourishment to migrate offshore (Larson and Kraus, 1992). The field experiments of Larson and Kraus (1992) suggest that for conditions with the Dean number (Eq. 1) larger than 7.2, undertow dominates the sediment transport direction causing the sediment to migrate offshore. Otherwise, for lower Dean numbers, wave skewness and cell-circulation patterns are proposed to dominate the hydrodynamics, resulting in onshore migration (Larson and Kraus, 1992). To validate the study, the criteria were tested for a nearshore berm at Silver Strand, California where it successfully predicted the onshore migration behavior of the nearshore berm (Larson and Kraus, 1992). Nowadays, this simple methodology based on Dean number is commonly used when designing a nearshore berm to estimate the cross-shore transport direction of grain-size fractions for poorly sorted sediment placed in the nearshore (Brutsché et al., 2019a).

The laboratory findings of Jacobsen and Fredsøe (2014) show that nourished sediment placed in the trough of a breaker bar increases offshore transport because of strong local erosion in the nourished sediment. Nourishing directly on the seaward side of the breaker bar yields a smaller loss of sediment to offshore relative to the reference profile. Furthermore, they concluded that a high and narrow nourishment placement seaward from the breaker bar protects the pre-nourished profile more than a wide and low nourishment.

Bed slope effects are partly responsible for the horizontal diffusion of shoreface nourishment. These are generally more important when the nourishment deforms analogous to a breaker bar with a relatively steep onshore slope (van der Zanden et al., 2017). Also the natural tendency to restore the equilibrium bed profile perturbed by nourishments leads to nourishment diffusion (van Leeuwen et al., 2007; Larson and Hanson, 2015; Chen and Dodd, 2019; Bain et al., 2021).

Deeper placed nourishments are primarily diffusive with limited migration (van Leeuwen et al., 2007; Smith et al., 2017a, 2017b; Chen and Dodd, 2019). According to van Leeuwen et al. (2007) nourishments with a larger alongshore scale (of the order of 1 km) decay much more slowly than shorter scale nourishments (of the order of 100 m). According to Chen and Dodd (2019) diffusion/migration is more prominent for higher/lower wave heights and shorter/longer wave periods. Alongshore migration of the nourishment body has been found to depend strongly on the variation in angle of wave incidence (Grunnet and Ruessink, 2005). For example, along the Holland section of the Dutch coast where the wave climate is bi-directional, alongshore migration is found to be limited, whereas at other sections where waves dominantly approach the coast under an angle, an alongshore migration of the nourishment body was observed.

3.3.4. Grain-size effect

Typically, sediment is used for nourishments that matches with the native sediment, but this is not always the case (e.g. at Terschelling and Noordwijk coarser sand was used, Guillén and Hoekstra, 1996; Ojeda et al., 2008). In the US, many states allow sediment with more fine material to be placed in the nearshore than is allowed to be placed on the sub-aerial beach (American Shore and Beach Preservation Associate and Coastal States Organization, 2023).

The grain-size distribution plays an important role in deeper water outside the active zone, where finer fractions are much more easily mobilized and suspended (Huisman et al., 2018). In more shallow water, grain-size mainly affects suspended load transport; bedload is only weakly dependent (van Rijn, 2007). Finer grains favor more suspended load, as a result of which the total net transport is modified.

According to Guillén and Hoekstra (1996), the nourished bar trough re-appeared and the grain-size distribution across the profile was nearly the same as the original one after six months. The average grain-size in the nourished area returned from 0.20 mm to its pre-nourishment value of 0.17 mm. The fact that the disturbance of the initial sediment composition was small is likely to have affected the recovery.

4. Numerical modeling

In this section, an overview is provided of the numerical modeling studies of shoreface nourishments focusing on 1) their aims, 2) the environmental conditions that were investigated, and 3) the approaches. This includes a description of how well the models were able to reproduce measured shoreface nourishment morphodynamics. An overview of the 15 modeling studies of the last 20 years we have identified is provided in Tables 3 and 4.

4.1. Aims of the studies

Initially, the modeling studies aimed to hindcast observed morphodynamic behavior (van Duin et al., 2004; Grunnet et al., 2004). A precise prediction of the spreading of nourished sand would help in the decision-making process. In practice, however, these simulations could

Table 3
Overview of the environmental conditions in shoreface nourishment modeling studies. The light gray shading indicates that the characteristic listed in column 1 is applicable.

Characteristic	V04	G04	G05	V07	J14	L15	P18	C19	H19	B21	C21	J21	L21/L22	C22	K24
Domain															
cross-shore profile	■		■		■	■		■			■		■	■	■
coastal area	■	■		■			■		■	■		■			
Bathymetry															
realistic	■	■	■		■	■	■		■	■	■		■	■	
idealized				■				■				■			■
Nourishment depth															
outside active zone						■				■					
seaward from bar crest	■				■	■			■	■					
bar crest								■			■			■	
bar trough		■	■			■				■		■			
elsewhere in active zone/no bars				■			■	■		■		■	■		■
Nourished sediment															
fine (< 0.20 mm)						■				■					
medium (0.20-0.50 mm)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Forcing															
tide	■	■	■						■						
wind		■	■												■
moderate waves ($H_{s0} < 3$ m)	■	■	■	■	■	■		■	■	■	■	■	■	■	■
energetic waves ($H_{s0} \geq 3$ m)		■	■	■			■		■		■	■		■	■

V04: van Duin et al. (2004), G04: Grunnet et al. (2004), G05: Grunnet and Ruessink (2005), V07: van Leeuwen et al. (2007), J14: Jacobsen and Fredsøe (2014), L15: Larson and Hanson (2015), P18: Park et al. (2018), C19: Chen and Dodd (2019), H19: Huisman et al. (2019), B21: Bain et al. (2021), C21: Chen and Dodd (2021), J21: Johnson et al. (2021), L21/L22: Li et al. (2021, 2022), C22: Chen et al. (2022), K24: Kettler et al. (2024).

Table 4
Overview of the modeling approaches in shoreface nourishment modeling studies. MA = modeling approach: 1 = practical model, 2 = behavior-oriented model, 3 = simplified cross-shore model, 4 = wave-averaged SWE model, 5 = intra-wave CFD model. Ref = reference, SD = spatial dimensions, 1DH = one-dimensional horizontal (cross-shore), 2DH = two-dimensional horizontal (cross- and alongshore), 2DV = two-dimensional vertical (depth-resolving cross-shore). SWE = shallow water equations, RANS = Reynolds-averaged numerical simulations, VoF = Volume of Fluids, AD = advection-diffusion model for suspended sand, MC = morphodynamic coupling, QV = quantitative validation, Y = yes, N = no.

Ref	MA	SD	Hydrodynamics	Sediment transport	MC	QV
V04	3	2DV	wave energy balance + quasi-3D current model based on horizontal momentum balance	AD + bedload formula	Y	Y
	4	2DH	wave action balance + wave-averaged SWE	AD + bedload formula	Y	Y
G04	4	2DH/3D	wave action balance + wave-averaged SWE	AD + bedload formula	Y	Y
G05	3	2DV	wave energy balance + quasi-3D current model based on horizontal momentum balance	AD + bedload formula	N	N
V07	4	2DH	wave energy balance + wave-averaged SWE	total load formula	N	N
J14	5	2DV	wave-resolving RANS-VoF	AD + bedload formula	Y	N
L15	2	1DH	not resolved	not resolved	Y	Y
P18	5	2DH	wave-resolving RANS	AD + bedload formula	Y	Y
C19	3	1DH	wave energy balance + analytical current formulations	analytical formulations	N	N
H19	4	2DH	wave action balance + infragravity wave-resolving SWE	AD accounting for bedload	N	Y
B21	1	2DH	simple wave formula; currents not computed	total load formulas	N	Y
C21	3	1DH	wave energy balance + quasi-2DV current model based on horizontal momentum balance	analytical formulations	Y	Y
J21	4	2DH	wave energy balance + wave-averaged SWE	suspended load formula	Y	N
L21/L22	3	2DV	wave energy balance + wave-averaged SWE	AD + bedload formula	Y	Y
C22	4	1DH	wave action balance + infragravity wave-resolving SWE	AD accounting for bedload	Y	N
K24	2	1DH	not resolved	not resolved	Y	Y

V04: van Duin et al. (2004), G04: Grunnet et al. (2004), G05: Grunnet and Ruessink (2005), V07: van Leeuwen et al. (2007), J14: Jacobsen and Fredsøe (2014), L15: Larson and Hanson (2015), P18: Park et al. (2018), C19: Chen and Dodd (2019), H19: Huisman et al. (2019), B21: Bain et al. (2021), C21: Chen and Dodd (2021), J21: Johnson et al. (2021), L21/L22: Li et al. (2021, 2022), C22: Chen et al. (2022), K24: Kettler et al. (2024).

not confidently resolve the predominantly cross-shore morphological changes of shoreface nourishments. For that reason the model aims were adjusted and the focus was shifted towards obtaining understanding of the relative importance of transport processes and environmental conditions for the observed morphological changes (e.g. Grunnet and Ruessink, 2005; Huisman et al., 2019).

Later, CFD (Computational Fluid Dynamics) models were applied to carry out simulations that cover a few hours of morphological change on cross-shore profiles (Jacobsen and Fredsøe, 2014), or - using a less advanced model - a 1 day storm event for a coastal stretch of about 2 km (Park et al., 2018). The models did provide more insight into the relative importance of some processes, although static bathymetries were also used rather than dynamically hindcasting the nourishment morphodynamics to keep computation times within practical limits.

Instead, other studies made the situation less complex by means of exploring the morphological changes of cross-shore profiles with idealized analytical formulations (Chen and Dodd, 2019), which then focused on obtaining understanding of the initial response of nourishments and its relation to geometrical and hydrodynamic conditions. Design rules were derived by Larson and Hanson (2015) using a theoretical/analytical approach for specific situations with rather diffusive morphological changes of nourishments under non-breaking wave conditions, so effectively providing answers for very specific subsets of situations. A different approach was chosen by Bain et al. (2021) who separately compute alongshore and cross-shore sand transport to estimate nourishment decay rates. Kettler et al. (2024) presented a behavior-oriented model aimed to evaluate nourishment strategies by simulating the decadal-scale response of coastal volume, shoreline position and beach width to repetitive nourishments.

4.2. Environmental conditions

The modeled conditions differ in terms of domain, bathymetry, depth of placement, sediment of the nourishment and hydrodynamic conditions (waves, tide and wind), see Table 3.

Some studies modeled the nourishment on a cross-shore profile, assuming alongshore uniformity, while other studies modeled coastal areas including the alongshore dimension as well. Note that van Duin et al. (2004) applied both methods. Most studies used bathymetric measurements including shoreface nourishments, which provides the advantage that results can be compared with the actual observed coastal area/profile changes. A few studies have idealized the profile shape to reduce the complexity. van Leeuwen et al. (2007) and Chen and Dodd (2019) used a linearly sloping beach with a super-imposed nourishment, whereas Johnson et al. (2021) used a more natural curved profile shape. Kettler et al. (2024) initialized their model with a multi-year average measured profile obtained from the JARKUS dataset. There were no breaker bars present in the studies by van Leeuwen et al. (2007), Park et al. (2018), Chen and Dodd (2019), Johnson et al. (2021) and Kettler et al. (2024).

