DESIGN OF RECREATIONAL BEACH IN MILD WAVE CONDTIONS

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BY LEO C. VAN RIJN

1. Introduction

An artificial island is planned in the lake Markermeer (area of about 2000 km^2; The Netherlands) with an almost constant water level and water depths between 3 and 5 m. Sufficient sand (5 to 10 million m^3) can be mined from deep mining pits elsewhere in the lake. The borders of the island are made as sand beaches. The main wave directions are from the sectors South-West and North-West.
Wind-driven circulations currents (clockwise direction) are generated during windy conditions.

The design of the beaches facing the two dominant wave directions involve the:
- determination of the hydrodynamic and sediment boundary conditions;
- determination of circulation currents;
- determination of beach dimensions, slopes, cross-sections;
- computation of longshore and cross-shore sand transport rates and erosion/deposition volumes.

The beach design is explained based on modelling using the **LONGMOR-model** and the **CROSMOR-model**.

2 Hydrodynamic and sediment boundary conditions

2.1 Soil composition

The stratigraphy of the lake bottom consists of several Holocene layers of sand, clay and peat with a total thickness of 5 to 10 m on top of a thick layer of pleistocene sand with d_{50} between 0.15 m and 0.6 mm.

2.2 Hydrodynamic conditions

2.2.1 Wind, waves and water levels

Figure 2.1 shows the wind rose with dominant wind directions in the sectors South-West (about 60% of the time).

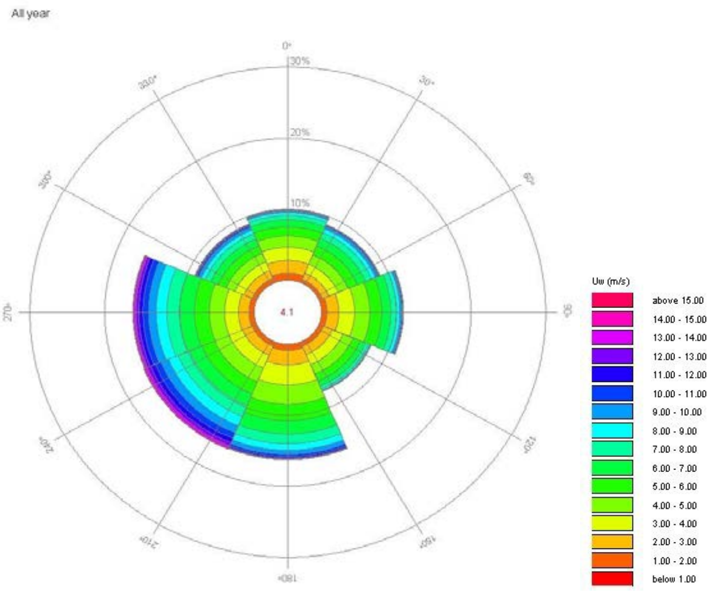


Figure 2.1 *Windrose*

Table 2.1 shows the maximum wave heights in the sectors South-West-North.

Wave direction	Wave height H_s (m)	Wave period T_p (s)	Water setup above winter lake level (m)	Water setup to NAP (m)	Frequency of occurrence
South-West	0.9	3.5	0.3	-0.1	Annual
	1.1	4.2	0.6	0.2	1x per year
	1.3	4.7	0.9	0.5	1x per 10 years
	1.5	4.8	1.1	0.7	1x per 50 years
	1.7	5.2	1.3	0.9	1x per 100 years
North-West	1.0	3.8	0.3	-0.1	1x per year
	1.2	4.4	0.5	0.2	1x per 10 years
	1.3	4.6	0.7	0.3	1x per 50 years
	1.5	4.8	0.8	0.4	1x per 100 years
North	0.6	2.8	-0.1	-0.5	1x per year
	0.7	3.1	-0.1	-0.5	1x per 10 years
	0.8	3.3	-0.2	-0.6	1x per 50 years
	0.9	3.4	-0.2	-0.6	1x per 100 years
South-Eeast	0.5	2.5	0	-0.4	1x per year
	0.6	2.8	0	-0.4	1x per 10 years
	0.75	3.2	0	-0.4	1x per 50 years
	0.8	3.5	0	-0.4	1x per 100 years

Table 2.1 *Storm waves*

Extreme waves can be obtained by extrapolation.
Extrapolation to 1x per 4000 year gives:
South-West (SW): H_s = 2.1 m and water setup = 1.9 m to winter lake level = +1.5 m NAP;
North-West (NW): H_s = 1.6 m;
South-East (SE) : H_s = 1.1 m.

2.2.2 Annual wave climate of daily waves

Long term wind data have been used to derive the long term wave climate (significant wave heights).
Two methods have been used:

1. Bretschneider-model (**Table 2.2**);
2. Mathematecal DELFT3D-model,(**Table 2.3**).

Wave height classes (m)	RGV 0° / RGT 180°	30° / 210°	60° / 240°	90° / 270°	120° / 300°	150° / 330°	180° / 360°	210° / 30°	240° / 60°	270° / 90°	300° / 120°	330° / 150°	Total
< 0.2	12.8	12.8	12.8	18.4	11.0	11.0	9.1	6.3	6,3	6.3	7.1	8.1	**122.0**
0.2-0.4	9.4	9.4	9.4	9.4	7.5	5.7	4.7	4.7	4,7	10.4	9.4	9.4	**94.1**
0.4-0.6	0.9			19	1.9	3.6	11.3	12.3	14,1	11.3	8.5	4.7	**70.5**
0.6-0.8						0.9	6.6	17.0	15,1	8.2	2.8		**50.6**
0.8-1.0							2.8	9.4	7,5	2.8			**22.5**
1.0-1.2							0.5	1.9	1.9	0.2			**4.5**
1.2-1.4								0.3	0.3				**0.6**
> 1.4								0.1	0.1				**0.2**
Total	**23.1**	**22.2**	**22.2**	**29.7**	**20.4**	**21.2**	**35.0**	**52.0**	**50.0**	**39.2**	**27.8**	**22.2**	**365 days**

RGV= Wave direction (to North) from where the waves are coming from
RGT= Wave direction (to North) to which the waves are going

Table 2.2 *Wave data based on Bretschneider-model*

Wave height classes (m)	RGV 0° / RGT 180°	30° / 210°	60° / 240°	90° / 270°	120° / 300°	150° / 330°	180° / 360°	210° / 30°	240° / 60°	270° / 90°	300° / 120°	330° / 150°	Total
< 0.2	11.1	6.4	7.9	7.3	9.1	7.6	7.1	7,0	11.7	9.6	9.7	7.2	**101.6**
0.2-0.4	10.3	8.9	10.8	8.3	9.8	8.3	9.4	10,2	18.9	13.5	9.0	4.9	**122.3**
0.4-0.6	3.6	3.6	5.2	4.3	5.3	7.8	9.8	12,9	21.2	4.0	2.3	1.0	**80.9**
0.6-0.8	0.6	0.6	1.1	1.1	1.8	3.4	6.5	9,6	13.3	1.2			**39.4**
0.8-1.0				0.1	0.2	0.9	3.4	6,0	6.2	0.3			**17.1**
1.0-1.2						0.1	0.6	1,1	1.2	0.1			**3.1**
1.2-1.4							0.1	0,2	0.2				**0.5**
> 1.4													
Totaal	**25.5**	**19.5**	**25.0**	**21.2**	**26.2**	**28.0**	**36.7**	**47,0**	**72.7**	**28.5**	**21.3**	**13.2**	**365 days**

RGV= Wave direction (to North) from where the waves are coming from
RGT= Wave direction (to North) to which the waves are going

Table 2.3 *Wave data based on DELFT3D-model*

Figure 2.2 shows the wave rose based on the annual wave climateod the Bretscheider-model.
The dominant wave directions are: 210^o and 240^o.
The wave rose is fairly symmetrical with respect to the axis South-West (235^o).

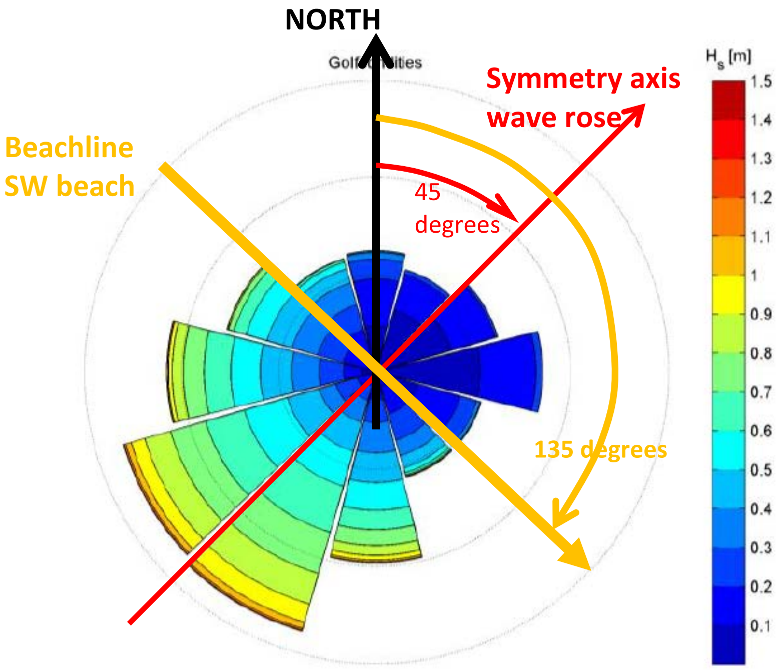


Figure 2.2 *Wave rose based on Bretschneider-model*

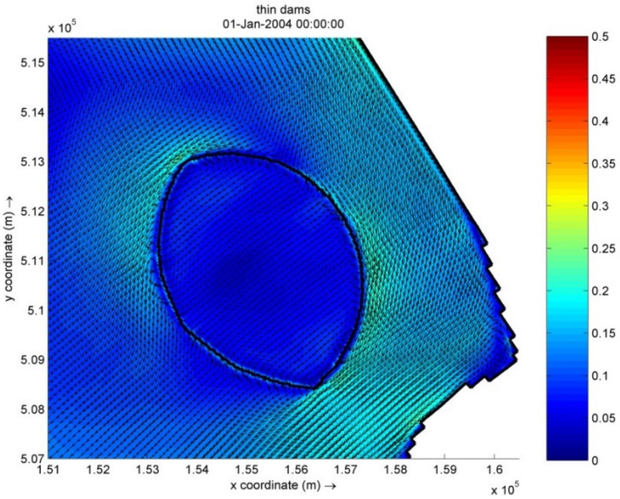


Figure 2.3 *Wind-driven flow; wind from South-West; velocity in m/s*

2.2.3 Circulation currents

Depending on the wind direction and wind strength, large-scale circulation currents are generated in the lake. Wind from South-West to West generates water setup in the North-Eeast corner of the lake, where the artificial island is situated.
In the upper part of the water column there will be a flow of water to this area causing a circulation from West to East (clockwise). At the bottom there will be back-flow to the South-West (return flow). The largest flow velocities according to the model computations are approximately 0.4 m/s (Beaufort wind scale 6 to 7) at the North-West point of the island, see **Figure 2.3**.

3 Design of beaches

3.1 Introduction

The South-West (SW) and North-West (NW) borders of the island consist of sand beaches, **Figure 3.1**.

The orientation of the SW-beach is perpendicular to the dominant wave direction (from the South-West). Often, artificial sandy beaches are enclosed by stone/rock groins on both ends. Wooden groins at regular intervals can be used to make smaller compartments; especially in those areas where significant net longshore transport may occur, depending on the wave climate and the location of the coastline.

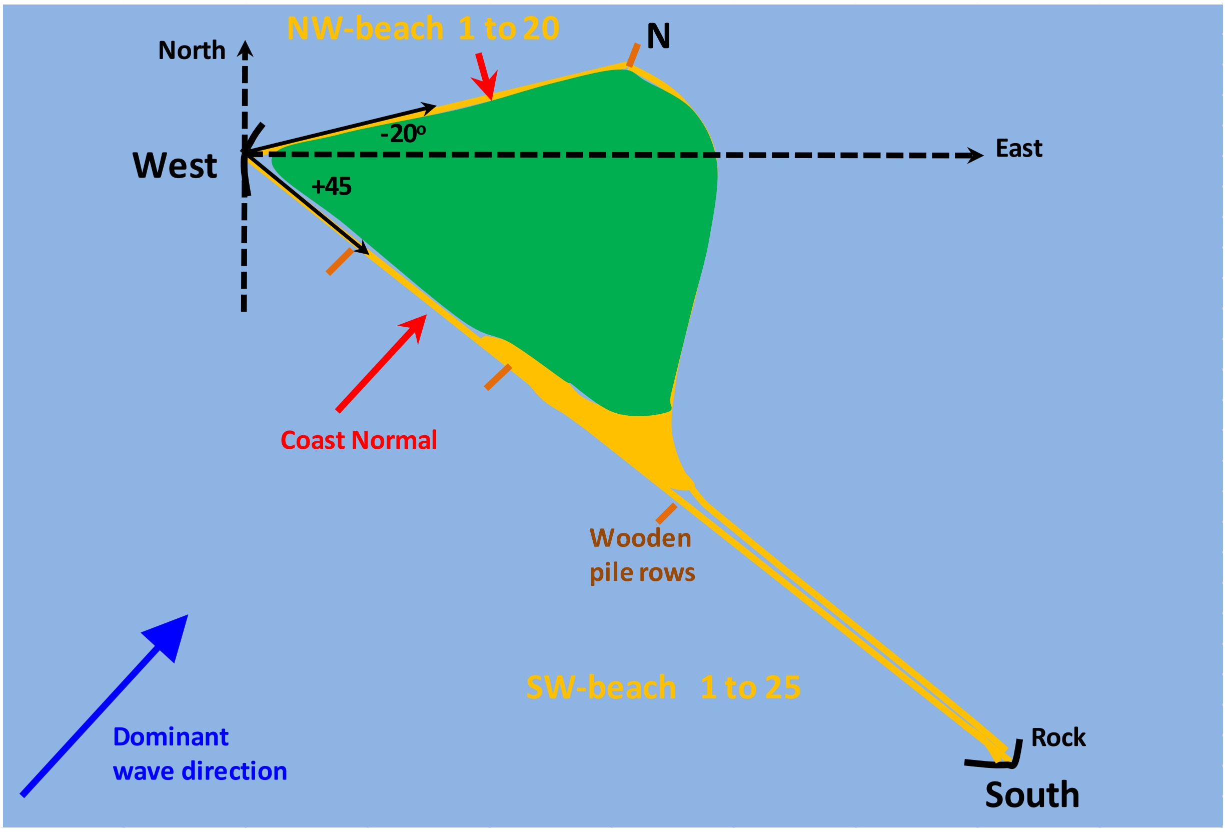


Figure 3.1 *Plan view of island with beaches*

3.2 Examples of artificial beaches

Figures 3.2.1, 3.2.2 and **3.2.3** show three examples of artificial beaches in mild wave conditions.

