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Development of a Washover Fan on a Transgressive Barrier, Skallingen, Denmark

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ABSTRACT

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In 1979 Skallingen, a transgressive barrier spit (12 km long and 2.5 km wide), became a state property and declared as a protected area, and washover fans were then permitted to develop according to Mother Nature's premises. A washover fan, formed in 1990, has been observed concerning the morphologic development as a consequence of repeating overwashes and the influence of aeolian processes. Establishment of new dunes on the fan were concentrated on its margin, while it obviously is very difficult for vegetation and dunes to develop in the central area and the throat of the washover fan. Calculations of the development of sediment volumes from 1990 until 2003 of a washover area document a positive net-sediment budget per metre coastline of + 950 m3 of which 615 m3 are deposited in the margin-dunes and only 345 m3 on the overwash fan itself. The coastline and barrier as a whole retreats averagely 3-4 m a-1, which leads to a sediment loss of - 135 m3 per metre coastline along the front of the overwash area. A more distinctive negative net-sediment budget (390 m3 per m metre coastline) was found along stretches with high foredunes.

ADDITIONAL INDEX WORDS: *Barrier, overwash, washover fan, sediment budget, dune/barrier management, Skallingen, Denmark.*

INTRODUCTION

Landward migration of barriers is a common phenomenon along barrier coastlines, reflecting the global sea level rise (LEATHERMAN, 1983; ROY *et al*., 1994). Increasing settlement on these barriers during the last century has brought the dynamics of transgressive barriers into focus. Two coastal processes dominate the sediment transport from the beach to the back barrier and the lagoon: Aeolian drift and overwash. While overwashes may form sediment fans stretching from the dune line far into the back barrier area, the aeolian drift mainly affects the narrow brim of the outermost coastal dunes (CHRISTIANSEN, 2003) as well as the overwash fans (LEATHERMAN, 1976). Aeolian transport at Skallingen is predominantly landward directed according to the wind climate contrary the coasts of eastern USA and Canada.

Recession of the Skallingen coastline is well documented from studies of old maps and air photos. During the last 20-30 years foredune erosion has been monitored frequently through profilings (AAGAARD *et al*., 1995). However, the evolution of washover fans and the role of overwash processes in the transgressive development has never been the key issue in this area.

In 1990 a major surge hit Skallingen and breached several foredune stretches and there has been a unique possibility to study the development of an overwash fan, both morphologically and concerning the sediment budget. This paper therefore will focus on an elected washover fan, from its formation, through several repeating overwashes and the consequences of the influence of aeolian processes, and compare this with a coastal section with high foredunes.

STUDY AREA

The barrier spit Skallingen (12 km long and about 2.5 km wide (Figure 1), encompasses three morphological zones typical of a barrier: a beach and intertidal zone, 80-100 m wide, a zone with dune ridges, 0.3-1 km wide, and a 1.5- 2 km wide back barrier covered by salt marsh and vegetated predominantly on the inner part by Puccinellia maritima (Juncus gerardii near the dunes) and on the outer part towards the lagoon by *Halimione (Atriplex) portulacoides*. *Ammorphila arenaria* and *Elymus arenarius* characterize the vegetation on the foredunes (NIELSEN and NIELSEN, 2002). The mean sediment grain size of both beach and dune sediments is 0.150-0.200 mm.

Tides at Skallingen are semidiurnal with a diurnal inequality. The tidal range is about 1.7 m at spring tide and 1.3 m at neap tide, a micro tidal environment. A spring astronomical high tide may reach 1.1 m DOD at Esbjerg. Monthly mean sea-levels display an annual variation of about 0.25 m with high means during the late part of the year and low means during the spring months (DMI, 1970). These variations contribute to the fact that the erosional events at Skallingen are most frequent during the autumn/winter months when westerly storms are common and intense.

Skallingen is exposed towards the west, and thereby to a moderately-high energy wind wave climate from the North Sea. The mean annual wave height is about 1.0 m with typical wave periods of 4-6 seconds. However, during intense storms, offshore wave heights may exceed 5 m with peak spectral wave periods of 10-13 seconds whereas swell is insignificant.