The studies modeled nourishments in deep water, outside the active zone (i.e. offshore from the inner DoC) as well as in the active zone at various locations relative to the bar crest. Some used reconstructed or measured wave time-series (e.g. as in Johnson et al., 2021), and others a wave climate that is representative for the morphological changes (e.g. as in van Duin et al., 2004). Tide and wind were also accounted for in some studies, either as forcing (e.g. Grunnet et al., 2004) or through a parameterized sediment exchange term with the dune area (Kettler et al., 2024).

A median sediment grain size of 0.2 – 0.3 mm was taken in most of the model simulations, which resembles actual nourishments in The Netherlands (see Table 2). In the US the used sediment can, however, also be fine sand (≈0.15 mm) or coarser sand (≈0.40 mm), which is discussed in Bain et al. (2021).

4.3. Modeling approaches

Table 4 presents an overview of modeling approach in shoreface nourishment modeling studies. We distinguish between five categories:

1. Practical models in which nourishments decay rates are inferred from sand transport rates computed with relatively simple sand transport formulations (Bain et al., 2021).
2. Behavior-oriented models to optimally simulate the cross-shore morphodynamics without resolving the underlying physics (Larson and Hanson, 2015; Kettler et al., 2024).
3. Cross-shore models with relatively simple wave and current solvers and sand transport formulations (van Duin et al., 2004; Grunnet and Ruessink, 2005; Chen and Dodd, 2019, 2021; Li et al., 2021, 2022).
4. Wave-averaged SWE models. These are based on a wave solver coupled to the (hydrostatic) shallow water equations (SWE), applied to a cross-shore beach profile (1DH) or a coastal area, usually in a depth-averaged way (2DH). Sand transport is computed by solving the advection-diffusion (AD) equation (van Duin et al., 2004; Grunnet et al., 2004; Huisman et al., 2019; Chen et al., 2022), supplemented with an empirical bedload formula. The idealized models adopt more simple, semi-empirical transport formulations (van Leeuwen et al., 2007; Johnson et al., 2021).
5. Intra-wave non-hydrostatic CFD models (Jacobsen and Fredsøe, 2014; Park et al., 2018). These solve the Reynolds-averaged Navier-Stokes (RANS) equations for the hydrodynamics and AD for suspended sand. Similar to the other approaches, bedload follows from an empirical formula.

It is noted that the vertical dimension is only resolved in 5 out of the 15 model studies, and that a significant amount of studies (8) only considered the cross-shore dimension.

4.3.1. Practical models

In the modeling approach of Bain et al. (2021) the alongshore and cross-shore net sand transport are computed separately using empirical formulas, based on offshore hindcast wave characteristics transformed to the nearshore. The alongshore and cross-shore transport rates are then superimposed to generate a total transport rate for the nourishment footprint. It is assumed that the nourishment acts exclusively as a sediment source, so zero sediment is added to the control volume at the upcurrent boundaries. These estimates of the nourishment decay rates were compared to data from 11 US field sites covering a wide range of conditions. The mean relative error was 72 %, and 45 % of the cases were predicted within a factor of 2 difference.

4.3.2. Behavior-oriented models

Larson and Hanson (2015) provided a cross-shore profile model with a relatively simple bedload transport formula in which transport direction depends on the deviation from the equilibrium bed slope. It was assumed that the nourishment is a disturbance of the equilibrium profile. The 1D Exner equation for morphological evolution was solved analytically and numerically including an empirically-fitted diffusion coefficient. The model agreed reasonably well with measured trends in bed levels at four shoreface nourishment sites, although the infilling of the adjacent, landward trough was overpredicted. The model only accounts for nourishment diffusion (no migration), which is a reasonable assumption in deep water (see Section 3.3.3). This bedload-only model is useful for a first estimation of time-scales of nourishments (with lengths much greater than their widths) placed in deep water with non-breaking waves.

Following the same principle, Kettler et al. (2024) developed the diffusion-type model named Crocodile (*Cross-shore Coastal Diffusion Long-term Evolution model*), building on the work of Stive et al. (1991). The model accounts for many processes including SLR and sediment exchange with the dunes. Crocodile showed a good reproduction of decadal trends in coastal volumes (overestimation of 10 %) and beach width (underestimation of 15 %) at Monster, Katwijk and Egmond, The Netherlands in response to different nourishment strategies. As the model is stationary forced, the model's outcomes represent the ‘climatology’ of the simulated coast and provide the anticipated ‘annual average’ value for a given coastal indicator at a particular time. The model cannot compute specific details of the cross-shore profile shape on short timescales. It includes a large number (14) of free parameters that need to be based on observations, numerical modeling and/or expert judgment. Furthermore, the equilibrium cross-shore profile needs to be known. This means that the model might be overfitted and is not universally applicable.

4.3.3. Cross-shore models with relatively simple solvers and formulations

Cross-shore models assume alongshore uniformity and do not include horizontal residual circulations. Unibest-TC is a relatively simple and computationally fast cross-shore model. The vertical distributions of the mean currents and suspended sand concentrations are computed locally and semi-empirically. It has been applied to shoreface nourishments by van Duin et al. (2004) and Grunnet and Ruessink (2005). The model of van Duin et al. (2004) was able to reproduce the outer bar detachment from the nourishment and, to some extent, the shoreward bar movement. However, the model overpredicted the sediment volumes in the inner surf zone.

Chen and Dodd (2019) developed a cross-shore profile model that accounts for sand transport due to wave skewness, asymmetry, undertow and bed slope effects in a schematized manner. This was done in a more parametrized way than the Unibest-TC approach, as the vertical structures of mean currents and suspended sand concentrations were not resolved. However, unlike Unibest-TC, the model by Chen and Dodd includes net sand transport related to wave asymmetry (acceleration-skewness). The model describes nourishments as a perturbation on the equilibrium profile, similar to Larson and Hanson (2015), in which only bed slope effects contribute to nourishment diffusion. It was not shown whether the no-nourishment case was indeed in equilibrium according to the model; the computed transport rates suggest that this was not the case.

The model was extended to include Longuet-Higgins boundary layer streaming and depth-varying mean return flow, and to arbitrary wave incidence angles in the follow-up study by Chen and Dodd (2021). The model was applied to the Terschelling 1993 nourishment in the bar trough (see Table 2). Recorded wave and tide signals were used to drive the model to simulate six months of the initial nourishment evolution. The observed overall migration rate was well described by the model. The details of the profile evolution showed a moderately good reproduction of those observed (Brier Skill Score = 0.52).

Li et al. (2021) reproduced the onshore nourishment migration measured in a small-scale lab experiment (see Table 1) with the CROSPE model. However, in a later study the model failed to reproduce the onshore migration for more energetic wave conditions (Li et al., 2022).

4.3.4. Wave-averaged SWE models

van Leeuwen et al. (2007) investigated the morphological evolution of a shoreface nourishment by interpreting the nourishment as a linear perturbation of the natural system. The idealized model is restricted to normal wave incidence, alongshore periodic nourishments placed at 4–8 m water depths on an alongshore uniform, plane beach. Most simulations were forced with energetic wave conditions (significant wave height of 3 m that only occur about 2 days per year in The Netherlands), which means that the nourishment decay is overestimated.

van Duin et al. (2004) and Grunnet et al. (2004) developed 2DH and 3D schematizations of shoreface nourishments using the Delft3D software (Lesser et al., 2004). The separation of the shoreface nourishment from the outer bar and the shoreward migration of the bars was not well captured, although the model did capture some of the sedimentation directly shoreward from the nourishments (van Duin et al., 2004). The beach morphology in general, and the breaker bars in particular, were flattened unrealistically according to the model by Grunnet et al. (2004). The models did have skill in predicting volume changes integrated over larger spatial scales. The 3D model did not perform much better than the 2DH model.

Huisman et al. (2019) modeled nourishments using XBeach (Roelvink et al., 2009), which (unlike Delft3D or Unibest-TC) resolves the long, infragravity waves explicitly in a depth-averaged modeling framework. Huisman et al. (2019) presented an efficient modeling approach using a look-up table filled with computed initial erosion–sedimentation rates for a range of potential environmental conditions at a single post-construction bathymetry. A data-model comparison showed that this approach can be used to accurately assess the erosion rates of shoreface nourishments at 19 NL sites (Table 2) in the first 3 years after construction.

Johnson et al. (2021) carried out numerical experiments utilizing the Coastal Modeling System. The idealized nourishments were placed in depths between 3 m and 7 m with a volume of approximately 100,000 m^3 and between 400 m and 1000 m in alongshore length on idealized cross-shore profile without breaker bars. The model not only showed dissipative shoreface nourishment behavior, but also some onshore migration, which is an improvement compared to the work by van Duin et al. (2004) and Grunnet et al. (2004). The model qualitatively reproduced the deflation of the 2015 nearshore berm at Vilano Beach (Table 2).

Chen et al. (2022) used a XBeach profile model (1DH) of a so-called “green nourishment”, considering a case with a nourishments with sea grass on top of it. The considered nourishment is rather high-up in the profile and on top of the bar. This is the zone where alongshore wave-driven currents act, but this was not captured by the cross-shore profile approach. The model showed sensitivity of the computed morphodynamic evolution to the presence of the nourishment and sea grass; no validation with field or experimental data was carried out.

4.3.5. Intra-wave non-hydrostatic CFD models

Jacobsen and Fredsøe (2014) modeled shoreface nourishment dynamics using a fully-coupled intra-wave 2DV morphodynamic model, implemented in OpenFOAM. The hydrodynamics were described by the RANS equations with a k-ω turbulence model and the Volume of Fluid (VoF) approach for discriminating between air and water. Sediment transport was computed by solving the advection diffusion equation for suspended load, augmented by a bedload formula. A net current over the cross-shore profile was introduced in some simulations to mimic the modifications that occur to the velocity field close to the bed when either a vertical re-circulation is enforced by the wind or there is a system of rip channels. Wave forcing was regular. The morphological development over 480 s took several weeks computation time.

Park et al. (2018) modeled the impact of a typhoon on a nearshore mound using a wave-resolving 2DH XBeach non-hydrostatic model. The morphological development over 12 h took 30 h computation time.

5. Discussion

5.1. Field observations and laboratory experiments

Field observations have provided important insights in the morphological development of shoreface nourishments and the surrounding nearshore morphology. Observational studies are mostly based on bed level observations. Next to increasing our understanding of nourished coastal beaches, these observations are essential for calibrating and testing prediction tools. However, it can be difficult to interpret the nourishments response due to natural variability and concurring other human interventions. Furthermore, the conditions are not controlled, making it even harder to identify and quantify the physical mechanisms that drive shoreface nourishments morphodynamics.