Figure 3.2.2 shows the presence of a curved bay-type beach in the lee of a groin. Minor deposition of mud may occur in the lee areas, which may stimulate plant growth.

Figure 3.2.3 shows the beach near Copenhagen, which has a length of 1300 m. The beach plain is covered with grass-type plants.

Figure 3.2.1 *Artifical beach Workum, Friesland (length 700 m; beach width at end 30 m)*

Figure 3.2.2 *Artificial beach Mirnser Cliff, Friesland (length 200 m, beach width near groin 30 m)*

Figure 3.2.3 *Artificial beach Copenhagen, Sont, Baltic (length 1300 m, width near ends 80 m)*

3.3 Beach characteristics

3.3.1 Sand composition

The available sand has the following properties:

- d_{50} = 0.265 mm (0.155 to 0.585 mm);
- d_{60}/d_{10} = 2.56 (1.8-3.4);
- 2.5% < 0.063 mm (0.1-9.6 %) and 4.1% > 2 mm (0.0-28.3 %).

Bore hole data show that the d_{50} increases from 0.15 to 0.45 mm with depth in the layers between -10 m and -25 m NAP. The beach above the -2 m depth contour will be made of sand taken from the sand layers between -18 m and -30 m NAP. The mean grain size of sand from these layers is about 0.35 mm (standard deviation σ_{d50}= 0.11 mm). The grain size used in the morphological computations is d_{50}= 0.2 mm to be on the safe side (upper limit). Some computations have been made using d_{50}= 0.35 mm.

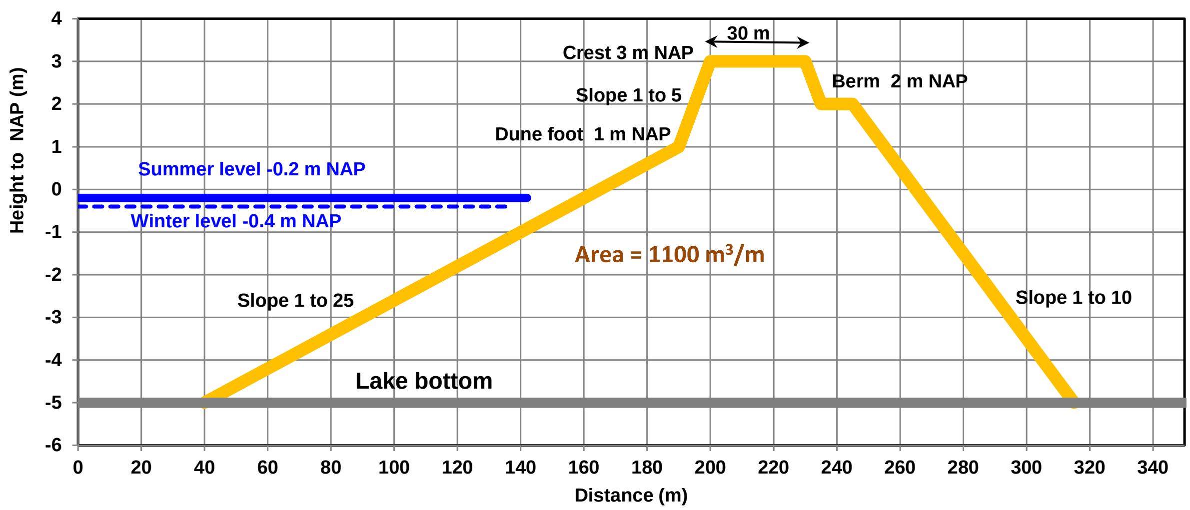
3.3.2 Cross-shore beach profile dimensions

SW-beach

Figure 3.3.1 shows the cross-section of the SW-beach. The beach slope should be as steep as possible to reduce on construction cost, but no so steep that excessive erosion is to be expected.
Given the mild wave conditions in the lake, the beach slope is selected to be 1 to 25 for 0.2 mm sand.

Beach characteristics:

- d_{50} of 0.2 to 0.35 mm;
- beachslope 1 to 25 between lake bottom and dunefoot at +1 m NAP;
- slope of 1 to 5 between dune foot and crest;
- crest level at +3 m NAP (after settlement);
- crest width 30 m; beach width 35 m (in summer);
- berm behind crest at +2 m NAP; lee side slope 1 to 10;
- areas cross-section of about 1100 m^2
- area cross-section above +0,5 m NAP of about 150 m^3/m;
- area cross-section above +1 m NAP of about 110 m^3/m.
-



Figuur 3.3.1 *Cross-section SW-beach; slope 1 to 25*

NW-beach

Figure 3.3.2 shows the cross-section of the NW-beach.

Beach characteristics:

- d_{50} of 0.2 to 0.35 mm;
- slope of 1 to 20 between lake bottom and dune foot at +1 m NAP;
- slope of 1 to 5 between dune foot and crest;
- crest level at +3 m NAP;
- crest width of 15 m;
- lee side slope of 1 to 10;
- area cross-section of about 700 m^3/m.

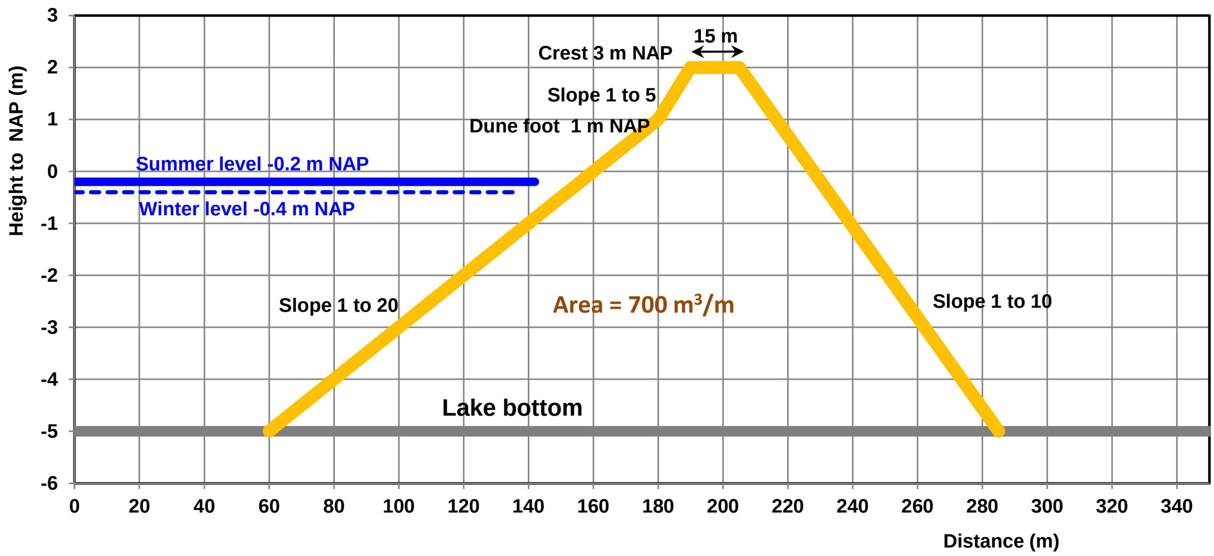


Figure 3.3.2 *Cross-section NW-beach; slope 1 to 20*

3.3.3 Wave overtopping

The wave overtopping of the SW-beach crest has been computed using the EUROTOP expressions (safety factor=1.5; tool Armour.xls) as function of crest level, slope and wave height.
Input data are:

- significant wave height of 1.3 m with frequency of 1x per 10 years; water setup= 0.9 m above winter lake level; slopes 1 to 3 and 1 to 5;
- significant wave height of 1.5 m with frequency of 1x per 50 years; water setup= 1.1 m above winter lake level; slopes 1 to 3 and 1 to 5.

According to **Figure 3.3.3**, the maximum wave overtopping is negligibly small (< 0.1 l/m/s) at a wave height of H_s= 1.5 m (1x 10 years), dune slope of 1 to 5 and crest level of 3.4 m above the winter lake level. The effect of the beach has been neglected. High waves will break on the beach yielding relatively low waves (30% lower) at the dune foot.

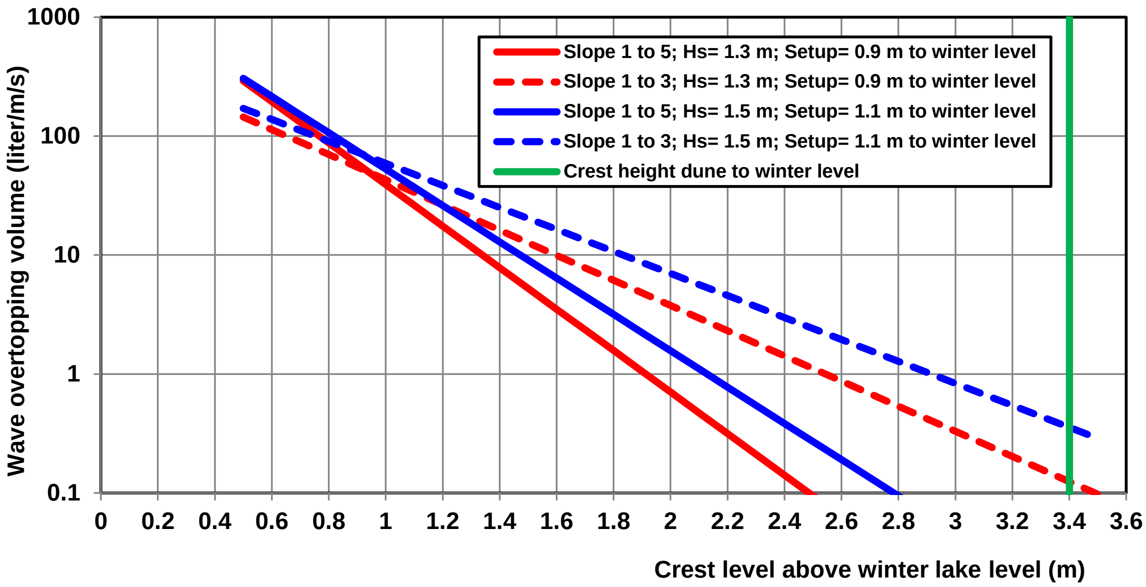


Figure 3.3.3 *Wave overtopping volume as function of crest level, slope and wave height*

3.4 Longshore sand transport

3.4.1 Net longshore transport based on Van Rijn

The langstransport formula of Van Rijn (2014) is a function of the particle size, the steepness of the beach, the wave height and the breaker angle at the breakerline, see **Annex A**. This formula has recently been improved and calibrated with a large number of field data, including conditions with relatively low waves. The formula is valid for sand and gravel. The formula is implemented in the spreadsheet model Littoral. xls (freeware).

The net annual longshore transport at a particular location can be computed by summation of all contributions of wave heights and wave directions (Littoral. xls) based on the deep water wave climate. The equilibrium position (equilibrium angle) of the beach is the angle at which the net longshore transport is approximately equal to zero.

Figure 3.4.1 gives a definition sketch of the wave angles and and the coast normal (Littoral. xls).

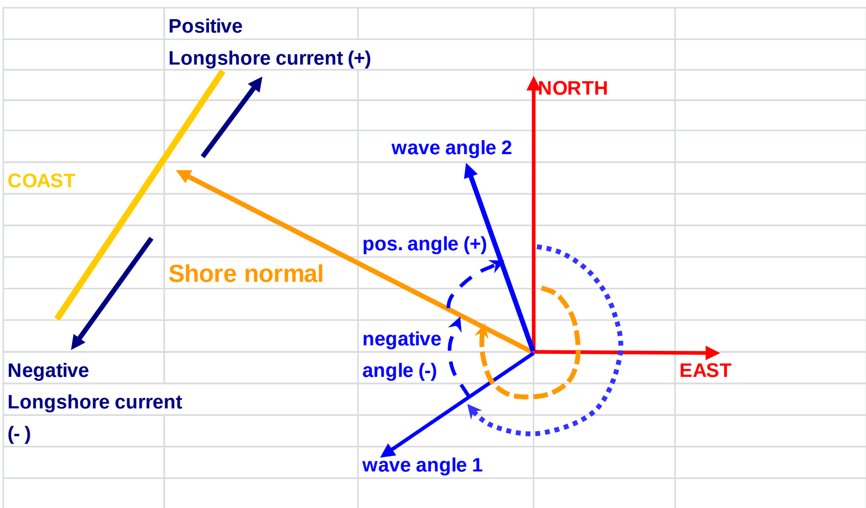


Figure 3.4.1 *Definition sketch of wave angles and coast (shore) normal*

SW-beach

The computed net longshore transport rates are shown in **Figure 3.4.3**. The transport directions are shown in **Figure 3.4.2**.
Two long-term wave climates are used: Bretschneider wave climate (**Table 2.2*)*** and DELFT3D wave climate (**Table 2.3**). The grain diameter is 0.2 mm. The beach slope is 1 to 30.

The equilibrium angle (net langstransport= zero) of the coast normal is:

- 38° with respect to the North (beach line makes angle of 38° with the West-East line) based on DELFT3D wave climate;
- 45° compared to North (beach line makes angle of 45° to the West-East line) based on Bretschneider wave climate.

Based on this, the angle of the coast normal at the SW-beach is selected to be 45° (coastline angle 45° with West-East line). The maximum net longshore transport for this orientation is about 5000 m^3/year.