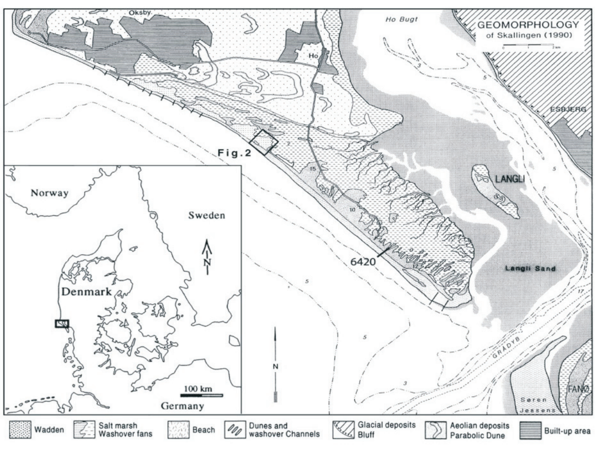

Figure 1. Study area and geomorphologic outline of Skallingen. The inserted box shows the washover area in Figure 4 and the profile 6420 is shown in Figure 5.

During the last 200 years the barrier spit has moved toward the mainland with a speed of about 3 m a-1. Regular surveys during the last three decades show that shoreline retreat still occurs at the same rate. The mean rate of sea level rise over the last century has been 1.26 mm a-1 at Esbjerg (AAGAARD *et al*., 1995). The current trend over the past 25 years is 4.21 mm a-1 (NIELSEN AND NIELSEN, 2002).

In the beginning of the last century, dike building and planting sealed up weak stretches of the foredune to increase the area with permanent vegetation and thus to improve the back barrier for cattle grasing, and from 1950 - 1960 the back barrier became covered by salt marsh vegetation. Another concern was that breaches might influence the stability of the tidal inlet, Grådyb, to the south (important navigation channel). Major storm surges, however, breached the dikes and foredune at several stretches (every 8 10 years), mainly to the north, but these scars were quickly restored. In 1979 Skallingen became a state property and declared as a protected area, and washover fans were thus permitted to evolve undisturbed.

The beach is backed by foredunes which are often scarped, indicating ongoing erosion, and the border between the backshore and the dune face is typically 2.40 m DOD (Danish Ordinance Datum). On the northern, proximal, part of the barrier, the foredunes are very weak and irregular and a series of groins have been constructed to stabilize the northernmost stretch (Figure 1). In the central and southern parts, the foredunes are more or less continuous for about 7 km. Dune heights are usually 3-7 m above the upper backshore (~ 5.5-9.5 m DOD), but 10-12 m high dunes are fairly common.

METHODS

The selected washover site (Figure 1) originated January 26, 1990. The geomorphology of the washover fan and its surroundings were surveyed shortly after its formation and the distribution of the vegetation and surface sediment texture was described (Figure 2). Furthermore a centreline perpendicular to the beach and two, later three cross-profiles with 100 m interval were surveyed (Figure 3 a, b and c). Finally a series of pits were dug to study the sediment structure and stratigraphy. Since then the profiles have been resurveyed at least once a year with a total station and in August 2003 the geomorphology of the fan was surveyed again using a GPS-pathfinder (Figure 2).

The central and southern parts of Skallingen are characterized by continuous, unbroken and high foredune. Profiles with one km interval covering the dune, beach and nearshore have been surveyed along this stretch, and one of these, Line 6420, 5.5 km south of the fan, has been selected for our research and monitored at least once a year (Figure 1 and 3d).

RESULTS AND DISCUSSION

The January storm surge of 1990 was the second largest in the last century at Skallingen, and the maximum sea-level was recorded to 3.72 m DOD according to measured driftwood lines in the dunes. In Esbjerg Harbour the sea level reached 4.12 m DOD (Figure 4). It was a westerly gale and hence the waves hit