More recently, these field data have been complemented by laboratory experiments. These offer the opportunity to examine effects of changing forcing and topography in an isolated manner, and bed levels and sand transport processes can be measured relatively accurately. We have identified 13 shoreface nourishment laboratory data sets (Table 1). The sediment used is generally too coarse in these Froude-scaled experiments with relatively small wave heights and periods. As a result, the sand transport processes and morphodynamics in model scale are different from the field. Furthermore, most laboratory experiments focus on bed levels. There is limited data of the underlying sand transport processes, especially at the intra-wave scale. Such data is required to understand and parameterize detailed sand transport processes, and to validate phase-resolving numerical models.

5.2. Shoreface nourishment morphodynamics

A first estimate of shoreface nourishment morphodynamics can be obtained from the depth of the nourishment body with respect to the empirical inner and outer depth of closure (DoC) of Hallermeier (1981). Data from 40 field sites (Table 2) generally confirm that nourishments are stable if $h_{\mathrm{nour}} > h_{\mathrm{outer}}$, and active if $h_{\mathrm{nour}} < h_{\mathrm{outer}}$ (Fig. 11). Herein, a nourishment was assessed stable if ≈ 60 % of the volume was still present in the placement area after approximately two years. The choice for this stability criterion is somewhat arbitrary, which will mainly affect

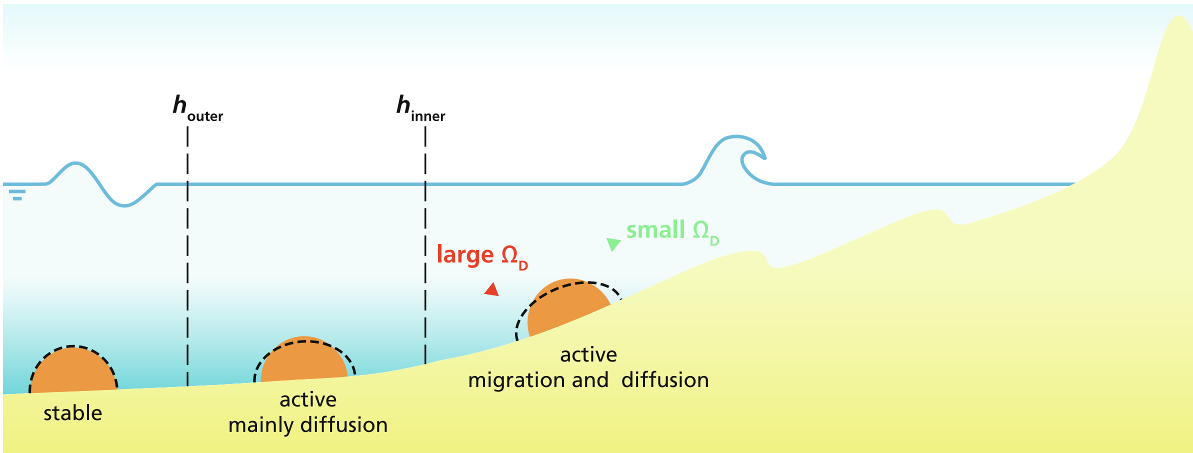

Fig. 11. Conceptual model of the cross-shore shoreface nourishment morphodynamics. A nourishment body is stable, mainly dispersive or displays both migration and dispersion, depending on the placement depth relative to the inner and outer depth of closure. Main drivers for cross-shore migration are breaking-induced sediment suspension and offshore-directed undertow, and onshore-directed transport related to wave skewness and horizontal circulation. The Dean number, Ω_D, is an indicator for the relative importance of these competing transport mechanisms.

the classification of nourishments placed near h_{outer}. Furthermore, the nourishment data base was biased with only 5 stable nourishments out of 40 cases. It also "only" includes data from NL/US project sites. It is recommended to extend this analysis with different kind of cases.

Shoreface nourishments morphodynamics are a manifestation of advection (migration) and dispersion (decay). The dynamics are determined by the nourishment geometry (height, cross-shore width and length), the depth at which it is placed, the median grain-size of the sediment used and the hydrodynamic forcing conditions. We hypothesize that the relative importance of migration and dispersion is mainly determined by the placement depth compared to the inner DoC. Dispersion of the nourished sand is estimated to be dominant for $h_{nour} > h_{inner}$ and migration for $h_{nour} < h_{inner}$ (Fig. 11).

These DoC calculations were derived based on data from unnourished coasts, but later proved to be applicable to nourished beaches too (e.g. Marsh et al., 1998). The equations only consider wave characteristics ignoring (alongshore) currents, which can be dominant, particularly near tidal inlets. Sediment characteristics are included only in the outer DoC definition.

Migration of active nourishment is mostly in the cross-shore

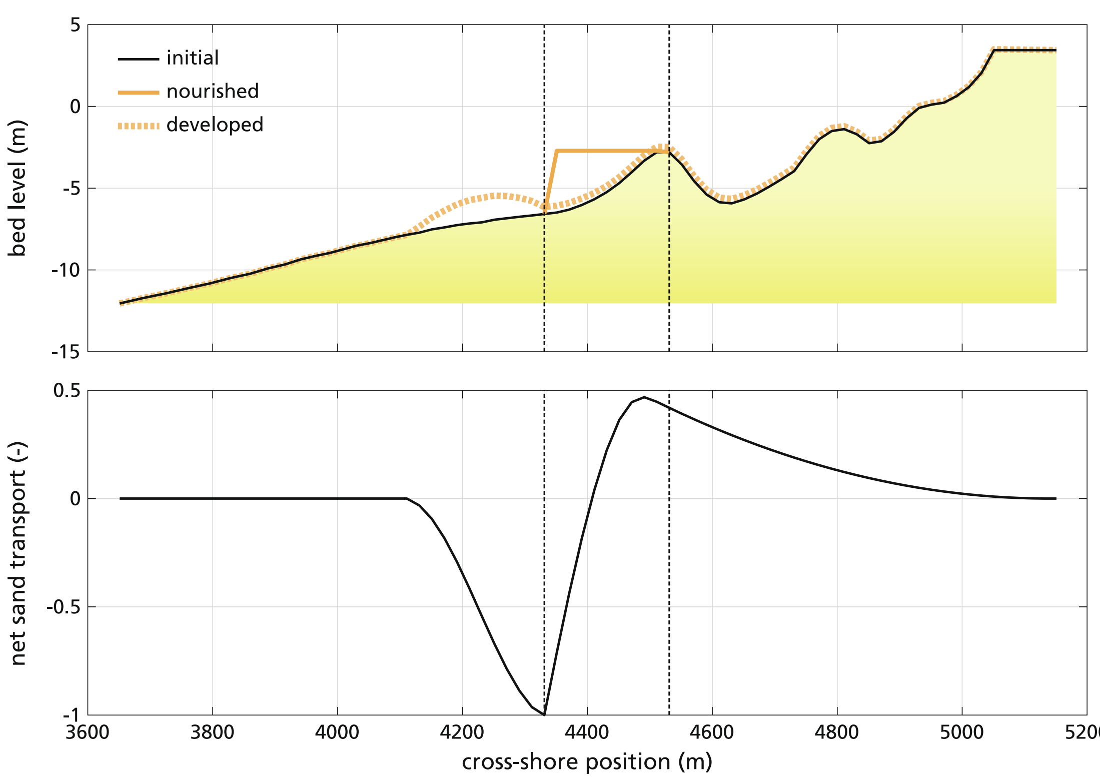

Fig. 12. Top panel: initial and nourished cross-shore profile representative for the Egmond coast, The Netherlands, as well as an imaginary developed profile. Bottom panel: net cross-shore transport (dimensionless) derived from integration of the mass balance equation from the nourished and developed bed profiles. The vertical dashed lines indicate the initial nourishment contours. The figure illustrates that a significant portion of nourished sand can be transported in the onshore direction, despite an offshore migration of the nourishment body.

direction. The alongshore migration is generally limited, except when waves have a dominant oblique angle of incidence, tidal currents are relatively strong (e.g. near a tidal inlet), and/or the wave climate is calmer (e.g. due to coastal structures). The relative importance of alongshore migration also depends on the nourishment location relative to the location of the (outer) breaker bar. Nourishments placed onshore from the breaker bar (inner surfzone) experience relatively stronger wave-driven alongshore currents and, consequently, alongshore migration than nourishments placed offshore from the breaker bar (outer surfzone). The latter is (more) common coastal management practice, hence there is a bias towards observations of cross-shore nourishment behavior. A complicating factor is that often alongshore migration is obtained by calculating displacement of the alongshore centre of gravity of the nourishment body. Using this metric, lateral variations in cross-shore redistribution (e.g. stronger erosion at one of the end sections) may falsely suggest alongshore migration of the nourishment body as a whole. Evidence for relationships between alongshore migration and tidal conditions, wave climate and nourishment location is based on a limited number of cases, which calls for further research.

We hypothesize that the Dean number, defined as the wave height divided by the fall velocity times the wave period (Eq. 1), can be used as a first estimate of the preferential cross-shore migration direction. For high Dean numbers wave-breaking and offshore-directed undertow is postulated to dominate sand transport causing nourishments to migrate offshore. Otherwise, for lower Dean numbers, wave skewness and cell-circulation patterns are proposed to dominate the hydrodynamics, resulting in onshore migration. Larson and Kraus (1992) proposed a threshold value of 7.2 for cross-shore bar migration. It is yet to be studied how universal this value is. Furthermore, this relatively simple cross-shore balance does not explicitly account for the fact that in the field the undertow is likely to be weaker, since the onshore-directed mass flux can also partly move in the alongshore direction (Fig. 9).

To include the beach slope effect on net sand transport, and hence migration direction, one can consider to use the slope-corrected version of the Dean's parameter developed by Hattori and Kawamata (1980). This correction improved the correlation with the direction and magnitude of surfzone sediment transport as measured by Dionísio António et al. (2023). Furthermore, we expect a dependency of nourishment migration rate and possibly direction on how far the initial beach profile is out of equilibrium (Eichentopf et al., 2019; Larsen et al., 2023).

It is important to note that an off−/onshore migration of the nourishment body does not imply that all nourished sediment is transported in the off−/onshore migration. This is illustrated in Fig. 12. In this imaginary case, inspired by the Egmond coast, The Netherlands, all sediment stays within the cross-shore profile (i.e. no alongshore loss/gain, no transport across the on- and offshore boundaries). Net cross-shore sand transport follows from integration of the mass balance equation, assuming constant bed porosity. These assumptions are generally violated in reality. As furthermore bed level measurements have an inaccuracy of at least 0.1 m (de Schipper et al., 2016), it is very hard/impossible to derive net transport rates from bed surveys in the field. For this purpose, laboratory experiments are needed.

It is not straightforward to determine the lifespan of shoreface nourishments. Over time, the nourished sand spreads over a large area and bed level changes are of a similar magnitude as measurement inaccuracies. Also, at least in The Netherlands, the impact of a single shoreface nourishment is hard to isolate from other, nearby beach and shoreface nourishments. Furthermore, there are different ways of defining nourishment lifetime. Brand et al. (2022) estimated (active) shoreface nourishments in The Netherlands to have a (measurable) effect on the sediment volume within the so-called MKL zone for 4 – 10 years. Bain et al. (2021) determined decay rates for 11 historical nearshore berms along the US coast based on the percentage of original sediment volume removed from the initial footprint for periods ranging from 1 month to 3.5 years. For the active nourishments, decay rates ranged between 50 and 1180 m^3/day, corresponding to lifespans of 0.3 – 12.3 years (average 4.1 years) assuming a linear trend. Bain et al. were able to partly explain this large variation using empirically computed transport rates (see also Section 4.3.1), which indicates a dependency of nourishment lifespan on wave conditions, placement depth, nourishment geometry and grain-size.