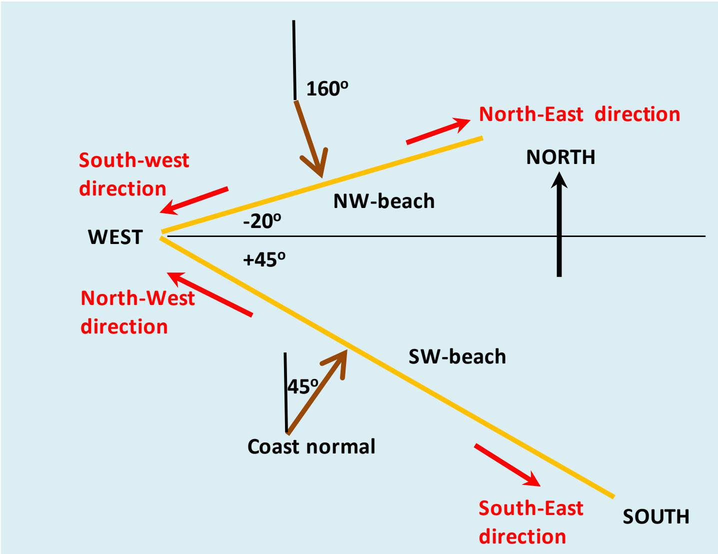


Figure 3.4.2 *Longshore sand transport directions*

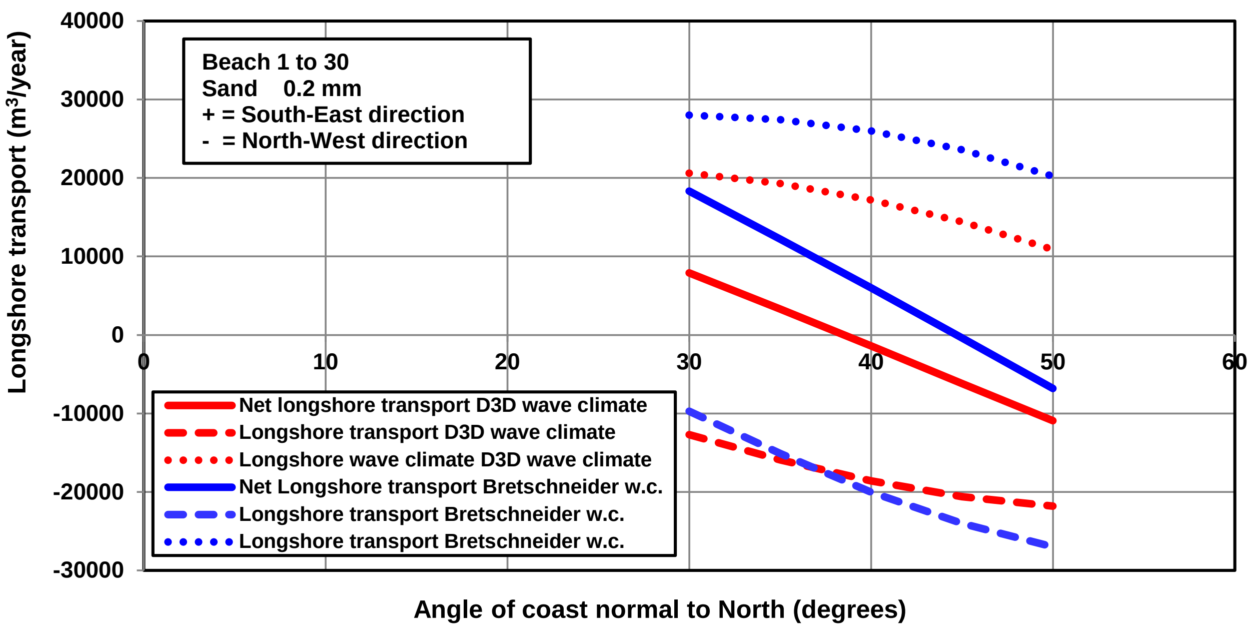


Figure 3.4.3 *Longshore sand transport as function of coast normal angle; d_{50}= 0.2 mm; SW-beach*

Figure 3.4.4 shows the influence of the particle size on the net longshore transport at the SW-beach. The net longshore transport is 30% smaller for a grain diameter of 0.35 mm than for a grain diameter of 0.2 mm. In practice, some beach sections may have a grain diameter of 0.2 mm, whereas other sections may have a grain diameter of 0.35 mm. This may give small gradients of the net longshore transport (≃2000 m^3/year).

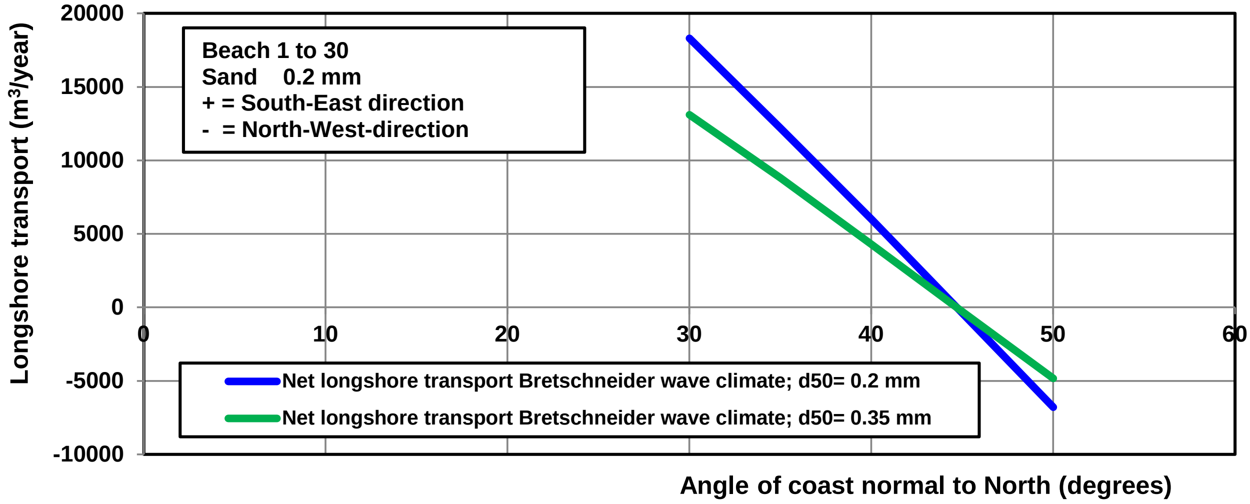


Figure 3.4.4 *Effect of grain size; SW-beach*

NW-beach

The computed net longshore transport rates are shown in **Figure 3.4.5**.
Two long-term wave climates are used: Bretschneider wave climate (**Table 2.2*)*** and DELFT3D wave climate (**Table 2.3**). The grain diameter is 0.2 mm. The beach slope is 1 to 20.
The equilibrium angle (net langstransport= zero) of the coast normal is:

- 150° with respect to the North (beach line makes angle -30° with the West-East line) based on DELFT3D wave climate;
- 190° compared to North (beach line makes angle of +10° to the West-East line) based on Bretschneider wave climate.

Based on this, the angle of the coast normal at the NW-beach is selected to be 160° (coastline angle -20° with West-East line), see **Figure 3.4.2**. The maximum net longshore transport is about 7500 m^3/year.

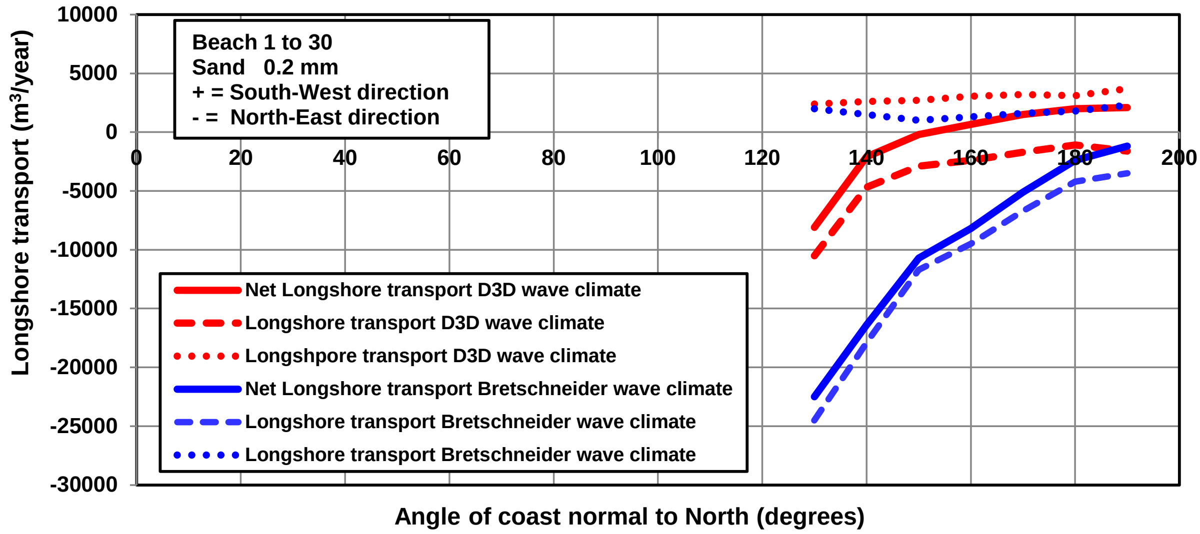


Figure 3.4.5 *Longshore sand transport as function of beach angle; d_{50}= 0.2 mm; NW-beach*

3.4.2 Longshore transport based on CROSMOR-model

The detailed CROSMOR-model (**Annex B**) has also been used to determine the longshore transport for one wave direction (South-West) making an angle of 45° to the coast normal at the SW-beach, see **Tables 3.4.1** and **3.4.2**.
The value of the longshore transport in NW direction (waves from South-West) is of the order of 25,000 m^3/year for 0.2 mm sand and beach slope of 1 to 30. This value is at the upper range of the values of 15,000 to 25,000 m^3/year given in **Figure 3.4.3**.
The longshore transport is about 12,000 m^3/year in NW direction for 0.35 mm sand, which is about 50% smaller than that for 0.2 mm sand.

Wave height H_s (m)	**Wave period T_p (s)**	**Wave angle to coast normal (°)**	**Water setup to winter lake level (m)**	**Duration (days)**	**Longshore transport North-West (m^3/hour)**	**Total longshore transport direction North-West (m^3)**
1.5 (1x 50 years)	6.0	-45	1.1	0,4	350	3360
1.3	6.0	-45	0.9	0,6	170	2450
1.1	5.5	-45	0.6	3	75	5400
0.9	5.0	-45	0,3	15	25	9000
0.7	4.5	-45	0.2	25	6	3600
0.5	4.0	-45	0	30	1.2	865
0.3	3.5	-45	0	40	0.1	100
Total				114 days		24,775 m^3

d_{50}= 0.2 mm; *slope 1 to 30*

Table 3.4.1 *Longshore transport in direction North-West based on CROSMOR-model; SW-beach*

Wave height H_s (m)	**Wave period T_p (s)**	**Wave angle to coast normal (°)**	**Water setup to winter lake level (m)**	**Duration (days)**	**Longshore transport North-West (m^3/hour)**	**Total longshore transport direction North-West (m^3)**
1.5 (1x 50 years)	6.0	-45	1.1	0.4	120	1150
1.3	6.0	-45	0.9	0.6	55	790
1.1	5.5	-45	0.6	3	27	1945
0.9	5.0	-45	0,3	15	12	4320
0.7	4.5	-45	0.2	25	4	2400
0.5	4.0	-45	0	30	1.2	865
0.3	3.5	-45	0	40	0.1	100
Total				144 days		11,570 m^3

d_{50}=0.35 mm; *slope 1 to 30*

Table 3.4.2 *Longshore transport in direction North-West based on CROSMOR-model; SW-beach*

Figure 3.4.6 shows the sand transport in longshore and cross-shore directions for a storm with H_s= 1.3 m with a frequency of 1 per 10 years. The longshore transport is about 1.6 kg/m/s x 50 m wide = 80 kg/s = 80 kg/s x 3600 s/1600 kg/m^3 ≅ 170 m^3/hour (incl. pores), see also **Table 3.4.1** (row 3).

The longshore transport during a storm is concentrated on the upper part of the beach (x > 1050 m); landward of the -2 m depth line. The cross-shore bed-load transport is directed landward in the shallow nearshore zone due to the predominant wave asymmetry effect. The cross-shore suspended transport is directed seaward due to the return flow caused by breaking waves in the nearshore zone (water depth < 1 m). When smaller waves are present, the sand transport is more close to the water line.

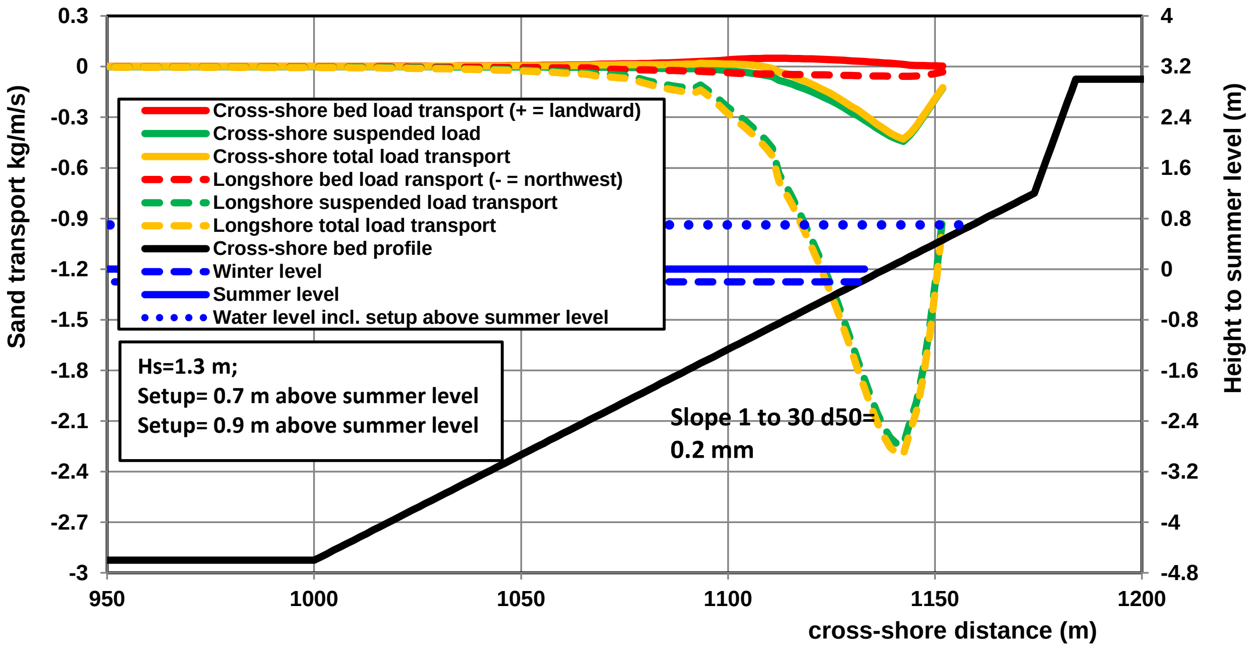


Figure 3.4.6 *Sandtransport in cross-shore and longshore directions based on CROSMOR-model; SW-beach; d_{50}= 0.2 mm; slope 1 to 30*

3.5 Orientation of SW-beach and NW-beach

3.5 Straight beach sections

The SW-beach and the NW-beach are under wave attack by waves from the sectors South-West and North-West. The positions of the SW-beach line (+45° with West-East line) and the NW-beach line (-20° with West-East line) are selected in such a way that the net longshore transport is minimum (Figures 3.4.3, 3.4.4, 3.4.5 and 3.5.1).

Beach characteristics:

- SW-beach is a straight beach with a length of 3 km making an angle of 45° with West-East line; beach slope of 1 to 25; cross-shore profile according to **Figure 3.3.1**;
- NW-beach is a straight beach with a length of 1.5 km making an angle of 20° with West-East line; beach slope of 1 to 20; cross-shore profile according to **Figure 3.3.2**;
- Beach heads (ends) are defended by stone/rock protections; wooden pile rows are constructed at various places to make small compartments (pile row length 100 m, diameter 0.2 m, space between piles 0.1 m; pile heads 0.5 m NAP at-2.5 m depth and +1 m NAP near dunefoot).