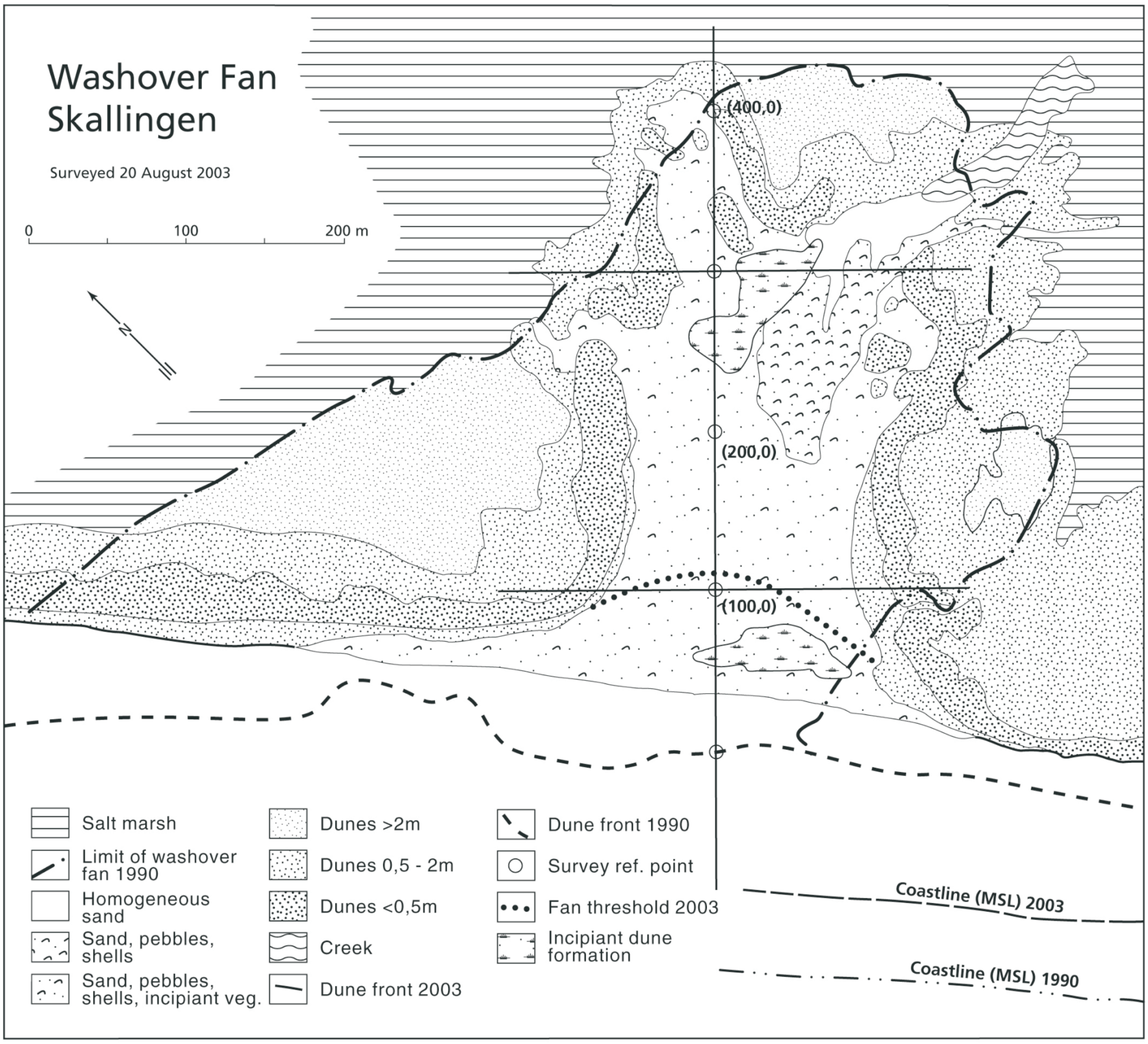

Figure 2: Geomorphology of the observed washover fan 2003. Outline of the 1990-fan is indicated.

the coast obliquely, which explain the direction and symmetry of the observed washover fan (Figure 2).

The overall length of the fan was c. 500 m and the width about 300 m and the threshold height at the throat was 1.9 m DOD.

Before the 1990-surge events the back barrier was covered by salt marsh, with a typical altitude of 1.6 m DOD, separated from the beach by a narrow zone with low (< 3 m) foredunes, partly artificially created by means of brushwood fences and by intensive planting.

The development of the washover fan on Skallingen during the last 13 years is shown on Figure 3 and Table 1. Since the formation of the fan in 1990, there have been 40 surge events, where the fan potentially has been overwashed (Figure 4). The dunes along the margins have grown substantially, especially along the southern part of the fan, where the dunes have become massive and now reach altitudes of 5 to 6 m (Figure 3b, 3c and 5).