5.3. Shoreface nourishment impact

Shoreface nourishments strongly interact with the subtidal bar system. Nourishments placed offshore from the outer bar temporally slow down, halt or sometimes even reverse the natural offshore migration of one or more sandbars. This effect can last for multiple years, in line with the nourishment lifespan. The original offshore bar migration is resumed when the nourishment merges with the outer bar or has migrated far offshore and diminished in size.

The nearshore shoreface nourishment impact is largely controlled by

Table 5
Pros and cons per numerical model category based on studies from the period 2004–2024.

Category/reference	Pros	Cons
Practical models		
Bain et al. (2021)	- computationally cheap	- highly empirical
	- along- and cross-shore processes	- no morphological feedback
		- essential transport processes missing - only useful to estimate nourishment decay
Behavior-oriented models		
Larson and Hanson (2015)	- computationally cheap	- highly empirical
Kettler et al. (2024)	- inclusion of many relevant processes - reproduction effects on coastal state indicators	- cross-shore only - only useful for annual average morphodynamics
Simplified cross-shore models		
van Duin et al. (2004)	- computationally cheap	- alongshore uniformity
Grunnet and Ruessink (2005)	- process-based	- simplified expressions for waves/current/sand transport
Chen and Dodd (2019)	- reproduction of breaker bar morphodynamics	- parametrization of intra-wave processes
Chen and Dodd (2021)		
Li et al. (2021, 2022)		
Wave-averaged SWE models		
van Duin et al. (2004)	- process-based	- parametrization of intra-wave processes
Grunnet et al. (2004)	- along- and cross-shore processes	- difficulty with reproducing cross-shore morphodynamics
van Leeuwen et al. (2007)	- quantitative comparisons with field data	
Huisman et al. (2019)		
Johnson et al. (2021)		
Chen et al. (2022)		
Intra-wave CFD models		
Jacobsen and Fredsøe (2014)	- process-based	- computationally expensive
Park et al. (2018)	- wave-resolving	- limited quantitative validation

the so-called lee-side and feeder effect (Fig. 9). Unraveling the contribution of the two mechanisms is difficult due to the variability in shoreline data. It is hypothesized that the lee-side effect is more important for beaches with unimodal oblique waves and deeper placed nourishments, and the feeder effect for shallower placed nourishments. The latter is in line with the increased importance of nourishment migration (Section 5.2). The feeder effect is partly due to a horizontal circulation with an onshore current at the middle section of the nourishment that feeds offshore currents at the lateral end sections of the nourishment. As a result, part of the nourished sand is transported in the offshore direction and this "loss" is relatively stronger for nourishments with shorter alongshore lengths.

The effect on the shoreline position lags behind the actual shoreface nourishment, and is damped. Natural variability in shoreline position, and possibly other human interventions, further obscure the signal of the nourishment response. As such, it is very hard to observe a direct link between deformation of an individual shoreface nourishment and shoreline change. However, the positive effects of the large-scale, long-lasting (since 1990) nourishment strategy in The Netherlands, with preferential shoreface nourishments, on the coastline were clearly demonstrated by Brand et al. (2022). The average shoreline retreat (MKL position) of 0.6 m between 1970 and 1990 was reversed to an advance of 42 m for the period 1990–2020. More recently, Löhr (2024) concluded that shoreface nourishments from 1999 onwards contributed most (compared to beach nourishments) to the shoreline expansion at the Egmond-Bergen section, Holland coast (50 m of the total 76 m between 1985 and 2023).

This beach volume increase is also beneficial for frontal dunes, mainly because aeolian transport increases due to a larger fetch (beach width) and sediment supply. Observations of the relation between dune volumes and nourishments are even more troubled by natural variability and other natural interventions than for beach volumes. Nevertheless, decadal scale nourished coastal sections in The Netherlands have been observed to increase dune volumes.

5.4. Numerical modeling

We have categorized 15 numerical model studies from the period 2004–2024 into five groups. The pros and cons of these model categories are presented in Table 5. Please note that these do not necessarily apply to all individual studies listed per category.

The practical model by Bain et al. (2021) can be used to get a first, quick estimate of nourishment decay rates at sites where sediment transport has not been extensively characterized and prior shoreface nourishment data are not available. The approach does not account for some essential transport processes such as undertow and morphological feedback, and the highly empirical nature hampers the general validity.

Behavior-oriented models (can) include many relevant processes, e.g. sediment exchange between the beach and dunes (Kettler et al., 2024). It is an efficient approach to reproduce effects of long-term nourishment strategies on coastal state indicators such as beach width and dune volume. Alongshore processes are not included, and specific details of the cross-shore profile shape on shorter than yearly time-scales (e.g. storm effects) are not computed. Unresolved physical processes are accounted for in a schematized manner with site-specific input parameters, which might not be readily available.

Although slower than the previous model categories, the relatively simple cross-shore models are computationally fast compared to wave-averaged SWE and intra-wave CFD models. In particular, the Unibest-TC model was able to reproduce observed onshore/offshore bar migration during mild/energetic wave conditions, as well as overall migration in the offshore direction accompanied with growth and decay (Ruessink et al., 2007; Walstra et al., 2012). Importantly, despite the assumption of alongshore uniformity, the alongshore current and associated sediment stirring is accounted for, which controls whether a bar grows or decays while migrating (Walstra et al., 2012). Such a strong validation case is yet to be made for shoreface nourishments, although Li et al. (2021) reproduced the onshore nourishment migration for a small-scale lab case. This model approach only works for alongshore uniform cases, i.e. for nourishments with (alongshore) lengths much greater than (cross-shore) widths. The relatively simple governing equations include empirical, crude parametrizations to account for unresolved intra-wave processes, such as wave-related sand transport, which are key to cross-shore shoreface nourishment morphodynamics.

The same applies to wave-averaged SWE models, which are also referred to as engineering morphological models, such as Delft3D (Lesser et al., 2004) and XBeach (Roelvink et al., 2009). These process-based models can include both alongshore and cross-shore processes. Model studies have made quantitative comparisons to field data, mostly bed levels. So far, these models were not successful in reproducing cross-shore shoreface nourishment morphodynamics. The underlying causes remain unclear. We hypothesize it is related to the (over)simplification of subtle (intra-)wave processes such as wave breaking, undertow and velocity skewness, and too strong numerical diffusion that tends to flatten out nourishments.

There is a limited use of wave-resolving CFD models to study shoreface nourishments. This approach is computationally expensive, allowing sometimes only cross-shore processes to be studied for now. The work by Jacobsen and Fredsøe (2014) showed promising results, but lacks a quantitative validation using observation data. The potential of such models is confirmed by Marchesiello et al. (2022) who were able to reproduce on−/offshore breaker bar migration during mild/energetic wave conditions as measured in the so-called LIP laboratory experiments (Roelvink and Reniers, 1995) using their CROCO (Coastal and Regional Ocean Community) model.

The limited ability to simulate shoreface nourishment morphodynamics might also be related to the so-called "morphological spin-up" (Wang and van der Werf, 2017). At the beginning of the simulation, model results may be unrealistic, and only after a certain period the model gives meaningful results. This is due to model errors (incomplete description of physics, numerical errors, inaccurate model input), as a result of which models require an initial adaption/spin-up period. The main causes and time-scales of the spin-up are yet unknown, and solutions are lacking.

Until now, aeolian contributions and marine-aeolian interactions are largely ignored in shoreface nourishment modeling studies, despite their relevance (see Figs. 8 and 10). The Delft3D-SWAN-AeoLiS coupling framework presented by van Westen et al. (2024) showed good agreement with the aeolian and marine volumetric development of the Sand Motor mega nourishment. This model approach could be developed and tested further in order to better understand and predict the morphodynamic response to nourishments across the land–water divide.

6. Conclusions & future perspectives

6.1. State-of-the-art

The knowledge of shoreface nourishment morphodynamics is based on field measurements and, since the last two decades, lab experiments and numerical modeling. We have identified 13 small-scale lab studies, mostly carried out in flumes (i.e. cross-shore only) and focusing on bed level development. We have described 15 numerical model studies covering a wide range of approaches and applications. None of these could successfully hindcast the complete morphological development and impact of shoreface nourishments. Yet, these were - to same degree - able to reproduce shoreface nourishment morphodynamics on a more aggregated scale, and to identify the relative importance of hydrodynamic drivers, sand transport processes and nourishment characteristics.

A first estimate of shoreface nourishment morphodynamics can be obtained from the depth of the nourishment body relative to the closure depths of Hallermeier (1981). Nourishments in deep water are stable, nourishments in intermediate depths are active and mainly diffusive, whereas nourishments in shallow water show both migration and diffusion. The observed migration of active nourishments is mostly in the onshore direction. Shoreface nourishments strongly interact with the subtidal bar system. Nourishments placed offshore from the outer bar temporally slow down, halt or sometimes even reverse the natural offshore migration of one or more sandbars. Shoreface nourishments augment the volume of sand landward of their placement due to the so-called lee-side and feeder effect. Repetitive shoreface nourishment increase the beach volume on longer time-scales (decades), which is also beneficial for frontal dunes.

6.2. Knowledge gaps

Based on the overview of studies on shoreface nourishment morphodynamics, we have identified the following key knowledge gaps:

1. The spreading of nourished sand through the coastal zone is poorly understood, and has not been quantified. This applies in particular to the sediment exchange between the sub-aqueous and sub-aerial parts of the beach.
2. It is unclear how design variables such as size, placement location and grain-size affect the lifetime, spreading and impact of shoreface nourishments.
3. The cumulative effect of repeated shoreface nourishments (scale: 1–10 km, 1–10 years) on the coastal system as a whole (100+ km, 50+ years) is unknown.
4. Numerical models cannot reliably predict the complete morphological development and impact of shoreface nourishments.

6.3. Proposed research methodology

To tackle these knowledge gaps we propose a research methodology that consists of field measurements, laboratory experiments and numerical modeling. These are complementary research activities. Field measurements capture the complex, real world setting. Laboratory experiments are controlled and repeatable, and offer the opportunity to measure with a relatively high level of detail and accuracy. Field and laboratory data can be used to develop and validate numerical models that can be used to enrich observation data and to explore what-if scenarios (numerical experiments).