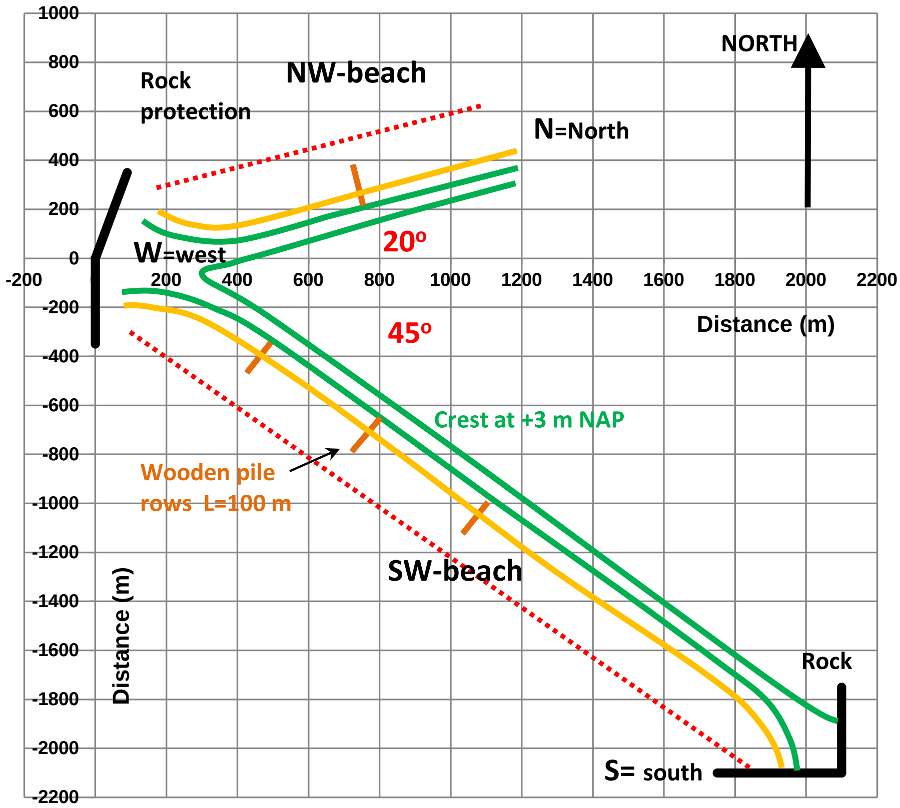


Figure 3.5.1 *Plan view of beaches*

3.5.2 Curved beach sections in lee of fixed boundary

A sandy beach in the lee of a fixed boundary (breakwater, groin, rocky cape or headland) has a curved shape caused by a combination of wave refraction and wave diffraction. A sandy beach enclosed by two fixed boundaries develops a curved shape at both ends. If two fixed boundaries are present, they influence each other, creating a small bay known as 'pocket beach'.
These types of beaches can be described by (Moreno and Kraus, 1999):

- logarithmic spiral function; especially for 'pocket beaches' with two fixed boundaries at short distance from each other;
- parabolic function and tangent-hyperbolic function for beaches in the lee of one fixed boundary.

According to **Moreno and Kraus (1999),** the beach in the lee of a fixed boundary can be described by:

$$Y = A\,[\tanh(BX)]^m$$

in which:
Y = cross-shore distance from origin (m); origin is beach end against the boundary (**Figure 3.5.2**);
X = alongshore distance from origin (m);
A = cross-shore distance from origin to straight beach section further away from the boundary (m);
B = coefficient determining the alongshore distance from the curved beach (1/m);
m = coefficient (about 0.5).

Moreno and Kraus (1999) have studied 28 small and large bays to determine the A, B, and m-values. It follows that m≅ 0.5 and B ≅ 1.2/A.

The above-given equation is used to determine the curved beach lines at both ends of the SW- and NW-beaches, with A = 100 m, B = 0.005 and m = 0.5. This gives an alongshore adjustment length of about 400 to 500 m (adjustment of about 1 in 4).

Figure 3.5.2 shows curved beach lines in the lee of the fixed boundary at corner point West. Cross-shore variations of 20 to 30 m may occur due to variation of the alongshore transport gradients (see also Figures 3.6.1 and 3.6.2)

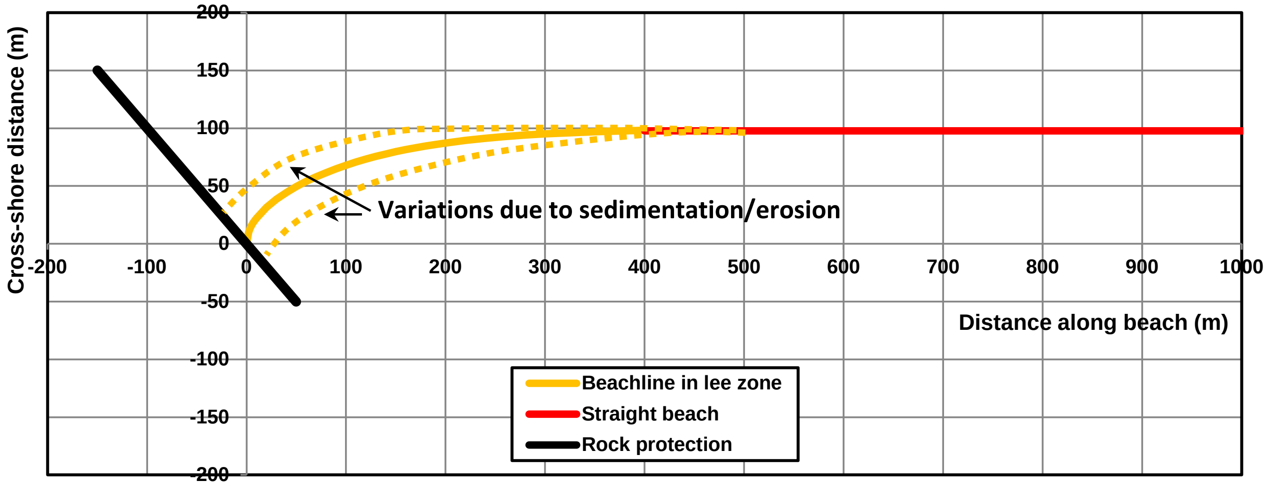


Figure 3.5.2 *Curved beachlines in lee of fixed boundary at corner point West*

3.6 Alongshore beach erosion (LONGMOR-modelling)

3.6.1 SW-beach

The LONGMOR-model (Van Rijn, 2006, 2012; **Annex A**) has been used to compute the longshore transport of sand and the beach line changes due to variations of the wave climate (wave directions).

The SW-beachline makes an angle of 45° with the line West-East (see **Figure 3.5.1**). The net longshore transport is maximum of the order of 5000 m^3/year according to **Figure 3.4.3**.

The settings of the LONGMOR model are given in **Table 3.6.1**.

PARAMETER	VALUE
Grid distance and beach length	5 m; 3000 m
Time step and grid-smoothing	0.05 day; 0.0001
Sand d_{50}, d_{90}	0.2 mm; 0.5 mm
Slope of beach in nearshore zone of 0 to -5 m NAP	1 to 25
Breaker coefficient	0.6
Layer thickness of active zone	5 m (between -2 m and + 3 m NAP)
Longshore transport formula; correction coefficient	Van Rijn 2014; 1 (default)
Angle of coast normal to North	135 and 140 degrees
Input file	markw1. inp (right Beach) markw2. inp (hollow beach)

Table 3.6.1 *Settings of LONGMOR-model for SW-beach*

The LONGMOR-computations have been made using a simplified annual wave climate (**Table 3.6.2**). The net longshore transport is calibrated to:

A. 1000 m^3/year in direction North-West based on an almost symmetric wave climate to the coast normal (beach angle of 135^o to North, see **Figure 3.4.3**);
B. 5000 m^3/year in direction North-West based on a asymmetric wave climate (beach angle of 140^o; shift angle of 5^o is uncertainty value of wave directions, see **Figure 3.4.3**.

Time **(days)**	**Significant wave height at deep water** **$H_{s,o}$ (m)**	**Peak wave period** **T_p (s)**	**Angle of wave direction to coast normal** **(degreees)**
0.	0.1	2.1	30 (transport in NW)
75 (75)	0.1	2.1	30 (transport in NW)
75.1	0.1	2.1	-30 (transport in SE)
150 (75)	0.1	2.1	-30 (transport in SE)
150.1	0.3	2.3	30
190 (40)	0.3	2.3	30
190.1	0.3	2.3	-30
230 (40)	0.3	2.3	-30
230.1	0.5	2.5	30
260 (30)	0.5	2.5	30
260.1	0.5	2.5	-30
290 (30)	0.5	2.5	-30
290.1	0.7	3.0	30
315 (25)	0.7	3.0	30
315.1	0.7	3.0	-30
340 (25)	0.7	3.0	-30
340.1	0.9	3.5	30
350 (10)	0.9	3.5	30
350.1	0.9	3.5	-30
360 (10)	09	3.5	-30
360.1	1.1	4.2	30
362 (2)	1.1	4.2	30
362.1	1.1	4.2	-30
364 (2)	1.1	4.2	-30
364.1	1.3	4.7	30
364.5 (0,5)	1.3	4.7	30
364.5	1.3	4.7	-30
365 (0,5)	1.3	4.7	-30

Table 3.6.2 *Simplified annual wave climate; Longmor-model; SW-beach*

Figure 3.6.1 shows the computed beach lines of the SW-beach after 10 years for the above-given net longshore transport values, taking into account the influence of the shadow areas (no transport) behind the curved breakwaters on both ends of the beach. The longshore transport is assumed to be zero at about 300 m from the beach end. The beach line is plotted for an observer on the beach facing the South-West. The maximum recession at the updrift end of the beach is about 5 m after 10 years, if the angle of the initial beach line is equal to the equilibrium angle (45^o with the line West-East).

If the angle of the initial beach line is shifted over 5°, the net langstransport in the direction North-West is about 5000 m^3/year. This gives a maximum recession of 25 m after 10 years. The maximum beach erosion volume over a length of 1500 m (half beach length) is of the order of 50,000 m^3 (layer thickness = 5 m between-2 m and + 3 m NAP) after 10 years.

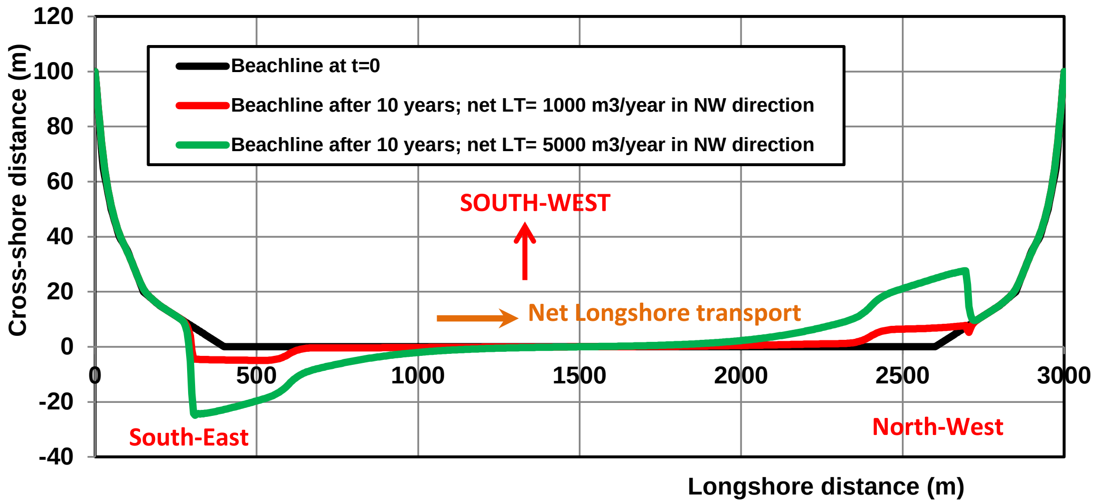
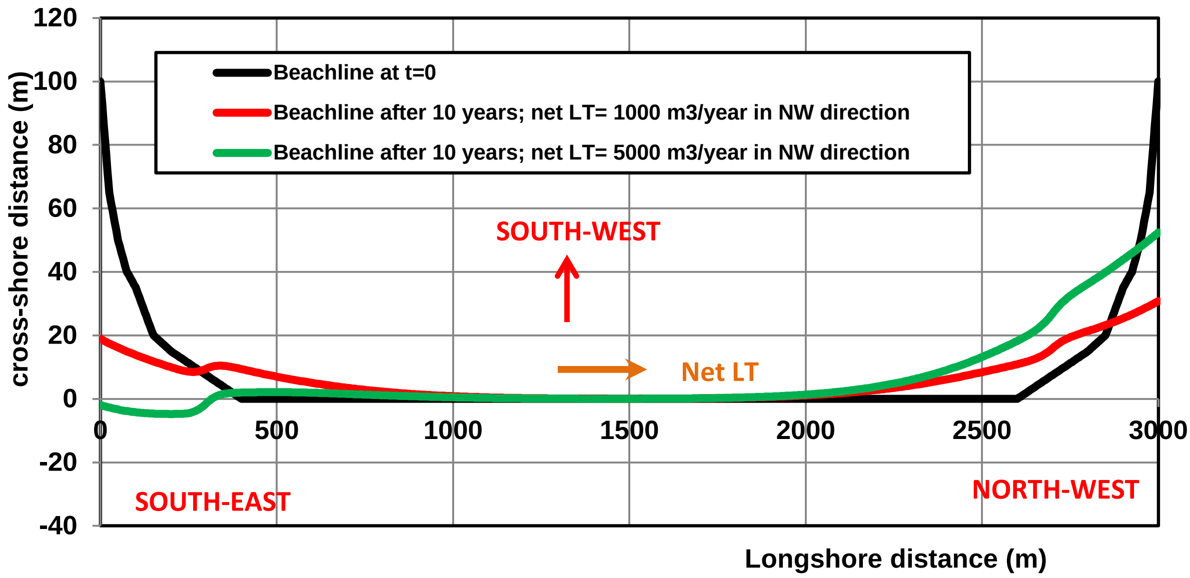