Pits dug in lines perpendicular to the coastline after the 1990-surge indicated that a cover of 25 45 cm sand was deposited on the marsh surface and consisted of parallel lamination or small scale ripple cross-lamination as recognized by Sedgwick and DAVIES JR. (2003), ARMON (1979), LEATHERMAN (1979), SCHWARTZ (1975), DAVIDSON-ARNOTT and FISHER (1992) and many others. Along the fan margin the stratigraphy displayed cross-bedding units up 30-40 cm in thickness indicating that deposition took place in standing water as the fan extended landward (Figure 5a). The texture of the fan sediment was generally homogeneous; consisting of sand with a mean size of 0.180 mm. Centrally, the surface of the fan exposed this sand, while a mixture of sand, pebbles and shells dominated the surface around the sand flat.

Figure 3d shows the development along the central and southern part of Skallingen during the study period. Notice that the storm surges in 1990 caused a coastal recession (+ 1 m DOD ~ high water line) of about 35 m, while the following relatively calm period until 1999 only resulted in a recession of 31 m.. Then the coastline retreated more than 15 m during a single storm in December1999. The total recession from 1990 until 2003 was 52 m, ~ 4 m a-1.

It is significant that deposition of aeolian sand transported from the beach and dune front to the lee side of the dune is limited. Therefore the general picture of this stretch is a continuous negative net sediment budget of the dune body (Table 1).

The average recession of the coastline is of the same order at the washover fan (about 3 m per year). Calculations of the development of sediment volumes from 1990 until 2003 (Table 1) of a washover area document a positive net-sediment budget per metre coastline of + 950 m3 of which 615 m3 are deposited in the margin-dunes and only 345 m3 on the overwash fan itself. The coastline and barrier as a whole retreats averagely 3-4 m a-1, which leads to a sediment loss of - 135 m3 per metre coastline along the front of the overwash area. A more distinctive negative net-sediment budget (390 m3 per m metre coastline) was found along stretches with high foredunes.

Since 1990, the sediment texture of the fan surface has by and large remained identical and consist of a central area covered by homogeneous sand flanked by a surface dominated by a mixture of sand, pebbles and shells (Figure 2). As observations of the sediment distribution on the fan surface was carried out immediately after overwash events, the concentration of pebbles and shells in the surface layer evidently is a result of the surge hydrodynamic and not a lag deposit formed through deflation as described by DAVISON-ARNOTT and FISHER (1991). Generally coarse sediment and shells are only found on the surface and not in the depth. The sediment body of the fan therefore indicates that when the fan is overwashed a substantial part of the existent sediment become mobilized and mixed up with new incoming sediment. In the saturated flow, sediment pebbles and shells are moved to the surface, so that the sediment packet remains similar to the one before the surge.

No less than 4 storm surge events >3 m DOD, all from W and WSW occurred within one year after the formation of the washover fan (Figure 4). This vigorous period was then followed by 8 relatively calm years with 25 high water events, but none of them exceeding 3 m DOD. Considering that the threshold level at the fan throat was just below 2 m DOD and that the maximum water level at the barrier normally is 30 40 cm below the registered level at Esbjerg Harbour, the morphologic effects of the overwashes have been limited. Only minor or non sand masses have been transported onto the fan during these overwash situations, which also appears from Figure 3a. The most important effect of the repeated overwashes has presumably been the soaking of the fan with salt water, which has prevented the vegetation to colonize the central part of the fan. CLEARY and HOSIER (1979) also underline the slow recovery of vegetation on the washover fan.

When the washover fan was created in January 1990, sand was deposited on an almost horizontal flat covered by salt marsh and Phragmites vegetation and with scattered small ½ - 1 m high dunes. The surface of the recent washover fan, however, appears rather irregular (Figure 3a). This is a result of a combination of remnants of the small original dunes, surrounded by scars cut by strong overwash currents in characteristic "comet-like" structures on the fan surface. During the first 10 years the surface of the central fan remained flat and even. Until 1999 the flat, central part of the fan mainly functioned as a highway for transport of aeolian sand from the beach to the fringing dunes, the heights of which increased more than 2 m (Figure 3b and c).

However, the elevation of the central flat area has in fact increased too, and accurate levelling shortly after surge events indicate that each overwash added sediment to the fan (Figure 3). After the heavy surge events in 1990 and 1991 the following 8 years were dominated by minor to medium surge events (2.4 to 3 m DOD, see Figure 4). In this period the height of the inner part of the fan increased only 0 15 cm while the area at the throat increased about 0.5 m.