In terms of field measurements, long-term and large-scale bathymetric monitoring programs are highly recommended to elucidate the morphological response to nourishments. These should cover the part of the coast that is active on a decadal time-scale, i.e. the (lower) shoreface, beach and dune. The yearly survey programs for the Dutch coastal area (JARKUS, since 1963), the Wadden island Sylt, German (since 1972, Gijsman et al., 2018) and the west coast of Denmark (since 1957, Rivero et al., 2018) are examples of such. Furthermore, we propose to carry out field campaigns to measure the processes that control the shoreface nourishments morphodynamics. With a range of sophisticated instruments the bed mobility as well as the flow velocities and the sand concentrations over the water column should be measured in order to determine suspended sand fluxes. Long time-series (i.e. spanning months to years) would be preferable as these may include moments with energetic wave breaking across a wide surfzone and nourishment body as well as more moderate conditions where onshore transport may be present on the sub-aqueous bars and nourishment (Hoefel and Elgar, 2003). Finally, we recommend field experiments in which size, placement location and grain-size are varied systematically, in order to explore how this affects the lifetime, spreading and impact of shoreface nourishments. The grain-size effect is of particular interest because of ecological implications (Rijkswaterstaat, 2020). Furthermore, it may be more cost-efficient (e.g. more nearby borrow site) and/or effective (e.g. more stable nourishments for coarser sands) to use nourished sands that deviate from native sands.

We recommend to carry out laboratory experiments on a prototype scale, to avoid scaling issues. Large wave flumes like the Delta Flume (Delft, The Netherlands) and the GWK+ (Hannover, Germany) are suitable for this purpose. These should be complimented with smaller-scale wave flume and basin experiments to extend the range of test conditions, and to investigate alongshore processes. In particular, detailed measuring techniques such as PTV (Particle Tracking Velocimetry), PIV (Particle Image Velocimetry, e.g. van der Werf et al., 2007), ACVP (Acoustic Concentration Velocity Profiler, Hurther et al., 2011) and CCP (Conductivity Concentration Profiler, Lanckriet et al., 2013) should be developed further and applied to quantify the wave-mean, oscillatory and turbulent sand flux components from the bed to the water surface.

We advocate a triple model approach to bridge the gap between the small, intra-wave sand grain scale (sub-millimeters, sub-seconds) relevant to sand transport, and the large-scale coastal morphodynamics (100 s of kms, decades). At first, detailed CFD modeling to unravel sand transport processes controlling cross-shore reshaping and spreading of nourished sediment at the time scale of hours to days. Second, more agile/versatile engineering SWE models (like Delft3D, XBeach) to replicate the complex physics of cross- and alongshore nourishment morphodynamics in a simplified, wave-averaged way for time-scales up to 20 years. Finally, computationally efficient models such as CROCO (Kettler et al., 2024) and the new free-form ShorelineS coastline model (Roelvink et al., 2020) to simulate the long-term (20–100 years) coastal response to different nourishment strategies. Special attention should be devoted to modeling the wet-dry interface (swash zone), and linking the sub-aqueous and sub-aerial parts of the coast in a seamless manner.

Finally, we stress the importance of productive interactions between researchers and with stakeholders to ensure the generation and valuation of scientifically robust and societally relevant knowledge. It is particularly important that the new scientific insights are synthesized into shared conceptual models to achieve impact in policy and practice (Lodder et al., 2023).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

References

Aagaard, T., Greenwood, B., 2008. Infragravity wave contribution to surf zone sediment transport — the role of advection. Mar. Geol. 251, 1–14. https://doi.org/10.1016/j.margeo.2008.01.017.

Aagaard, T., Jensen, S.G., 2013. Sediment concentration and vertical mixing under breaking waves. Mar. Geol. 336, 146–159. https://doi.org/10.1016/j.margeo.2012.11.015.

Aidala, J.A., Burke, C.E., McLellan, T.N., 1992. Hydrodynamic forces and evolution of a nearshore berm at South Padre Island, Texas. In: Proceedings Hydraulic Engineering at Water Forum, Reston, VA, USA, pp. 1,234–1,239.

Aleman, N., Certain, R., Robin, N., Barusseau, J.P., 2017. Morphodynamics of slightly oblique nearshore bars and their relationship with the cycle of net offshore migration. Mar. Geol. 392, 41–52. https://doi.org/10.1016/j.margeo.2017.08.014.

American Shore and Beach Preservation Associate, Coastal States Organization, 2023. White Paper: Sediment Placement Regulations of the US Coastal States and Territories, Towards Regional Sediment Management Implementation. Technical Report. https://www.coastalstates.org/wp-content/uploads/2022/02/Sediment-Regs-White-Paper_ASBPA.CSO_revised_20220201.pdf.

Andrassy, C.J., 1991. Monitoring of a nearshore disposal mound at Silver Strand State Park. In: Proceedings Coastal Sediments Conference, Seattle, Washington, USA, pp. 1,971–1,984.

Arens, S.M., 2010. Effecten van suppleties op duinontwikkeling. Geomorfologie. Technical Report. Rijkswaterstaat, The Netherlands. URL. https://www.vliz.be/imisdocs/publications/ocrd/223088.pdf (in Dutch).

Atkinson, A.L., Baldock, T.E., 2020. Laboratory investigation of nourishment options to mitigate sea level rise induced erosion. Coast. Eng. 161. https://doi.org/10.1016/j.coastaleng.2020.103769.

Bain, R., McFall, B.C., Krafft, D., Hudson, A., 2021. Evaluating transport formulations for application to nearshore berms. Evaluating transport formulations for application to nearshore berms. J. Waterw. Port Coast. Ocean Eng. 147. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000668.

Bakker, M.A.J., van Heteren, S., Vonhögen, L.M., van der Spek, A.J., van der Valk, B., 2012. Recent coastal dune development: effects of sand nourishments. J. Coast. Res. 28, 587–601. https://doi.org/10.2112/JCOASTRES-D-11-00097.1.

Barnard, P.L., Erikson, L.H., Hansen, J.E., Elias, E., 2009. The performance of nearshore dredge disposal at Ocean Beach, San Francisco, California, 2005–2007. Open-File Report no. 2008-134. USGS, USA.

Bayle, P.M., Beuzen, T., Blenkinsopp, C.E., Baldock, T.E., Turner, I.L., 2021. A new approach for scaling beach profile evolution and sediment transport rates in distorted laboratory models. Coast. Eng. 163. https://doi.org/10.1016/j.coastaleng.2020.103794.

Bergsma, L.S.M., 2018. Rip Current Dynamics at a Nourished Sandy Beach, Egmond aan Zee (the Netherlands). Master's thesis. Utrecht University, The Netherlands. URL. https://studenttheses.uu.nl/handle/20.500.12932/31847.

Bertin, X., de Bakker, A., van Dongeren, A., Coco, G., André, G., Ardhuin, F., Bonneton, P., Bouchette, F., Castelle, B., Crawford, W.C., Davidson, M., Deen, M., Dodet, G., Guérin, T., Inch, K., Leckler, F., McCall, R., Muller, H., Olabarrieta, M., Roelvink, D., Ruessink, G., Sous, D., Stutzmann, Éléonore, Tissier, M., 2018. Infragravity waves: from driving mechanisms to impacts. Earth Sci. Rev. 177, 774–799. URL: https://www.sciencedirect.com/science/article/pii/S0012825217303239 https://doi.org/10.1016/j.earscirev.2018.01.002.

Bodge, K.R., 1994. Performance of nearshore berm disposal at Port Canaveral, Florida. In: Proceedings Dredging Conference, 1, pp. 182–1,191.

Brand, E., Ramaekers, G., Lodder, Q., 2022. Dutch experience with sand nourishments for dynamic coastline conservation – an operational overview. Ocean Coast. Manag. 217, 106008. https://doi.org/10.1016/j.ocecoaman.2021.106008.

Bridges, T.S., King, J.K., Simm, J.D., Beck, M.W., Collins, G., Lodder, Q., Mohan, R.K., 2021. International Guidelines on Natural and Nature-Based Features for Flood Risk Management. Technical Report.. U.S. Army Engineer Research and Development Center, Vicksburg, MS. https://doi.org/10.21079/11681/4194.

Bruins, R., 2016. Morphological Behaviour of Shoreface Nourishments along the Dutch Coast, Data Analysis of Historical Shoreface Nourishments for a Better Understanding and Design. Master's thesis.. Delft University of Technology, The Netherlands.

Brutsché, K.E., Wang, P., Beck, T.M., Rosati, J.D., Legault, K.R., 2014. Morphological evolution of a submerged artificial nearshore berm along a low-wave microtidal coast, Fort Myers Beach, west-Central Florida, USA. Coast. Eng. 91, 29–44. https://doi.org/10.1016/j.coastaleng.2014.04.010.

Brutsché, K.E., McFall, B.C., Bryant, D.B., Wang, P., 2019a. Literature Review of Nearshore Berms. Report ERDC/CHL SR-19-2.. U.S. Army Engineer Research and Development Center, Vicksburg, MS, USA.

Brutsché, K.E., McFall, B.C., Li, H., McNinch, J.E., Ousley, J.D., Engle, J.A., Magglio, C. K., 2019b. Strategic placement of dredged material in Vilano Beach, Florida, USA. In: Proceedings Coastal Sediments Conference, St. Petersburg, Florida, USA, 2, pp. 793–2,804.

Bryant, D.B., McFall, B.C., 2016. Transport of nearshore dredge material berms. In: Proceedings of the 6th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science (Coastlab16).

Chen, W., Dodd, N., 2019. An idealised study for the evolution of a shoreface nourishment. Cont. Shelf Res. 178, 15–26. https://doi.org/10.1016/j.csr.2019.03.010.

Chen, W., Dodd, N., 2021. A nonlinear perturbation study of a shoreface nourishment on a multiply barred beach. Cont. Shelf Res. 214. https://doi.org/10.1016/j.csr.2020.104317.

Chen, W., Muller, P., Grabowski, R.C., Dodd, N., 2022. Green nourishment: an innovative nature-based solution for coastal erosion. Front. Mar. Sci. 8, 814589. https://doi.org/10.3389/fmars.2021.814589.

Coco, G., Murray, A.B., 2007. Patterns in the sand: from forcing templates to self-organization. Geomorphology 91, 271–290. https://doi.org/10.1016/j.geomorph.2007.04.023, 38th Binghamton Geomorphology Symposium: Complexity in Geomorphology.

Cohn, N., Ruggiero, P., Ortiz, J., Walstra, D., 2014. Investigating the role of complex sandbar morphology on nearshore hydrodynamics. J. Coast. Res. 70, 53–58. https://doi.org/10.2112/SI65-010.1.

Dan, S., Vos, G., Montreuil, A.L., Verwaest, T., Thoon, D., 2019. Beach versus shoreface nourishment experiment. In: Coastal Sediments Conference, Tampa, USA, pp. 287–295.

de Bakker, A.T.M., Brinkkemper, J.A., van der Steen, F., Tissier, M.F.S., Ruessink, B.G., 2016. Cross-shore sand transport by infragravity waves as a function of beach steepness. J. Geophys. Res. Earth 121, 1786–1799. https://doi.org/10.1002/2016JF003878.

de Schipper, M.A., de Vries, S., Ruessink, G., de Zeeuw, R.C., Rutten, J., van Gelder-Maas, C., Stive, M.J.F., 2016. Initial spreading of amega feeder nourishment: observations of the Sand Engine pilot project. Coast. Eng. 111, 23–38. https://doi.org/10.1016/j.coastaleng.2015.10.011.

de Schipper, M., Hopkins, J., Wengrove, M., Saxoni, I., Kleinhans, M., Senechal, N., Castelle, B., Ribas, F., Ruessink, B.G., Murphy, B., McLelland, S., 2019. MODEX: Laboratory experiment exploring sediment spreading of a mound under waves and current. In: Coastal Sediments Conference, Tampa, USA, pp. 511–524.

de Schipper, M.A., Ludka, B.C., Raubenheimer, B., Luijendijk, A.P., Schlacher, T.A., 2020. Beach nourishment has complex implications for the future of sandy shores. Nat. Rev. Earth Environ. 2, 70–84. https://doi.org/10.1038/s43017-020-00109-9.

de Sonneville, B., van der Spek, A., 2012. Sediment- and morphodynamics of shoreface nourishments along the North-Holland coast. In: Proceedings 33rd International Conference on Coastal Engineering, Santander, Spain.