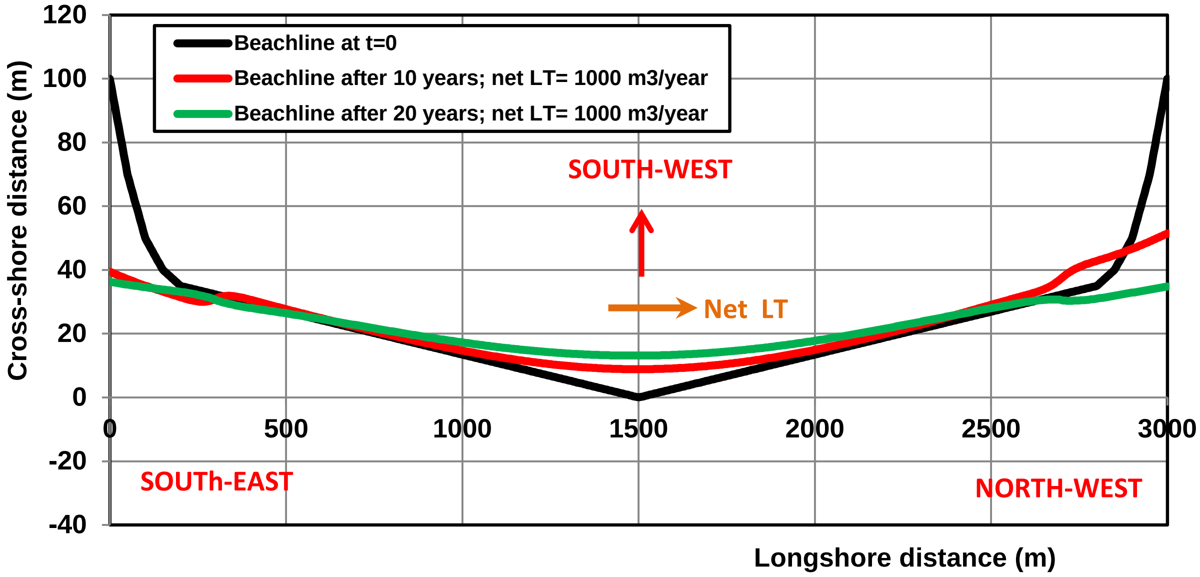
Figure 3.6.1 *SW-beachline based on LONGMOR-model **with** lee areas on both ends*

Figure 3.6.2 shows similar results neglecting the lee areas. In this case the longshore transport is zero at both ends. The volume of sand of about 50,000 m^3 in the lee area at the South end (updrift end) is completely eroded after 10 years in the situation with shift of 5° of the wave directions (net longshore transport of 5000 m^3/year).



Figuur 3.6.2 *SW-beachline based on LONGMOR-model **neglecting** lee areas on both ends*

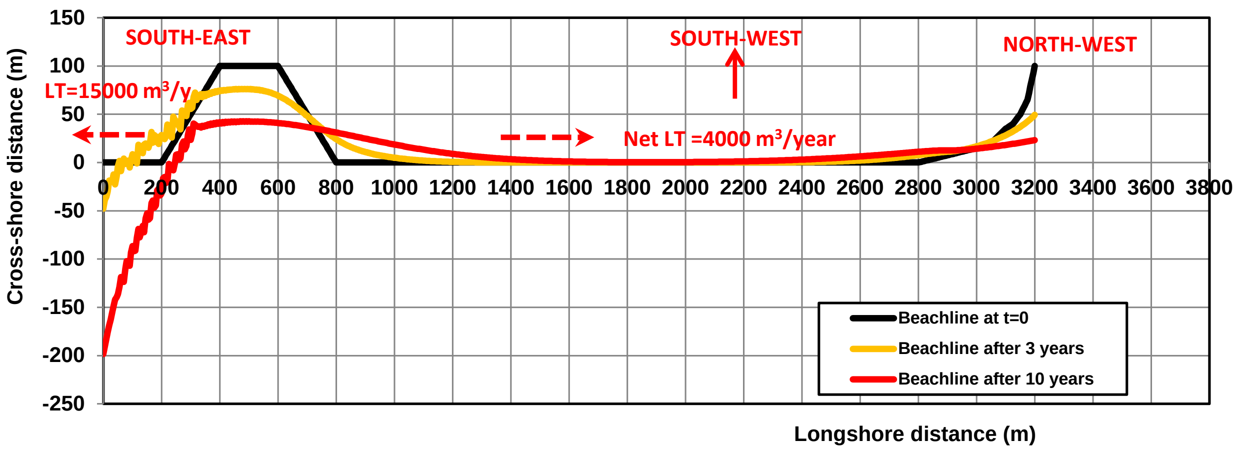
Figure 3.6.3 shows the computed beach line in the situation with a hollow beach section (at t = 0), neglecting in the lee areas. The longshore transport is zero at both ends. The middle part of the beach is gradually straightened because sand is carried from the boundaries to the middle. A bulbous beach will also be straightened, because sand will be carried from the middle to both ends.



Figuur 3.6.3 *SW-beach based on LONGMOR-model neglecting lee areas; hollow type of beach*

Effect of beach extension at one end (south end)

Figure 3.6.4 shows the computed beach line for a situation with a large beach extension at the South-East end. The beach extension consists of a widened beach (about 100 metres) over an alongshore distance of about 600 m. The beach extension will gradually be spread out along the beach. After 10 years the width of the beach extension is reduced to about 50 m. The tip (point S) of the beach is eroded strongly and a beach hook is formed. After 10 years, about 150,000 m^3 of sand has passed the corner point South-East.



Figuur 3.6.4 *SW-beach based on LONGMOR-model; beach extension at corner South-East*

3.6.2 NW-beach

The NW-beach makes an angle of -20° (coast normal angle of 160°) with the line West-East. The net longshore transport in the North-East direction amounts to 5000 m^3/year, see **Figure 3.4.5**.
Similar to the computations in **Section 3.6.1,** the maximum erosion is assumed to be 50,000 m^3 after 10 years. Erosion will occur at the updrift (South-West) and deposition of sand at the downdrift side (North-EAST).

3.7 Cross-shore erosion of SW-beach due to daily waves (CROSMOR modelling)

3.7.1 Introduction

The beach profile as given in the **Figure 3.3.1** is not a natural equilibrium profile. The initial profile will be changed into a more natural profile with sand bars and troughs by cross transport processes.
To study the beach profile changes on the long term, the CROSMOR-model has been used (over 5 to 10 years).

3.7.2 Cross-shore profile

Various initial beach slopes have been studied: 1 to 25, 1 to 30 and 1 to 25 (with and without steep toe of 1 to 10). Two grain diameters have been used: d_{50}= 0.2 and 0.35 mm.

3.7.3 Wave climate

The annual wave climate of daily waves is given in **Table 3.7.1**.
The highest wave is H_s= 1.1 m with water level setup of 0.4 m with respect to the summer lake level (0.6 m to winter level).

Time (days)	**Wave heights H_s en H_{rms} (m)**	**Wave period T_p (s)**	**Wave angle to coast normal (°)**	**Water level setup to summer lake level (m)**
0. tot 140 (140)	0.1; 0.07	3	0	0
140.1 tot 220 (80)	0.3; 0.21	3.5	0	0
220.1 tot 260 (40)	0.5; 0.35	4.0	45	0
260.1 tot 290 (30)	0.5; 0.35	4.0	-45	0
290.1 tot 315 (25)	0.7; 0.5	4.5	45	-0.1
315.1 tot 340 (25)	0.7; 0.5	4.5	-45	-0.1
340.1 tot 350 (10)	0.9; 0.64	5.0	45	0.1
350.1 tot 362 (8)	0.9; 0.64	5.0	-45	0.1
362.1 tot 364 (2)	1.1; 0.79	5.5	45	0.4
364.1 tot 366 (2)	1.1; 0.79	5.5	-45	0.4

Table 3.7.1 *Simplified annual wave climate used in CROSMOR-model; SW-beach*

3.7.4 Settings of CROSMOR-model

The model settings are given in **Table 3.7.2**.

PARAMETERS	VALUES
Water depth at deeper water	4.6 m
Beach slope	1 to 25, 1 to 30 and 1 to 40
Dune foot	1.2 m above summer lake level
End depth = water depth in last grid point	0.2 m
Grid distance	10 m (deep water) to 2 m (beach)
Total length	1500 m
Number of wave classes	1
Wave asymmetry	Yes, according to Isobe-Horikawa
Longuet-Higgins coefficient; roller effect	0.5 (default = 1); 0.5 (default = 1)
Grain diameter sand d_{50}	0.2 mm; 0.35 mm
Coefficients sand transport formulas	1 (default = 1)
Coefficient sand transport by wave asymmetry	0.2 (default = 1)
Coefficient return flow (undertow)	1 (default)
Extra sand stirring at dune front (sef)	1 (default; no effect)
Bed roughness	Automatically
Temperature and salinity	10 degrees and 0 promille
Files	markw20. inp; markw30. inp; markw40. inp mw30BB. inp (breaker bar); mw30oos. inp

Table 3.7.2 *CROSMOR-model settings; SW-beach*

3.7.5 Cross-shore beach profile erosion

Figure 3.7.1 shows the initial bed profile (slope 1 to 30) and the computed profiles after 1, 5 and 10 years (according to CROSMOR) for sand d_{50}= 0.2 mm. **Table 3.7.3** shows the computed erosion volumes. The maximum beach erosion after 10 years is of the order of 20 m^3/m for the annual wave climate without extreme storms. The value of 20 m^3/m erosion is already present after 1 year and remains fairly stable after that. The beach is protected by the breaker bar, which is generated during the first year. The outer flank of the breaker bar is relatively steep, which can lead to local instability. As a result, additional sand can be carried to the toe of the beach; especially for relatively coarse sand (0.35 mm).
Because the water level variations of the lake are relatively small, the position of the breaker bar in the shallow zone will be rather stable. The computed deposition of sand at the toe of the profile is not realistic because no sand can be supplied from the original lake bottom, which is rather muddy.

Figure 3.7.2 shows the initial bed profile (slope 1 to 30) and the computed bed profiles after 1 and 5 years (according to CROSMOR) for sand d_{50}= 0.35 mm. The computation for 10 years is not stable because sand is constantly supplied from deeper water (not realistic). The slope of the breaker bar is too steep. The wave climate applied contains no storm waves that can erode the breaker bar.
The maximum beach erosion after 5 years is of the order 5 m^3/m for the wave climate without extreme storms. The value of 5 m^3/m erosion is already present after 1 year and remains stable after that. The beach is protected by the breaker bar.

Figure 3.7.3 shows the initial bed profile (slope 1 to 40) and the computed bed profile after 1, 5 and 10 years (according to CROSMOR) for sand d_{50}= 0.2 mm.
The maximum beach erosion after 10 years is of the order 10 m^3/m for the wave climate without extreme storms. The beach is protected by the breaker bar.

Figure 3.7.4 shows the initial bed profile (slope 1 to 40) and the computed bed profile after 1, 5 and 10 years (according to CROSMOR) for sand d_{50}= 0.35 mm. In the case of an initial slope of 1 to 40 with sand of 0.35 mm, there is no beach erosion for an annual wave climate without extreme storms. In the first year, a breaker bar is formed protecting the beach for additional erosion.

Figure 3.7.5 shows the initial bed profile for slope 1 to 25 and the computed bed profile after 3 years (according to CROSMOR) for sand d_{50}= 0.2 mm. The erosion after 3 years is approximately 15 m^3/m and is somewhat less than the erosion for a slope of 1 to 30, see **Table 3.7.3**. This is due to the effect of the breaker bars.
In the case with a slope of 1 to 10 at the toe of the beach, the erosion after 3 years increases from 15 m^3/m to 22 m^3/m (40% increase). The steep toe is smoothed out with sand coming from the upper profile. This will lead to more beach maintenance on the long term.

In summary:

- the erosion due to the annual wave climate is concentrated in water depths smaller than 1 m;
- a small breaker bar is formed at a water depth of about 1 m below the summer lake level;
- the erosion at a beach slope of 1 to 25 may be somewhat less than for a beach slope of 1 to 30 (sand 0.2 mm), because the breaker bar is formed at a higher position along the beach face (more protection);
- the erosion is less (30%) at a beach slope of 1 to 40 than that at a slope of 1 to 30 (sand 0.2 mm);
- a beach slope of 1 in 25 (SW-beach) is sufficiently stable in the long term;
- a steep toe (1 in 10) gives more erosion of the beach at the water line.

Wave climate	**Water setup to winter lake level (m)**	**Initial slope**	**Sand d_{50} (mm)**	**Computed erosion volume of beach (m^3/m)**			
				after 1 year	**3 years**	**5 years**	**10 years**
H_s = 0.1 to 1.1 m	0 to 0.6	1 to 30	0.2	18	-	20	20
H_s = 0.1 to 1.1 m	0 to 0.6	1 to 30	0.35	5	-	7	(instable)
H_s = 0.1 to 1.1 m	0 to 0.6	1 to 40	0.2	10	-	12	15
H_s = 0.1 to 1.1 m	0 to 0.6	1 to 40	0.35	0	-	0	0
H_s = 0.1 to 1.1 m	0 to 0.6	1 to 25	0.2	12	15	-	-
H_s = 0.1 to 1.1 m	0 to 0.6	1 to 25 1 to 10 at toe	0.2	18	22	-	-

Table 3.7.3 *Beach erosion based on CROSMOR-model; SW-beach*

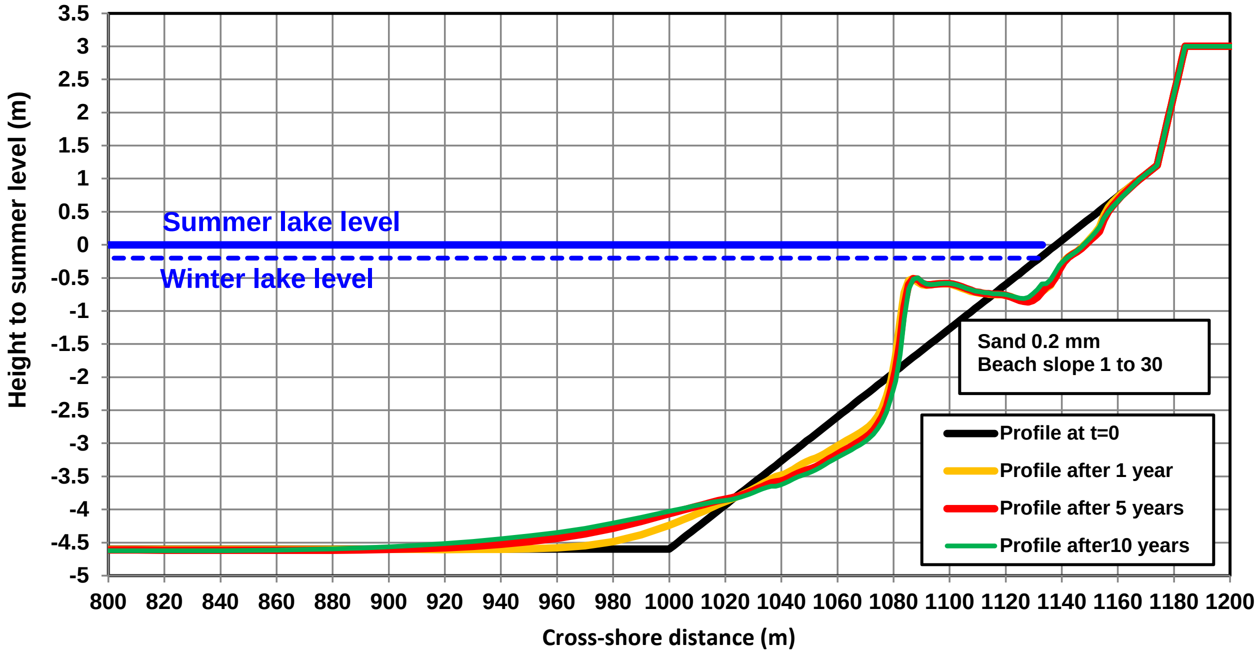


Figure 3.7.1 *Computed bed profile based on CROSMOR-model; SW-beach; annual wave climate; slope 1 to 30, d_{50}=0.2 mm*