In December1999, a violent westerly storm hit the coast and caused a surge of more than 4 m DOD. This single event added more than 0.5 m sand to the fan, which apparently reached a critical level concerning the depositional environment. Now, in between the overwashes, rainfall became able to reduce the amount of salt and in dry periods the sand became well drained. A large depot of sediment was hereafter at disposal for aeolian processes, which is obvious from the profiles. More than 1 m sand was deposited on the dune crests from 1999 until 2003 simultaneously with a lowering of the central fan area (Figure 3a. b and c).

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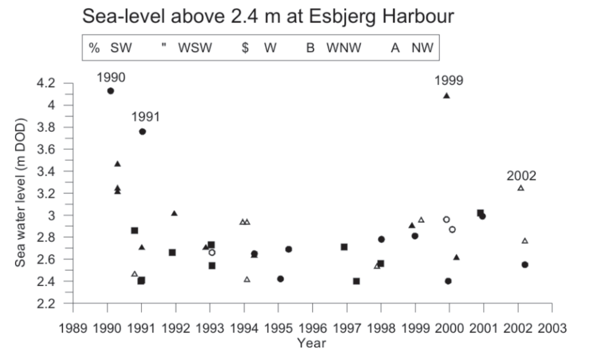

Figure 3. Surge occurrences between 1990 and 2003 at Esbjerg and coincident wind directions. 40 surge events hit the coast within the study period and all are generated by winds from SW to NW. Sea level above 3.0 m DOD is locally regarded as a storm surge.

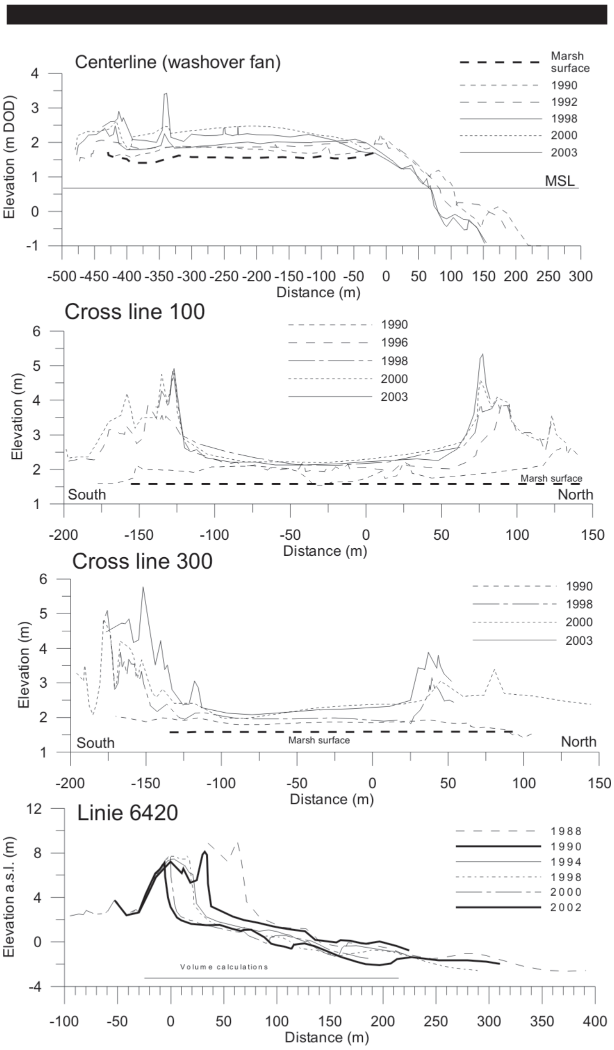

Figure 4. Selected profiles representing the development of the washover fan from its formation until 2003. a) Centre line of the fan, b) cross line 100 close to the throat of the fan, c) cross line 300 situated 200 m landward of b, d) profiles representing the development of high foredunes at the mid and distal part of the barrier.

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In 2002 scattered appearance of small vegetation tuffs primarily Elytrigia junceiforme, Ammophila arenaria and Elymus arenarius appeared on the fan for the first time since 1990. This development has escalated through 2003, where more or less continuous areas are characterized by scattered vegetation and aeolian sediments (Figure 2 and 5b).