Dionísio António, S., van der Werf, J., Horstman, E., Cáceres, I., Alsina, J., van der Zanden, J., Hulscher, S., 2023. Influence of beach slope on morphological changes and sediment transport under irregular waves. J. Mar. Sci. Eng. 11. https://doi.org/10.3390/jmse11122244.

Eichentopf, S., van der Zanden, J., Cáceres, I., Alsina, J.M., 2019. Beach profile evolution towards equilibrium from varying initial morphologies. J. Mar. Sci. Eng. 7. https://doi.org/10.3390/jmse7110406.

Elgar, S., Gallagher, E.L., Guza, R., 2001. Nearshore sandbar migration. J. Geophys. Res. Oceans 106, 11623–11627. https://doi.org/10.1029/2000JC000389.

Ferreira, C.C., Silva, P.A., Bernabeu, A.M., Abreu, T., 2023. Transport of heterometric sediments in wave-dominated flows – tracer experiments. Mar. Geol. 459, 107042. https://doi.org/10.1016/j.margeo.2023.107042.

Gailani, J., Brutsché, K.E., Godsey, E., Wang, P., Hartman, M.A., 2019. Strategic Placement for Beneficial Use of Dredged Material. Technical Report ERDC/CHL SR-19-3. Vicksburg, MS, USA..

Gijsman, R., Visscher, J., Schlurmann, T., 2018. A method to systematically classify design characteristics of sand nourishments. In: Proceedings Coastal Engineering Conference, Baltimore, USA. https://doi.org/10.9753/icce.v36.papers.95.

Grasso, F., Michallet, H., Barthélemy, E., 2011. Experimental simulation of shoreface nourishments under storm events: a morphological, hydrodynamic, and sediment grain size analysis. Coast. Eng. 58. https://doi.org/10.1016/j.coastaleng.2010.09.007.

Grunnet, N.M., Ruessink, B.G., 2005. Morphodynamic response of nearshore bars to a shoreface nourishment. Coast. Eng. 52, 119–137. https://doi.org/10.1016/j.coastaleng.2004.09.006.

Grunnet, N.M., Walstra, D.J.R., Ruessink, B.G., 2004. Process-based modelling of a shoreface nourishment. Coast. Eng. 51, 581–607. https://doi.org/10.1016/j.coastaleng.2004.07.016.

Guillén, J., Hoekstra, P., 1996. The "equilibrium" distribution of grain size fractions and its implications for cross-shore sediment transport: a conceptual model. Mar. Geol. 135, 15–33. https://doi.org/10.1016/j.coastaleng.2004.07.016.

Hall, J.V., Herron, W.J., 1950. Test of nourishment of the shore by offshore deposition of sand, Long Branch, New Jersey. Technical Memo no. 17. USACE, Washington, DC, USA.

Hallermeier, R.J., 1981. A profile zonation for seasonal sand beaches from wave climate. Coast. Eng. 4, 253–277.

Hamm, L., Capobianco, M., Dettec, H.H., Lechugad, A., Spanhoff, R., Stive, M.J.F., 2002. A summary of european experience with shore nourishment. Coast. Eng. 47, 237–264.

Hands, E.B., Allison, M.C., 1991. Mound migration in deeper water and methods of categorizing active and stable depth. In: Proceedings Coastal Sediments Conference, Seattle, Washington, USA, pp. 1985–1991.

Hands, E.B., Bradley, K.P., 1990. Results of Monitoring the Disposal Berm at Sand Island, Alabama; Report I: Construction and First Year's Response. Technical Report DRP-90-2.. USACE, Vicksburg, MS, USA.