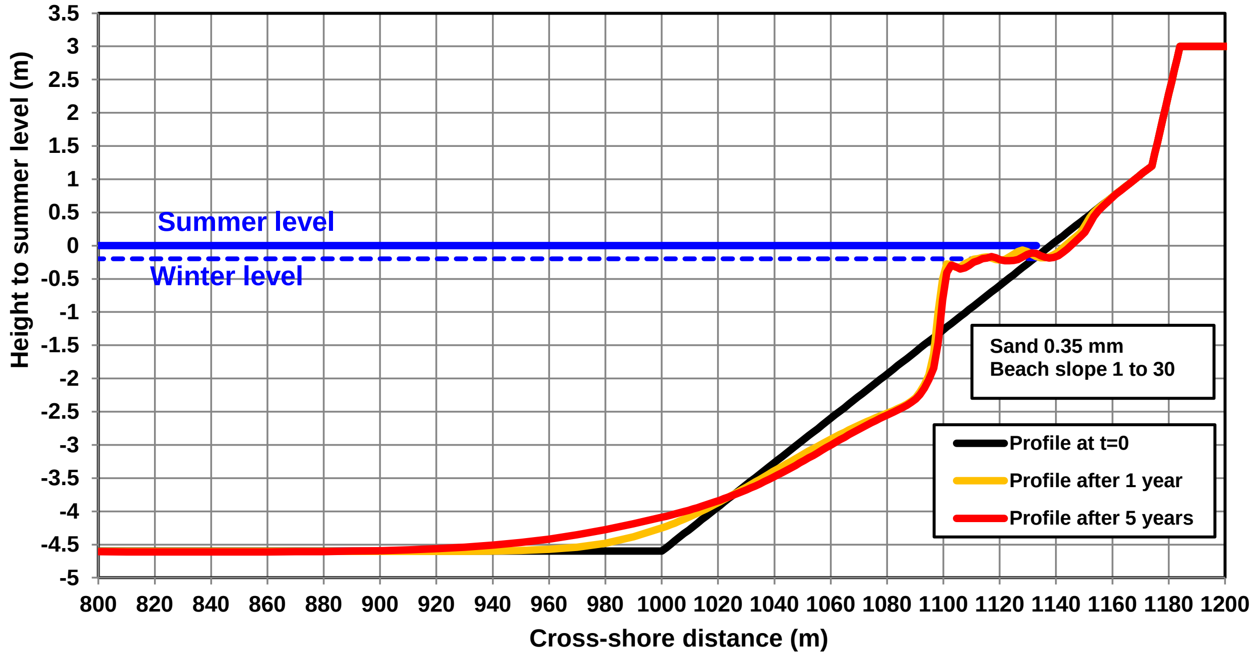
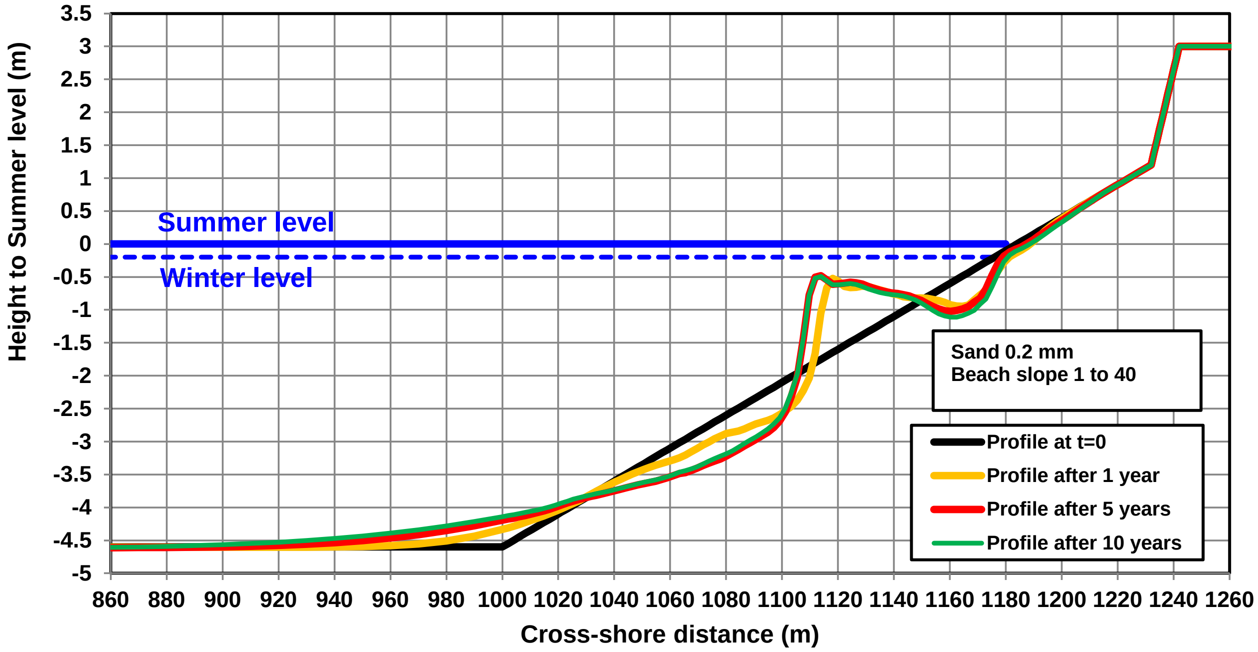
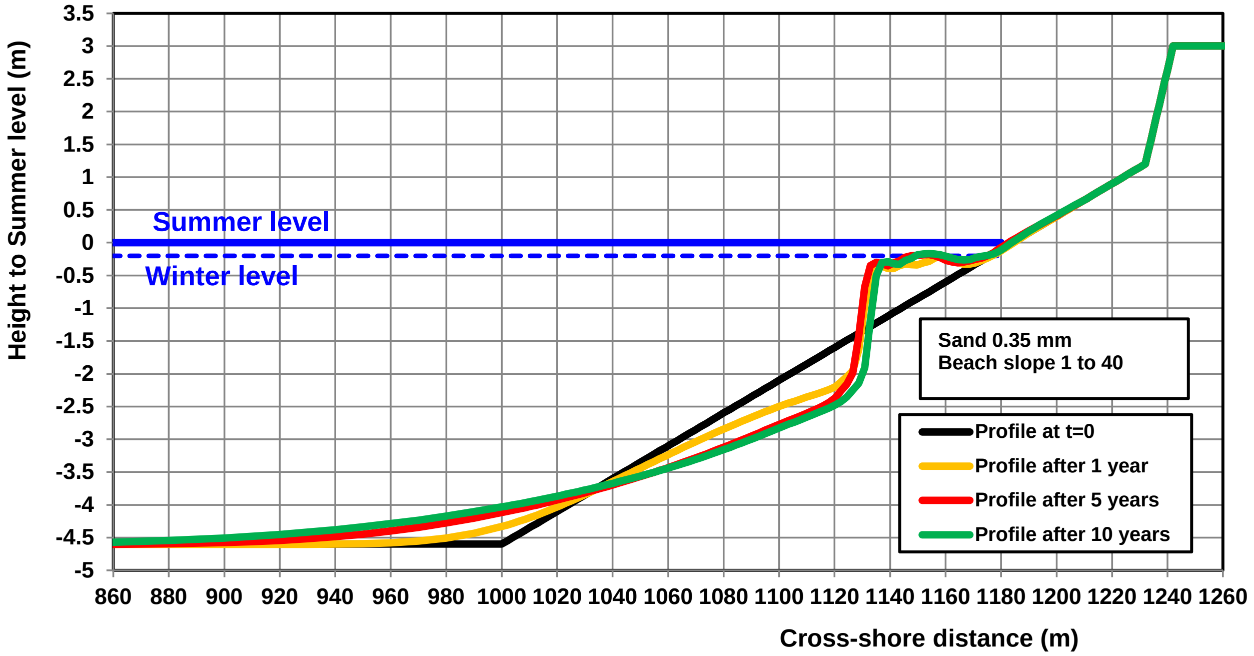


Figure 3.7.2 *Computed bed profile based on CROSMOR-model; SW-beach; annual wave climate; slope 1 to 30, d_{50}=0.35 mm*



Figuur 3.7.3 *Computed bed profile based on CROSMOR-model;*
SW-beach; annual wave climate; slope 1 to 40, d_{50}=0.2 mm



Figuur 3.7.4 *Computed bed profile based on CROSMOR-model;*
SW-beach; annual wave climate; slope 1 to 40, d_{50}=0.35 mm

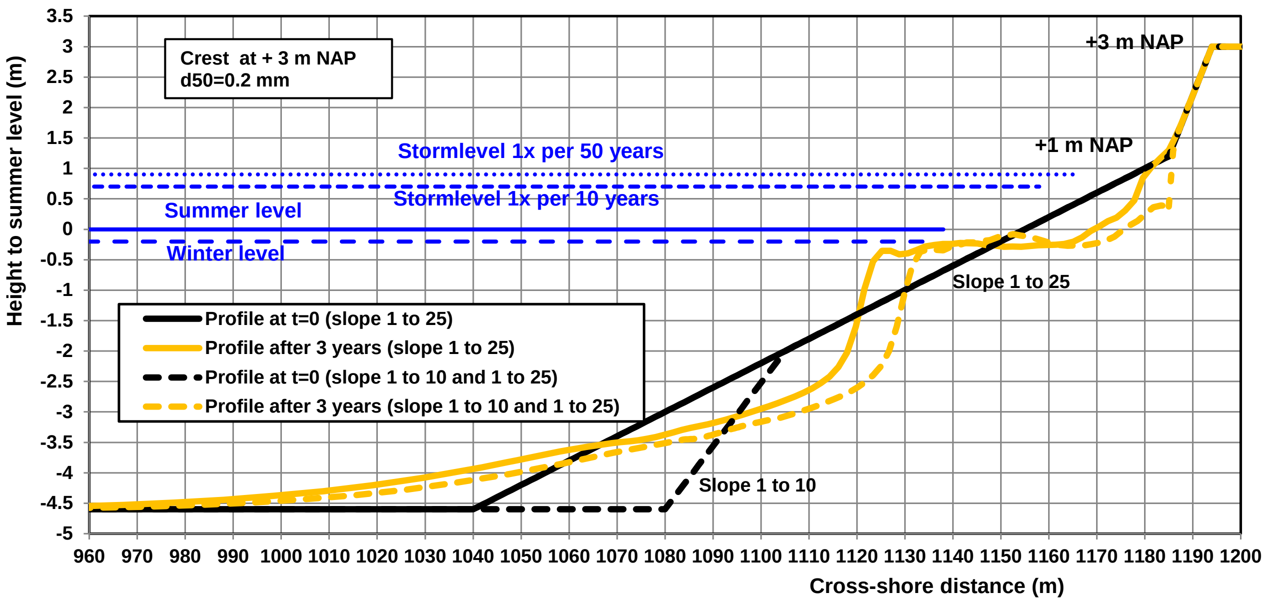


Figure 3.7.5 *Computed bed profile based on CROSMOR-model; SW-beach; annual wave climate; slope 1 to 25 and 1 to 10,* d_{50}*=0.2 mm*

3.7.6 Expected beach profile with breaker bar

Figure 3.7.6 shows the initial bed profile (slope 1 to 25) and the expected beach profile on the long term. The straight initial profile will over time (order 1 year) be changed into a profile with a breaker bar. The beach landward of the breaker bar may become slightly steeper (1 to 20). The beach profile seaward of the breaker bar may become somewhat milder (1 to 30). The dune front will be somewhat steeper due to wind transport (1 to 3). The breaker bar will act as a underwater dam at which the waves will break similar to the breaking of waves on a stone dam. Landward of the breaker bar, the wave heights will be much smaller.