Evolution of the Central and Distal Barrier Stretch Since 1990

The violent storm surge in 1990 resulted in a coastal recession of more 30 m along most of the Skallingen barrier spit (Figure 3a and 3d) and long stretches on the proximal part of the barrier was overwashed. Headlines in newspapers declared that the barrier would end up as an island within 15 years. Around 30 m3 m-1a-1 on average has been lost since the 1990-surge in a zone including the intertidal area, beach and the active foredune. The average rate of coastal recession here is of the same order as along the proximal stretch of the barrier including the section with washover fans. The net-sediment budget at the observed fan, however, has been positive (Table 1) during the last 13 years. Presumably this tendency will decrease, if the incipient dune developing in 2002 and 2003 at the fan throat grows continuously in the years to come and thereby closing the gap in the established foredunes. The new foredune will then prohibit overwashes caused by minor to moderate surges stop the aeolian transport from the beach to the dunes on the fan. The net-sediment budget of the fan will then become negative as a result of the general coastal recession until a new extraordinary storm surge once again breaches the foredunes.

The constantly registered negative sediment budget of the distal part of the barrier (Table 1) may be a consequence of human interference, see also LEATHERMAN (1977).

To prevent breaches of the original massive zone of foredunes along this stretch, wind eroded scars on the dune front have quickly been replanted, and at sections where the foredunes were low and threatened, sand dikes were constructed. The effect of these operations was that the foredunes reached unnatural heights and all surges removed sand, which disappeared into the sea. When the status of the barrier was pronounced a protected area, the intensive management stopped. The volume of the artificially high foredunes are now strongly reduced, and in a near future several foredune sites also along the distal part of the barrier are supposed to be breached consequently with a reduction of the net-sediment loss. And the visions that Skallingen will end up as a small island may hopefully be forgotten.

Table 1: *Sediment budget 1990 – 2003 of the washover fan and line 6420.*

Year	Month	Washover area m^3 Dunes	Fan	Beach and Intertidal zone	Total	Washover area $m^3\ m^{-1}$ coastline	6420 $m^3\ m^{-1}$ coastline
1990	MAR	0	0	0	0	0	0
1991	MAR			-3200			-31
1992	MAR			-2000			-96
1994	APR			-6000			-164
1995	SEP						-156
1996	APR						-150
1997	APR	61200	16700	-20400	57500	288	-217
1998	APR	68400	25500	-25600	68300	342	-216
1999	AUG	75000	35200	-28000	82200	411	-250
2000	SEP	85200	53850	-27600	111450	557	-338
2001	AUG	102200	28650				
2002	AUG	96800	26000				-402
2003	JUN	104400	37200	-27600	114000	570	-391
					Shoreline retreat (+ 1m DOD):	$3\ m\ a^{-1}$	$4\ m\ a^{-1}$

Figure 5. a) Southern fringe of the washover fan two months after its formation. View towards NE. b) Dune development at the same spot in 2003. View towards SW. (Photos N. Nielsen)

CONCLUSIONS

(1) The study indicates that the observed washover fan, born in 1990, went through three main phases of development. Two essential factors play a role in this development: 1) Repeated overwashes until 1999 increased the level of the washover fan slowly but gradually. Dune formations in this phase were restricted to the margins of the fan. Then the central part of the fan apparently reached a critical level of about 2.5 m, whereupon vegetation was able to invade the fan flat and embryonic dune formation commenced. 2) The beach in front of the fan throat widened by 60 70 metres as the fan threshold moved landward. This means an increasing loss of wave run-up energy and a larger source area for the aeolian transport. 1) and 2) favourite conditions for dune growth. In 2003, aeolian processes dominated the majority of the washover fan, and if no extreme storm surges occur in the following one or two years our best guess is that 3) the throat will be closed by foredunes and the presently positive net-sediment budget of the washover fan will be reduced or even become negative.

(2) In spite of an average coastal recession of about 3 m a-1 at the washover fan area, the sediment budget is positive from 1990 until 2003, where + 160.000 m3 have been added including a loss of 27.500 m3 according to a coastal retreat all calculated within a 200 wide belt perpendicular to the coastline.

(3) During the same period (1990 2003) the distal part of the barrier, where the foredunes earlier were reinforced by human intervention, the coastal retreat has been 4 ma-1 in average, and here the net sediment budget was very negative: 78.000 m3 within a similar 200 m belt.

(4) This study confirms that the formation of washover fans is essential in order to maintain a stable sediment volume of transgressive barriers. A considerable positive net-sediment budget of the overwash area is balanced with sediment loss along adjacent coast lines, where low foredunes are eroded.

(5) The present threshold on the washover fan corresponds to a position (about 80 m behind the general dune front) where vegetation is able to establish as a base for new dune formations. This position could have been the position of the dune front of Skallingen to day, if no human intervention on the barrier had been conducted.

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