Hands, E.B., DeLoach, S.R., 1998. An Offshore Mound Constructed of Dredged Material, in: Dredging and Dredged Material Disposal.
Hanson, H., Brampton, A., Capobianco, M., Dette, H., Hamm, L., Laustrup, C., Lechuga, A., Spanhoff, R., 2002. Beach nourishment projects, practices, and objectives - a European overview. Coast. Eng. 47, 81–111. https://doi.org/10.1016/S0378-3839(02)00122-9.
Hattori, M., Kawamata, R., 1980. Onshore-offshore transport and beach profile change. In: Proceedings 17th International Conference on Coastal Engineering, Sydney, NSW, Australia, pp. 1,175–1,193.
Haverkate, S.M., 2020. Nearshore Dynamics of a Nourished Coast with Respect to a Neighbouring Natural Coast. Master's thesis. Utrecht University The, Netherlands. URL. https://studenttheses.uu.nl/handle/20.500.12932/39858.
Hoefel, F., Elgar, S., 2003. Wave-induced sediment transport and sandbar migration. Science 299, 1885–1887. https://doi.org/10.1126/SCIENCE.1081448.
Hoekstra, P., Houwman, K.T., Kroon, A., Ruessink, B.G., Roelvink, J.A., Spanhoff, R., 1996. Morphological development of the Terschelling shoreface nourishment in response to hydrodynamic and sediment transport processes. In: Proceedings 25th International Conference on Coastal Engineering, Orlando, Florida, USA, pp. 2,897–2,910.
Hoonhout, B., De Vries, S., 2017. Field measurements on spatial variations in aeolian sediment availability at the Sand Motor mega nourishment. Aeolian Res. 24, 93–104.
Houthuys, R., Trouw, K., Delgado, R., Verwaest, T., Mostaert, F., 2014. Evaluation of a Shoreface Nourishment in De Haan. Report WL2014R00_128_2. Flanders Hydraulics Research, Belgium. URL. https://www.vliz.be/imisdocs/publications/267586.pdf.
Huisman, B.J.A., Ruessink, B.G., de Schipper, M.A., Luijendijk, A.P., Stive, M.J.F., 2018. Modelling of bed sediment composition changes at the lower shoreface of the sand motor. Coast. Eng. 132, 33–49. https://doi.org/10.1016/j.coastaleng.2017.11.007.
Huisman, B.J.A., Walstra, D.J.R., Radermacher, M., De Schipper, M.A., Ruessink, B.G., 2019. Observations and modelling of shoreface nourishment behaviour. J. Mar. Sci. Eng. 7. https://doi.org/10.3390/jmse7030059.
Hurther, D., Thorne, P., Bricault, M., Lemmin, U., Barnoud, J., 2011. A multi-frequency acoustic concentration and velocity profiler (ACVP) for boundary layer measurements of fine-scale flow and sediment transport processes. Coast. Ocean Eng. 58, 594–605. https://doi.org/10.1016/j.coastaleng.2011.01.006.
Hwung, H.H., Huang, Z.C., Hwang, K.S., 2010. An experimental study of the cross-shore evolution of artificial submerged sand bars. Coast. Eng. J. 52, 261–285. https://doi.org/10.1142/S057856341000221X.
IPCC, 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/9781009325844.
Jackson, L.A., Corbett, B.B., 2023. Nearshore nourishment theory and application. In: Australasian Coasts & Ports Conference, pp. 33–39.
Jacobsen, N.G., Fredsøe, J., 2014. Cross-shore redistribution of nourished sand near a breaker bar. J. Waterw. Port Coast. Ocean Eng. 140, 125–134.
Johnson, B.D., Smith, E.R., 2012. Material placement in the nearshore: Laboratory and numerical model investigation. In: Proceedings 34th Coastal Engineering Conference, Santander, Spain.
Johnson, C.L., McFall, B.V., Krafft, D.R., Brown, M.E., 2021. Sediment transport and morphological response to nearshore nourishment projects on wave-dominated coasts. J. Mar. Sci. Eng. 9. https://doi.org/10.3390/jmse9111182.
Juhnke, L., Mitchell, T., Piszker, M.J., 1990. Construction and monitoring of nearshore placement of dredged material at Silver Strand State Park, San Diego, California. In: Dredging Research Technical Notes DRP-1-01. USACE, Vicksburg, MS, USA.
Kettler, T., de Schipper, M., Luijendijk, A., 2024. Simulating decadal cross-shore dynamics at nourished coasts. Coast. Eng. 190. https://doi.org/10.1016/j.coastaleng.2024.104491.
Kroon, A., Hoekstra, P., Houwman, K.T., Ruessink, G., 1994. Morphological monitoring of a shoreface nourishment-NOURTEC experiment at Terschelling, the Netherlands. In: Proceedings 24th Conference on Coastal Engineering, Kobe, Japan, pp. 2,222–2,236.
Kuang, C., Ma, Y., Han, X., Pan, S., Zhu, L., 2020. Experimental observation on beach evolution process with presence of artificial submerged sand bar and reef. J. Mar. Sci. Eng. 8. https://doi.org/10.3390/jmse8121019.
Lanckriet, T., Puleo, J.A., Waite, N., 2013. A conductivity concentration profiler for sheet flow sediment transport. IEEE J. Ocean. Eng. 38, 55–70. https://doi.org/10.1109/joe.2012.2222791.
Lansu, E.M., Reijers, V.C., Höfer, S., Luijendijk, A., Rietkerk, M., Wassen, M.J., Lammerts, E.J., van der Heide, T., 2024. A global analysis of how human infrastructure squeezes sandy coasts. Nat. Commun. 15. https://doi.org/10.1038/s41467-023-44659-0.
Larsen, B.E., van der A, D.A., Carstensen, R., Carstensen, S., Fuhrman, D.R., 2023. Experimental investigation on the effects of shoreface nourishment placement and timing on long-term cross-shore profile development. Coast. Eng. 180. https://doi.org/10.1016/j.coastaleng.2022.104258.
Larson, M., Hanson, H., 2015. Model of the evolution of mounds placed in the nearshore. J. Integr. Coast. Zone Manag. 15, 21–33. https://doi.org/10.5894/rgci530.
Larson, M., Kraus, N., 1992. Dynamics of longshore bars. In: Proceedings 23rd Conference on Coastal Engineering, Venice, Italy.
Lee, S.B., Wengrove, M.E., de Schipper, M.A., Hopkins, J., Kleinhans, M.G., Ruessink, G., 2023. The contribution of sand ripple and slope driven sediment flux to morphologic change of an idealized mound under waves. J. Geophys. Res. Earth 128, e2021JF006467. https://doi.org/10.1029/2021JF006467.
Lesser, G.R., Roelvink, J.A., Van Kester, J.A.T.M., Stelling, G.S., 2004. Development and validation of a three-dimensional morphological model. Coast. Eng. 51, 883–915. https://doi.org/10.1016/j.coastaleng.2004.07.014.
Li, Y., Zhang, C., Cai, Y., Xie, M., Qi, H., Wang, Y., 2021. Dissipation and sediment transport patterns during shoreface nourishment towards equilibrium. J. Mar. Sci. Eng. 9. https://doi.org/10.3390/jmse9050535.
Li, Y., Zhang, C., Dai, W., Chen, D., Sui, T., Xie, M., Chen, S., 2022. Laboratory investigation on morphology response of submerged artificial sandbar and its impact on beach evolution under storm wave condition. Mar. Geol. 443. https://doi.org/10.1016/j.margeo.2021.106668.
Lodder, Q., Sørensen, P., 2015. Comparing the morphological behaviour of Dutch Danish shoreface nourishments. Coast. Manag. https://doi.org/10.1680/cm.61149.397.
Lodder, Q., Slinger, J., Wang, Z., van der Spek, A., Hijma, M., Taal, M., van Gelder-Maas, C., de Looff, H., Litjens, J., Schipper, C., Löffler, M., Nolte, A., van Oeveren, C., van der Werf, J., Grasmeijer, B., Elias, E., Holzhauer, H., Tonnon, P., 2023. The coastal genesis 2 research programme: outputs, outcomes and impact. Ocean Coast. Manag. 237, 106499. https://doi.org/10.1016/j.ocecoaman.2023.106499.
Löhr, J., 2024. Multi-Temporal Shoreline Dynamics of the Repeatedly Nourished Coast of Egmond-Bergen Quantified from Satellite Imagery. Master's thesis. Utrecht University, The Netherlands. URL. https://studenttheses.uu.nl/handle/20.500.12932/46405}.
Longuet-Higgins, M.S., 1953. Mass transport in water waves. Philos. Trans. R. Soc. 345, 535–581.
Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., Aarninkhof, S., 2018. The state of the world's beaches. Sci. Rep. 8. https://doi.org/10.1038/s41598-018-24630-6.
Marchesiello, P., Chauchat, J., Shafiei, H., Almar, R., Benshila, R., Dumas, F., Debreu, L., 2022. 3d wave-resolving simulation of sandbar migration. Ocean Model 180. https://doi.org/10.1016/j.ocemod.2022.102127.
Marsh, S.W., Nicholls, R.J., Kroon, A., Hoekstra, P., 1998. Assessment of depth of closure on a nourished beach: Terschelling, the Netherlands. In: Proceedings 26th International Conference on Coastal Engineering, Copenhagen, Denmark, pp. 3,110–3,123.
McFall, B.C., Brutsché, K.E., Priestas, A.M., Krafft, D.R., 2021. Evaluation techniques for the beneficial use of dredged sediment placed in the nearshore. J. Waterw. Port Coast. Ocean Eng. 147. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000648.
McGill, S.P., Harris, B.D., McFall, B.C., Krafft, D.R., Bain, R.L., Olsen, N.R., Conery, I.W., Chasten, M.A., 2022. Morphological analysis of a nearshore nourishment along the Atlantic Coast of New Jersey, USA. J. Mar. Sci. Eng. 10.
McLellan, T.N., Truitt, C.L., Flax, P.D., 1988. Nearshore placement techniques for dredged material. In: Proceedings 21st Annual Dredging Seminar, College Station, Texas, USA, pp. 24–35.
Mendes, D., Pais-Barbosa, J., Baptista, P., Silva, P.A., Bernardes, C., Pinto, C., 2021. Beach response to a shoreface nourishment (Aveiro, Portugal). J. Mar. Sci. Eng. 9. https://doi.org/10.3390/jmse9101112.
Mesa, C., 1996. Nearshore berm performance at Newport Beach, California, USA. In: Proceedings 25th International Conference on Coastal Engineering, Orlando, Florida, USA, pp. 4636–4649.
O'Donoghue, T., Doucette, J.S., van der Werf, J.J., Ribberink, J.S., 2006. The dimensions of sand ripples in full-scale oscillatory flows. Coast. Eng. 53 (997–1), 012.
Ojeda, E., Ruessink, B., Guillen, J., 2008. Morphodynamic response of a two-barred beach to a shoreface nourishment. Coast. Eng. 55, 1,185–1,196. https://doi.org/10.1016/j.coastaleng.2008.05.006.
Ojeda, E., Guillén, J., Ribas, F., 2011. Dynamics of single-barred embayed beaches. Mar. Geol. 280, 76–90. https://doi.org/10.1016/j.margeo.2010.12.002.
Onnink, C.J., 2020. Dynamic Shoreline Response to a Shallow Concentrated Nearshore Berm Nourishment. Master's thesis. TU Delft, The Netherlands. URL. http://resolver.tudelft.nl/uuid:b4d73a8e-a22a-48b9-b4bb-784e516f9314.
Otay, E.N., 1994. Long-Term Evolution of Nearshore Disposal Berms. Ph.D. thesis.. University of Florida, USA.
Otto, P., Piter, A., Gijsman, R., 2021. Statistical analysis of beach profiles – a spatiotemporal functional approach. Coast. Eng. 170. https://doi.org/10.1016/j.coastaleng.2021.103999.
Pan, Y., Kuang, C., Zhang, J., Chen, Y., Mao, X., Ma, Y., Zhang, Y., Yang, Y., Qiu, R., 2017. Postnourishment evolution of beach profiles in a low-energy sandy beach with a submerged berm. J. Waterw. Port Coast. Ocean Eng. 143. https://doi.org/10.1061/(ASCE)WW.1943-5460.000038.
Park, W., Moon, Y., Chang, S., Jeong, W., Chae, J., Ryu, K., Chang, Y., Jin, J., 2018. Nonlinear transformation of storm waves and impacts on nearshore mound in haeundae beach, Korea. J. Coast. Res. 85, 1131–1135. https://doi.org/10.2112/SI85-227.1.
Pinto, C., Taborda, R., Andrade, C., Baptista, P., Silva, P., Mendes, D., Pais-Barbosa, J., 2022. Morphological development and behaviour of a shoreface nourishment in the portuguese western coast. J. Mar. Sci. Eng. 10. https://doi.org/10.3390/jmse10020146.
Radermacher, M., de Schipper, M.A., Price, T.D., Huisman, B.J.A., Aarninkhof, S.G.J., Reniers, A.J.H.M., 2018. Behaviour of subtidal sandbars in response to nourishments. Geomorphology 313, 1–12. https://doi.org/10.1016/j.geomorph.2018.04.005.
Ranasinghe, R., 2020. On the need for a new generation of coastal change models for the 21st century. Sci. Rep. 10. https://doi.org/10.1038/s41598-020-58376-x.
Reniers, A., Thornton, E., Stanton, T., Roelvink, J., 2004. Vertical flow structure during sandy duck: observations and modeling. Coast. Eng. 51, 237–260. https://doi.org/10.1016/j.coastaleng.2004.02.001.
Rijkswaterstaat, 2020. Kustgenese 2.0: Kennis voor een veilige kust. Technical Report WVL1220ZB001 (in Dutch).
Rijkswaterstaat, 2024. Annual Coastal Observations JARKUS Dataset. https://data.overheid.nl/dataset/27b66c3e-0b1b-485f-8fa2-5bdea40a6250 (in Dutch).