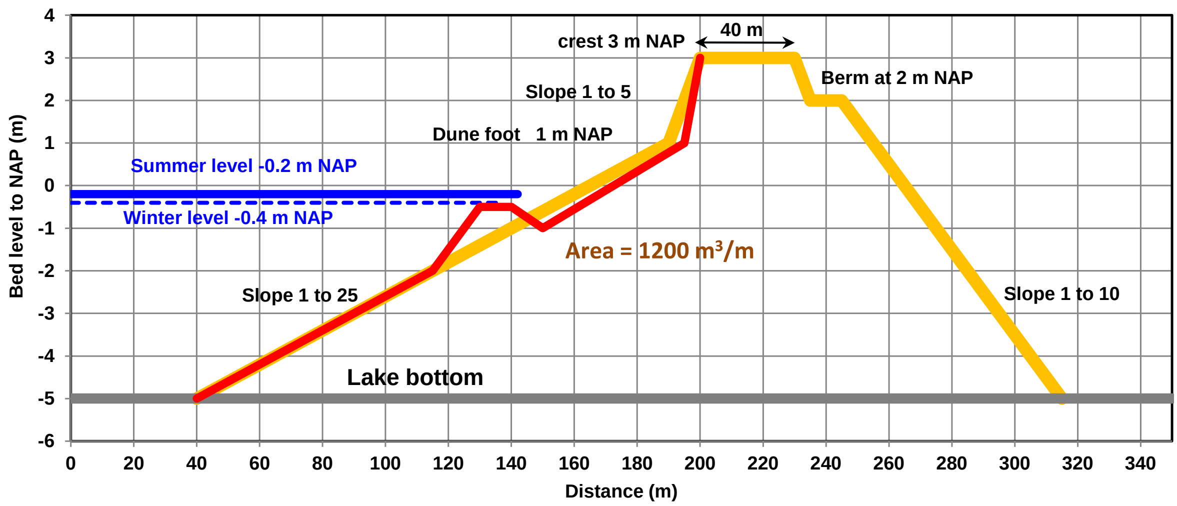


Figure 3.7.6 *Beach profile with breaker bar*

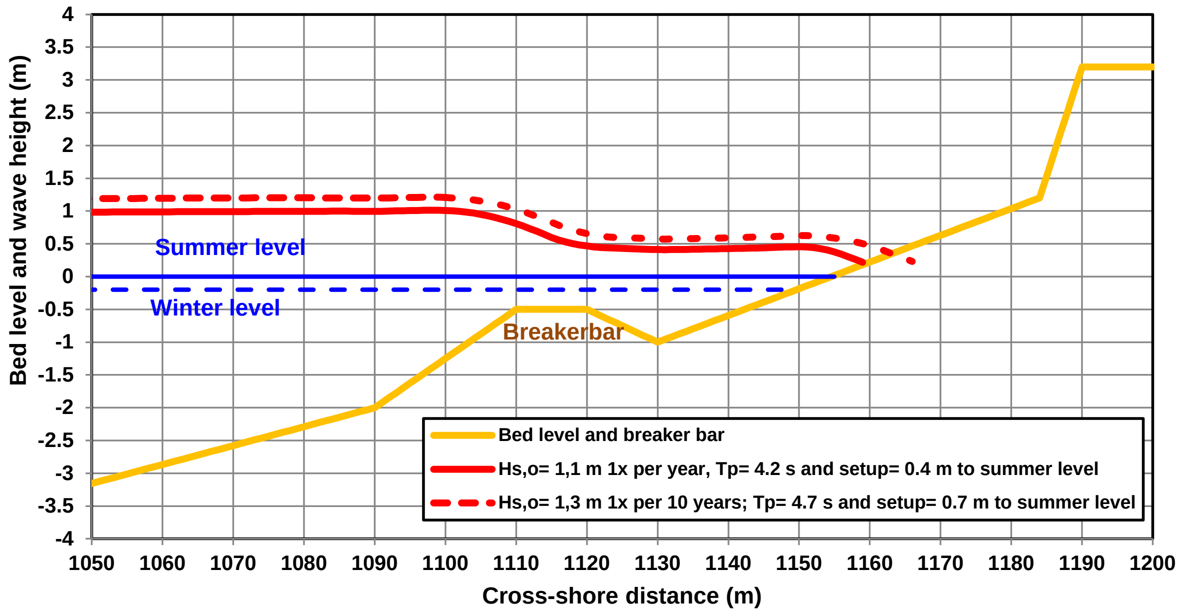


Figure 3.7.7 *Wave height pattern over breaker bar*

Figure 3.7.7 shows the wave transformation at the breaker bar according to the CROSMOR-model. The wave spectrum is single-topped with 10 wave classes based on a Rayleigh distribution. The wave height landward of the breaker bar is < 0.25 m during normal conditions. During a storm of 1 x per 10 years, the incoming wave height decreases from H_s= 1.3 m to 0.6 m (reduction of 55%) due to the presence of the breaker bar. The mean water line (including setup) during a storm of 1 per 10 years is approximately 1.1 m above the summer lake level.

3.8 Cross-shore erosion of NW-beach due to daily waves (CROSMOR modelling)

Similar compoutations using the CROSMOR-model have been made to determine the beach erosion of the NW-beach. The computed beach erosion values are somewhat less than that for the SW-beach, see **Table 3.7.3**.

3.9 Cross-shore erosion of SW-beach due to storm waves

3.9.1 Modelling approach

The dimensions of the beach and dune are largely determined by the expected erosion during storms. The sand volume above the water line should be larger than the expected dune erosion due to storm waves.

Various models have been used to compute the storm erosion:

- DUROSPLUS-model;
- CROSMOR-model;
- Dune erosion equation.

Two storm conditions are considered: 1 x per 50 years and 1 x per 4000 years.

3.9.2 Erosion due to storm 1x 50 years

Storm erosion based on DUROSPLUS-model

The DUROSPLUS-model does not predict erosion for a storm with frequency of 1x per 50 years (water level at +0.7 m NAP).
This model is only suitable for extreme storms with a water level above the dune foot level.

Storm erosion based on CROSMOR-model (ANNEX B)

The wave conditions are taken from **Table 3.9.2**. The wave incidence angle of the storm waves is 45^o to the coast normal at deep water. The d_{50} of the sand is 0.2 mm. Various initial beach slopes have been applied, see **Table 3.9.1**. The model settings are given in **Table 3.9.1**.

PARAMETERS	VALUES
Water depth at deep water	4.6 m
Beach slope	1 to 30; 1 to 25; 1 on 25 + 1 to 10
Dune foot	1.2 m above summer lake level
End depth = water depth in last grid point	0.2 m
Grid distance	10 m (deep water) to 2 m (beach)
Total length	1500 m
Number of wave classes	1
Wave asymmetry	Yes, according to Isobe-Horikawa
Coefficient Longuet-Higgins; roller effect	0.5 (default = 1); 0.5 (default = 1)
Grain diameter sand d_{50}	0.2 to 0.35 mm
Coefficients sand transport formulas	1 (default = 1)
Coefficient sand transport wave asymmetry	0.2 (default = 1)
Coefficient return flow (undertow)	1 (default)
Additional stirring of sand at dune front (sef)	1.5
Bed roughness	Automatically
Temperature and salinity	10 degrees and 0 per mille
Files	markw25. inp; markw30. inp; mw30oos. inp

Table 3.9.1 *Settings of CROSMOR-model; SW-beach*

Figures 3.9.1 and 3.9.2 show the computed bed profiles (initial slope 1 to 30) after storms of 6 and 12 hours; H_s = 1.5 m (1 x per 50 years). **Table 3.9.2** shows the computed erosion volumes.
The erosion volume is between 12 and 28 m^3/m. The erosion is the largest for a duration of 12 hours and d_{50} of 0.2 mm. The maximum recession is about 10 m at the dune foot. The beach erosion volume below the storm water level is about equal to the dune erosion volume above the storm water level.

Figure 3.9.3 shows the bed profiles (initial slope 1 on 30) after 3 storms with H_s= 1.3 m (1x per 10 years) with a total duration of 3 x 12 = 36 hours. The beach-dune erosion volume is approximately 30 m^3. The recession of the dune foot is about 5 m.

Figure 3.9.4 shows the bed profiles (initial slope 1 to 30) after 20 storms with H_s= 1.1 m (1x per year) with a total duration of 20 x 12 = 240 hours. The beach-dune erosion volume is approximately 35 m^3. There is no erosion at the dune foot.

Based on the results (see **Table 3.9.2**), the erosion after a period of 20 years with 20 storms of H_s= 1.1 m, 2 storms of H_s= 1,3 m and 1 storm of H_s= 1.5 m is estimated to be about 85 m^3/m (d_{50}= 0.2 mm; initial slope 1 to 30) between the -1 m + 3 m NAP lines. Most erosion takes place at the beach. The maximum recession of the dune foot is 15 to 20 m after a period of 20 years.
The erosion is less (about 30%) for sand with grain diameter of d_{50}= 0.35 mm.

Wave height H_s (m)	Wave period T_p (s)	Wind setup above winter level (m)	Wave angle (°)	Storm duration (hours)	Number of storms (-)	Sand d_{50} (mm)	Beach slope (-)	Computed erosion volume beach +dune (m^3/m)
1.1 (1x year)	5	0.6	45	12	20	0.2	1 op 30	35
1.3 (1x 10 years)	5.5	0.9	45	12	3	0.2	1 op 30	30
1.5 (1x 50 years)	6	1.1	45	6	1	0.2	1 op 30	20
1.5 (1x 50 years)	6	1.1	45	12	1	0.2	1 op 30	28
1.5 (1x 50 years)	6	1.1	45	6	1	0.35	1 op 30	12
1.5 (1x 50 years)	6	1.1	45	12	1	0.35	1 op 30	20
1.5 (1x 50 years)	6	1.1	0	12	1	0.2	1 op 25	10
1.5 (1x 50 years)	6	1.1	15	12	1	0.2	1 op 25	28
1,5 (1x 50 years)	6	1.1	45	12	1	0.2	1 op 25	28
1,5 (1x 50 years)	6	1.1	45	12	1	0.2	1 op 25 1 op 10	28

Table 3.9.2 *Input and output results of CROSMOR-model; SW-beach*

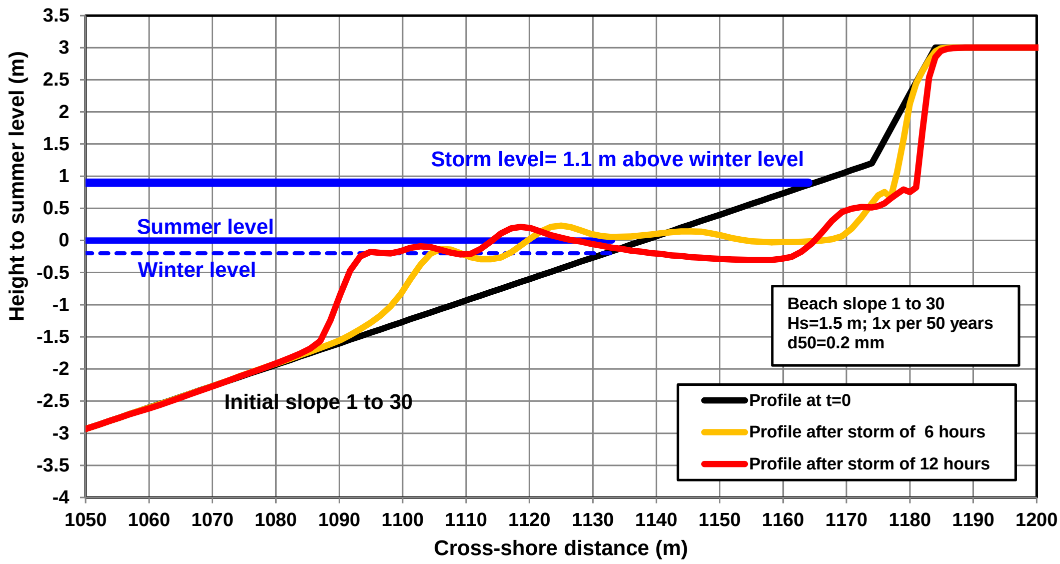


Figure 3.9.1 *Computed bed profiles CROSMOR-model (1 storm); SW-beach*
Wave H_s= 1.5 m, setup= 1.1 m above winter level, beach slope 1 to 30, d_{50}=0.2 mm

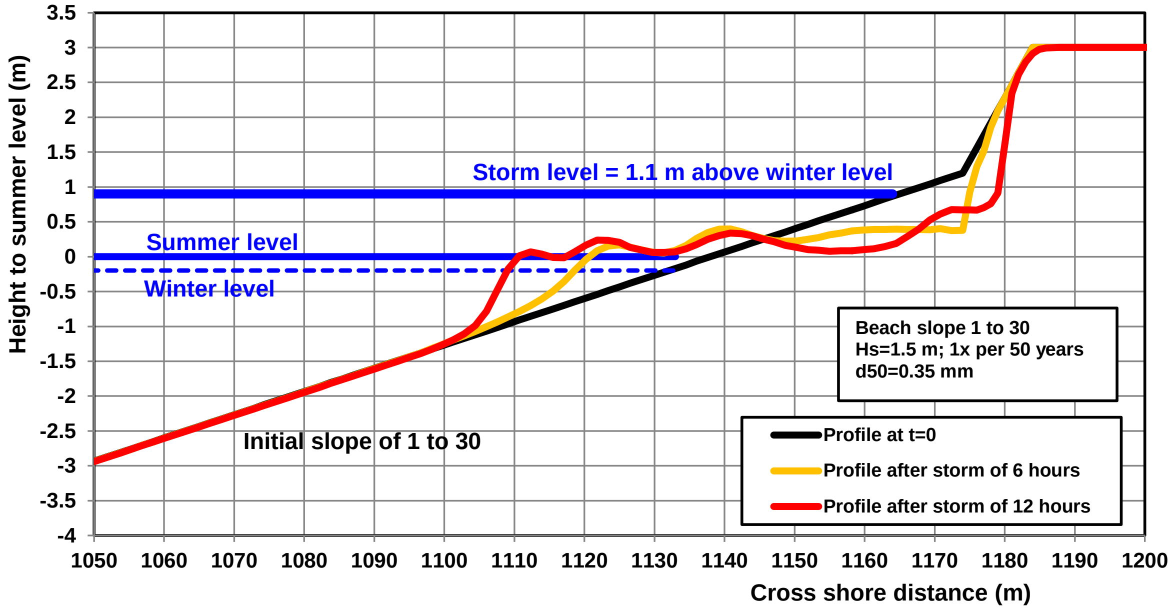


Figure 3.9.2 *Computed bed profiles CROSMOR-model (1 storm); SW-beach*
Wave H_s= 1.5 m, setup= 1.1 m above winter level, beach slope 1 to 30, d_{50}=0.35 mm

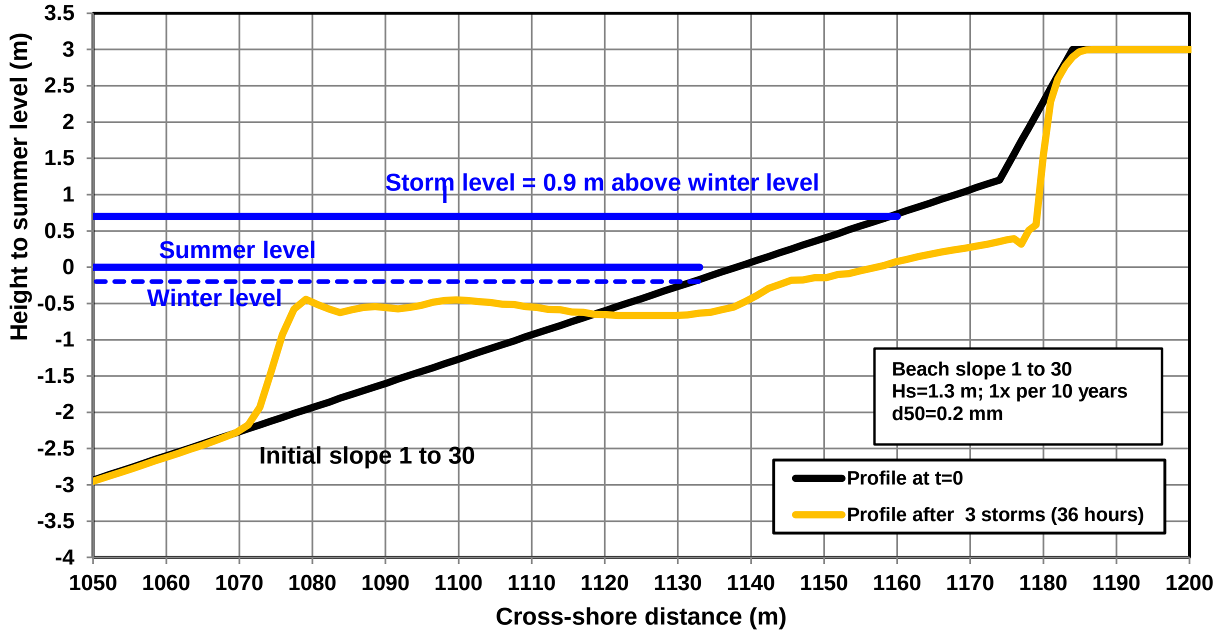


Figure 3.9.3 *Computed bed profiles CROSMOR-model (3 storms= 36 hours); SW-beach*
Wave H_s= 1.3 m, setup= 0.9 m above winter level, beach slope 1 to 30, d_{50}=0.2 mm