Rivero, O., Astrup, S., Lassen, A., 2018. Shoreface Nourishment Effects, an Analysis of the 2011 Nourishment Performed at Skodbjerge. Technical Report. Kystdirektoratet, Denmark. URL. https://northsearegion.eu/media/5721/systems-description-of-skodbjerge_10082018_web.pdf.
Roelvink, J.A., Reniers, A.J.H.M., 1995. LIP 11D Delta Flume Experiments, A dataset for profile model validation. Technical Report H2130.. WL | Delft Hydraulics, The Netherlands.
Roelvink, D., Reniers, A., Van Dongeren, A., Thiel, Van, de Vries, J., McCall, R., Lescinski, J., 2009. Modelling storm impacts on beaches, dunes and barrier islands. Coast. Eng. 56, 1133–1152. https://doi.org/10.1016/j.coastaleng.2009.08.006.
Roelvink, D., Huisman, B., Elghandour, A., Ghonim, M., Reyns, J., 2020. Efficient modeling of complex sandy coastal evolution at monthly to century time scales. Front. Mar. Sci. 7. https://doi.org/10.3389/fmars.2020.00535.
Roest, B., Vries, S.D., Schipper, M.D., Aarninkhof, S., 2021. Observed changes of a mega feeder nourishment in a coastal cell: five years of sand engine morphodynamics. J. Mar. Sci. Eng. 9. https://doi.org/10.3390/jmse9010037.
Ruessink, B.G., Kroon, A., 1994. The behaviour of a multiple bar system in the nearshore zone of Terschelling, the Netherlands: 1965–1993. Mar. Geol. 121, 187–197.
Ruessink, B.G., Kuriyama, Y., 2008. Numerical predictability experiments of cross-shore sandbar migration. Geophys. Res. Lett. L01603, 56–63. https://doi.org/10.1029/2007GL032530.
Ruessink, B.G., Terwindt, J.H.J., 2000. The behaviour of nearshore bars on the time scale of years: a conceptual model. Mar. Geol. 163, 289–302. https://doi.org/10.1016/S0025-3227(99)00094-8.
Ruessink, B.G., Houwman, K.T., Hoekstra, P., 1998. The systematic contribution of transporting mechanisms to the cross-shore sediment transport in water depths of 3 to 9 m. Mar. Geol. 152, 295–324. https://doi.org/10.1016/S0025-3227(98)00133-9.
Ruessink, B.G., Wijnberg, K.M., Holman, R.A., Kuriyama, Y., van Enckevort, I.M.J., 2003. Intersite comparison of interannual nearshore bar behavior. J. Geophys. Res. Oceans 108. https://doi.org/10.1029/2002JC001505.
Ruessink, B.G., Kuriyama, Y., Reniers, A.J.H.M., Roelvink, J.A., Walstra, D.J.R., 2007. Modeling cross-shore sandbar behavior on the timescale of weeks. J. Geophys. Res. 112, F03010. https://doi.org/10.1029/2006JF000730.
Ruessink, B.G., van der Grinten, R.M., Vonhögen-Peeters, L.M., Ramaekers, G., Lodder, Q.J., 2012. Nearshore evolution at Noordwijk (NL) in response to nourishments, as inferred from Argus video imagery. In: NCK-Days 2012: Crossing Borders in Coastal Research. University of Twente.
Schwartz, R.K., Musialowski, F.R., 1977. Nearshore disposal: Onshore sediment transport. In: Proceedings Coastal Sediments Conference, Reston, VA, USA, pp. 85–101.
Shand, R.D., 2003. Relationships between episodes of bar switching, cross-shore bar migration and outer bar degeneration at Wanganui, New Zealand. J. Coast. Res. 19, 157–170.
Shand, R.D., Bailey, D.G., Shepherd, M.J., 1999. An inter-site comparison of net offshore bar migration characteristics and environmental conditions. J. Coast. Res. 15, 750–765.
Sherwood, C.R., van Dongeren, A., Doyle, J., Hegermiller, C.A., Hsu, T.J., Kalra, T.S., Olabarrieta, M., Penko, A.M., Rafati, Y., Roelvink, D., van der Lugt, M., Veeramony, J., Warner, J.C., 2022. Modeling the morphodynamics of coastal responses to extreme events: what shape are we in? Annu. Rev. Mar. Sci. 14, 457–492. https://doi.org/10.1146/annurev-marine-032221-090215.
Smith, S.J., Marsh, J., Puckette, T., 2007. Analysis of fluorescent sediment tracer for evaluating nearshore placement of dredged material. In: Proceedings 18th World Dredging Congress, pp. 1345–1358.
Smith, E.R., D'Alessandro, F., Tomasicchio, G.R., Gailani, J.Z., 2017a. Nearshore placement of a sand dredged mound. Coast. Eng. 126, 1–10. https://doi.org/10.1016/j.coastaleng.2017.05.002.
Smith, E.R., Mohr, M.C., Chader, S.A., 2017b. Laboratory experiments on beach change due to nearshore mound placement. Coast. Eng. 121, 119–128. https://doi.org/10.1016/j.coastaleng.2016.12.010.
Soulsby, R., 1997. Dynamics of Marine Sands. Telford, London, UK.
Spanhoff, R., van de Graaff, J., 2007. Towards a better understanding and design of shoreface nourishments. In: Proceedings 30th International Conference on Coastal Engineering, San Diego, USA, pp. 4141–4153. https://doi.org/10.1142/9789812709554_0348.
Steijn, R., 2005. Effectiviteit van vooroeversuppleties langs de waddenkust: Aanzet tot ontwerprichtlijnen voor het ontwerp van vooroeversuppleties. Technical report A1539. Alkyon, The Netherlands (in Dutch).
Stive, M.J.F., Nicholls, R.J., de Vriend, H.J., 1991. Sea-level rise and shore nourishment: a discussion. Coast. Eng. 16, 147–163. https://doi.org/10.1016/0378-3839(91)90057-N.
Tătui, F., Vespremeanu-Stroe, A., Ruessink, G.B., 2016. Alongshore variability of cross-shore bar behavior on a nontidal beach. Earth Surf. Process. Landf. 41, 2085–2097. https://doi.org/10.1002/esp.3974.
Ton, A.M., 2023. Sandy Beaches in Low-Energy, Non-tidal Environments: Unraveling and Predicting Morphodynamics. Ph.D. thesis.. Delft University of Technology, The Netherlands.
USACE, 2022. RSM Navigation Sediment Placement Database (1998-present). Database. US Army Corps of Engineers, Washington, DC, USA. URL. https://rsm.usace.army.mil/budb/ (accessed 8 March 2022).
Valiente, N.G., Masselink, G., Scott, T., Conley, D., McCarroll, R.J., 2019. Role of waves and tides on depth of closure and potential for headland bypassing. Mar. Geol. 407, 60–75. https://doi.org/10.1016/j.margeo.2018.10.009.
van der A, D.A., Ribberink, J.S., van der Werf, J.J., O'Donoghue, T., Buijsrogge, R.H., Kranenburg, W.M., 2013. Practical sand transport formula for non-breaking waves and currents. Coast. Eng. 76, 26–42.
van der Lugt, M.A., Bosma, J.W., de Schipper, M.A., Price, T.D., van Maarseveen, M.C.G., van der Gaag, P., Ruessink, G., Reniers, A.J.H.M., Aarninkhof, S.G.J., 2024. Measurements of morphodynamics of a sheltered beach along the dutch wadden sea. Earth Syst. Sci. Data 16, 903–918. https://doi.org/10.5194/essd-16-903-2024.
van der Spek, A., Elias, E., 2013. The effects of nourishments on autonomous coastal behavior. In: Proceedings Coastal Dynamics Conference, Arcachon, France, pp. 1,753–1,762.
van der Wal, D., 2004. Beach-dune interactions in nourishment areas along the Dutch coast. J. Coast. Res. 20, 317–325.
van der Werf, J.J., Doucette, J.S., O'Donoghue, T., Ribberink, J.S., 2007. Detailed measurements of velocities and suspended sand concentrations over full-scale ripples in regular oscillatory flow. J. Geophys. Res. 114. https://doi.org/10.1029/2006JF000614.
van der Werf, J., Ribberink, J., Kranenburg, W., Neessen, K., Boers, M., 2017. Contributions to the wave-mean momentum balance in the surf zone. Coast. Eng. 121, 212–220. https://doi.org/10.1016/j.coastaleng.2016.12.007.
van der Zanden, J., van der A, D., Hurther, D., Cáceres, I., O'Donoghue, T., Hulscher, S., Ribberink, J., 2017. Bedload and suspended load contributions to breaker bar morphodynamics. Coast. Eng. 129, 74–92. https://doi.org/10.1016/j.coastaleng.2017.09.005.
van Duin, M.J.P., Wiersmaa, N.R., Walstra, D.J.R., van Rijn, L.C., Stive, M.J.F., 2004. Nourishing the shoreface: observations and hindcasting of the Egmond case, the Netherlands. Coast. Eng. 161, 813–837. https://doi.org/10.1016/j.coastaleng.2004.07.011.
van Enckevort, I.M.J., Ruessink, B.G., 2003. Video observations of nearshore bar behavior. Part 1: alongshore uniform variability. Cont. Shelf Res. 23, 501–512. https://doi.org/10.1016/S0278-4343(02)00234-0.
van Koningsveld, M., Mulder, J.P.M., 2004. Sustainable coastal policy developments in the Netherlands. A systematic approach revealed. J. Coast. Res. 20, 375–385. https://doi.org/10.2112/1551-5036(2004)020[0375:SCPDIT]2.0.CO;2.
van Leeuwen, S., Dodd, N., Calvete, D., Falqués, A., 2007. Linear evolution of a shoreface nourishment. Coast. Eng. 54, 417–431. https://doi.org/10.1016/j.coastaleng.2006.11.006.
van Rhijn, T., 2019. Sediment Transport during the Execution of the Pilot Nourishment Ameland Inlet. Master's thesis.. Delft University of Technology, The Netherlands.
van Rijn, L.C., 2007. Unified view of sediment transport by currents and waves, I: initiation of motion, bed roughness, and bed-load transport. J. Hydraul. Eng. 133, 649–667.
van Rijn, L.C., 2011. Coastal erosion and control. Ocean Coast. Manag. 54, 867–887. https://doi.org/10.1016/j.ocecoaman.2011.05.004.
van Rijn, L.C., 2013. Principles of Fluid Flow and Surface Waves in Rivers, Estuaries, Seas and Oceans. Aqua Publications, Amsterdam, The Netherlands.
van Rijn, L.C., Tonnon, P.K., Walstra, D.J.R., 2011. Numerical modelling of erosion and accretion of plane sloping beaches at different scales. Coast. Eng. 58, 637–655.
van Rijn, L.C., Ribberink, J.S., van Der Werf, J.J., Walstra, D.J.R., 2013. Coastal sediment dynamics: recent advances and future research needs. J. Hydraul. Res. 51, 475–493.
van Westen, B., Luijendijk, A.P., de Vries, S., Cohn, N., Leijnse, T.W., de Schipper, M.A., 2024. Predicting marine and aeolian contributions to the sand engine's evolution using coupled modelling. Coast. Eng. 188, 104444. https://doi.org/10.1016/j.coastaleng.2023.104444.
Vellinga, P., 1986. Beach and Dune erosion during Storm Surges. Ph.D. thesis.. Delft University of Technology, The Netherlands.
Vermeer, N.P., 2021. The Effect of Repeated Sand Nourishments on Long-Term Nearshore Evolution: A Case Study for Noordwijk aan Zee, the Netherlands. Master's thesis. Utrecht University, The Netherlands. URL. https://studenttheses.uu.nl/handle/20.500.12932/1133}.
Vitousek, S., Vos, K., Splinter, K.D., Erikson, L., Barnard, P.L., 2023. A model integrating satellite-derived shoreline observations for predicting fine-scale shoreline response to waves and sea-level rise across large coastal regions. J. Geophys. Res. Earth 128. https://doi.org/10.1029/2022JF006936.
Vousdoukas, M.I., Ranasinghe, R., Mentaschi, L., Plomaritis, T.A., Athanasiou, P., Luijendijk, A., Feyen, L., 2020. Sandy coastlines under threat of erosion. Nat. Clim. Chang. 10, 260–263. https://doi.org/10.1038/s41558-020-0697-0.
Walstra, D.J.R., 2016. On the Anatomy of Nearshore Sandbars. Ph.D. thesis.. Delft University of Technology, The Netherlands.
Walstra, D.J.R., Hoyng, C.W., K, P., van Rijn, L.C., 2010. Experimental study investigating various shoreface nourishment designs. In: Proceedings 32nd International Conference on Coastal Engineering, Shanghai, China. https://doi.org/10.9753/icce.v32.management.30.
Walstra, D., Reniers, A., Ranasinghe, R., Roelvink, J., Ruessink, B., 2012. On bar growth and decay during interannual net offshore migration. Coast. Eng. 60, 190–200. https://doi.org/10.1016/j.coastaleng.2011.10.002.
Walstra, D.J.R., Ruessink, B.G., Reniers, A.J.H.M., Ranasinghe, R., 2015. Process-based modeling of kilometer-scale alongshore sandbar variability. Earth Surf. Process. Landf. 40, 995–1005. https://doi.org/10.1002/esp.3676.
Wang, Z.B., van der Werf, J.J., 2017. Spin-up phenomenon in morphodynamic modelling. In: Proceedings 10th Symposium on River, Coastal and Estuarine Morphodynamics, Trento - Padova, Italy.
Wijnberg, K.M., Holman, R.A., 2007. Video-observations of shoreward propagating accretionary waves. In: Proceedings RCEM Conference, Enschede, The Netherlands, pp. 773–743.
Wijnberg, K., Poppema, D., Mulder, J., van Bergen, J., Campmans, G., Galiforni-Silva, F., Hulscher, S., Pourteimouri, P., 2021. Beach-dune modelling in support of Building with Nature for an integrated spatial design of urbanized sandy shores. In: Building with Nature Perspectives: Cross-Disciplinary BwN Approaches in coastal regions. TU Delft open, pp. 241–259.

Wright, L.D., Short, A.D., 1984. Morphodynamic variability of surf zones and beaches: a synthesis. Mar. Geol. 56, 93–118.
Young, D.L., Brutsché, K.E., Li, H., McFall, B.C., Maloney, E.C., McClain, K.E., Bucaro, D. F., LeRoy, J.Z., Duncker, J.J., Johnson, K.K., Jackson, P.R., 2020. Analysis of Nearshore Placement of Sediments at Ogden Dunes, Indiana. Technical Report ERDC/CHL TR-20-4.. USACE, Vicksburg, MS.
Zwamborn, J.A., Fromme, G.A.W., FitzPatrick, J.B., 1970. Underwater mound for the protection of Durban's beaches. In: Proceedings 12th International Conference on Coastal Engineering, Washington D.C., USA, pp. 978–994.