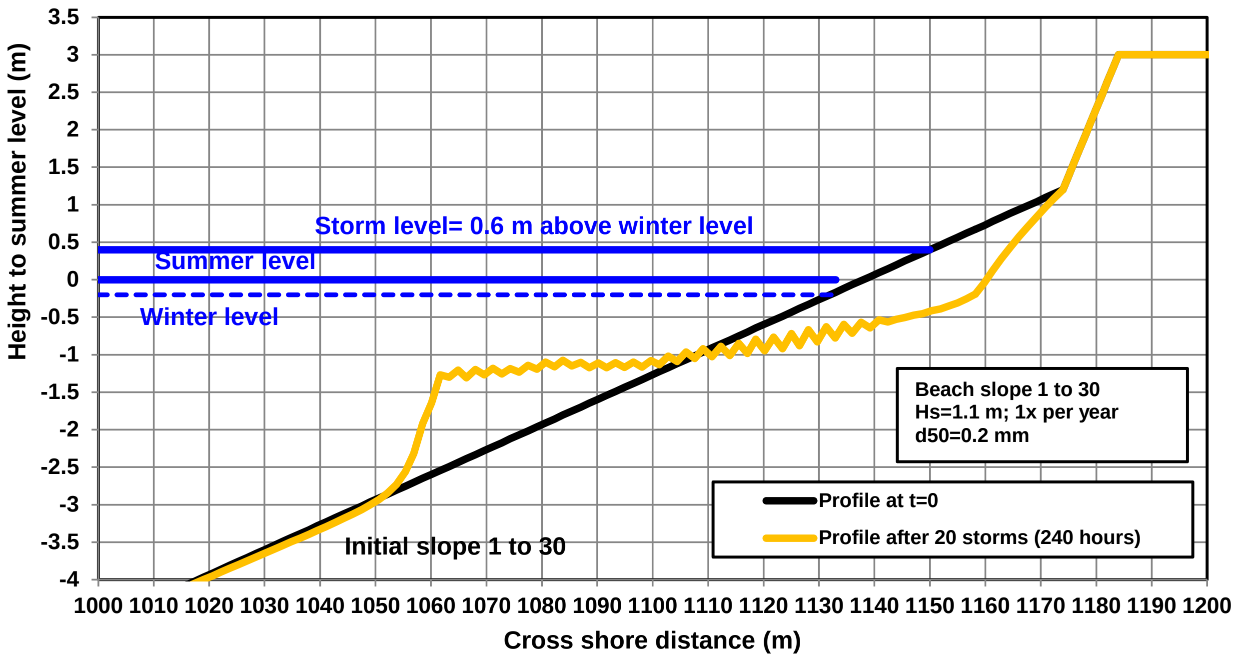


Figure 3.9.4 *Computed bed profiles CROSMOR-model (20 storms= 240 hours); SW-beach Wave H_s= 1.1 m, setup= 0.6 m above winter level, beach slope 1 to 30, d_{50}=0.2 mm*

Figure 3.9.5 shows the bed profiles (initial slope 1 to 25) after 1 storm of 12 hours with H_s= 1.5 m (1x per 50 years). The beach-dune erosion volume is approximately 10 m^3/m for perpendicular wave attack (wave angle = 0^o). The erosion increases to about 28 m^3/m for wave angles of 15^o and 45^o, see **Table 3.9.2**. Oblique waves cause longshore currents resulting in larger transport rates and erosion values. The maximum recession is about 10 m at the dune foot.

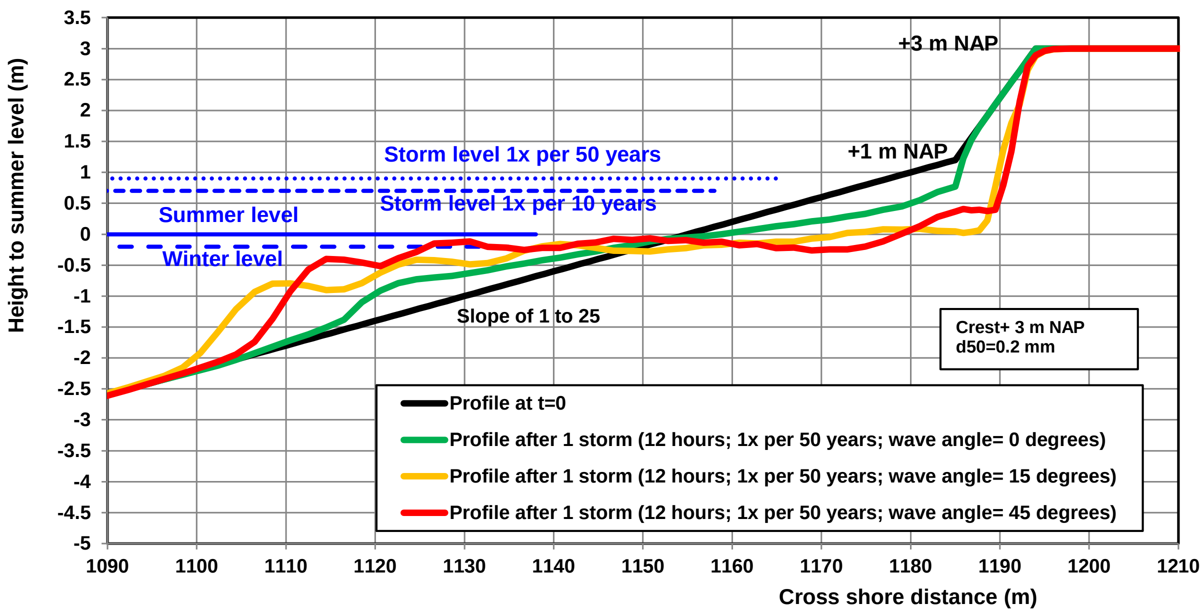


Figure 3.9.5 *Computed bed profiles CROSMOR-model (1 storm= 12 hours); SW-beach Wave H_s= 1,5 m, setup= 1,1 m above winter level, beach slope 1 to 25, d_{50}=0.2 mm*

Figure 3.9.6 shows the bed profiles (initial slope slope 1 to 10 and 1 to 25) after 1 storm of 12 hours with H_s= 1.5 m (1x per 50 years). The wave angle is 45°. The beach-dune erosion volume is approximately 28 m^3/m. The recession is about 10 m at the dune foot. These values are approximately equal to the values for an initial slope of 1 to 25 without the steep toe of the beach.

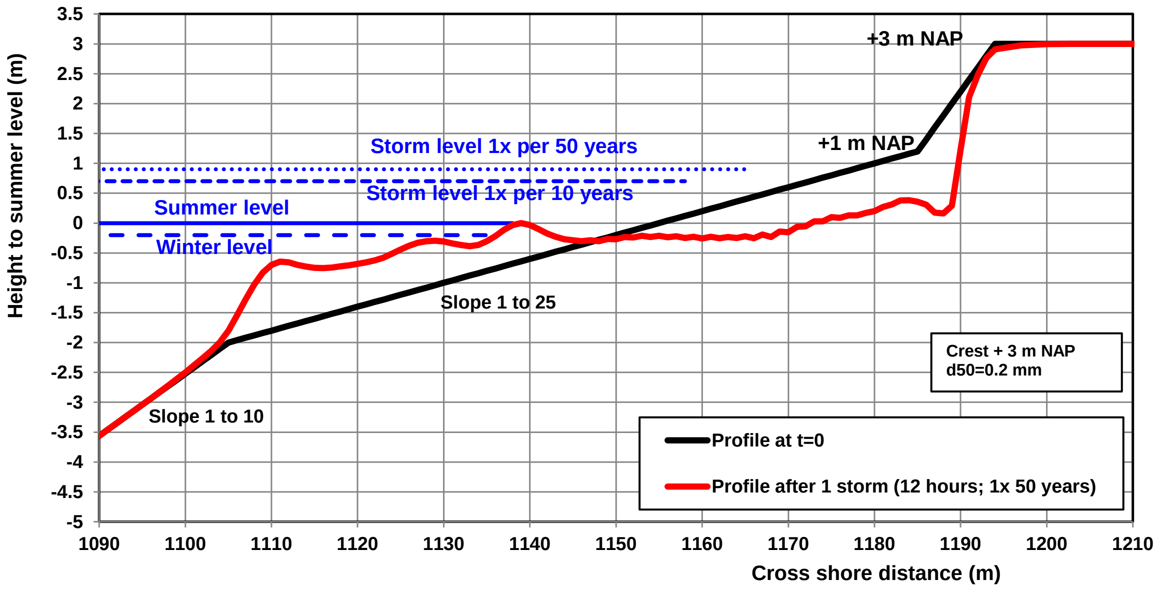


Figure 3.9.6 *Computed bed profiles CROSMOR-model (1 storm= 12 hours); SW-beach*
Wave H_s= 1.5 m, setup= 1.1 m above winter level, toe slope 1 to 10, d_{50}=0.2 mm

Storm erosion based on Dune erosion rule for storm 1x per 50 years

Equations 1 and 4 of **ANNEX C** have been used to compute the beach and dune erosion after 6 hours.

Input data:

- grain diamaters d_{50}= 0.2 en 0.35 mm;
- dune crest= 2 m above dune foot (crest at + 3 m NAP; dune foot at +1 m NAP);
- beach slope = 0.1 (1 to 10); dune slope =0.33 (1 to 3);
- water depth at deep water = 5 m;
- storm duration = 6 and 12 hours.

The wave heights, period and water levels are given in **Table 3.9.3**.

The computed erosion volume above the storm level is given in **Figure 3.9.7**. The erosion volumes (above the storm level) are between 7 and 15 m^3/m for a storm with H_s= 1.5 m with wind setup of 1.1 m above the winter lake level (1 x per 50 years). If it is assumed that the beach erosion below the storm level is roughly equal to the erosion above the storm level (see **Figures 3.9.1** and **3.9.2**), then the total erosion is about 15 to 30 m^3/m. These values are similar to those of the CROSMOR-model, see **Table 3.9.2**.

Significant wave height (m)	Peak wave period (s)	Water level setup to winter lake level (m)	
0.5	2.5	0.	
0.7	2.8	0.1	
0.8	3.2	0.15	
0.9	3.5	0.3	
1.0	3,7	0.45	
1.1	4.0	0.6	1x per year
1.2	4.2	0.75	
1.3	4.5	0.9	1x per 10 years
1.4	4.7	1.0	
1.5	5.0	1.1	1x per 50 years
1.6	5.5	1.15	
1.7	6.0	1.3	1x per 100 years

Table 3.9.3 *Wave and water level data; SW-beach*

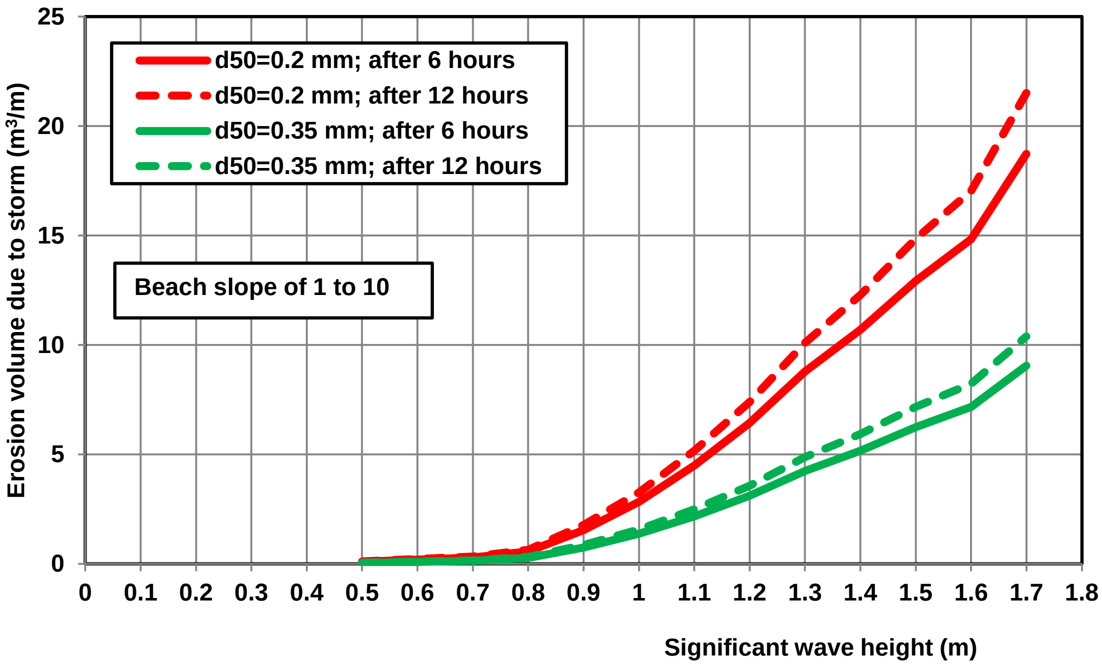


Figure 3.9.7 *Erosion volume (above storm level) as function of d_{50}, slope, wave height; SW-beach*

3.9.3 Erosion due to storm 1x per 4000 years

Storm erosion based on DUROSPLUS-model

The DUROSPLUS-model has been used to compute the dune erosion for extreme conditions with a frequency of 1 x per 4000 years. The storm duration is 5 hours.
This condition yields: H_s = 2.1 m, T_p = 6 s and water level setup = 1.9 m above the winter lake level = 1.5 m NAP for 1 x per 4000 years. The d_{50} is 0.2 mm.

Figure 3.9.8 shows the computed erosion profile for a beach with d_{50}= 0.2 mm and initial slope 1 to 25. The total erosion volume is about 15 m^3/m and 18 m^3/m including 25% uncertainty. The maximum recession at the dune foot is about 10 m.

Similar computations have been made for a beach with d_{50}= 0.2 mm and initial slope 1 to 30. The total erosion volume is about 12 m^3/m and 15 m^3/m including 25% uncertainty. The maximum recession at the dune foot is about 10 m.
The total erosion volume is negligibly small for a beach with d_{50}= 0.35 mm and slope of 1 to 30.

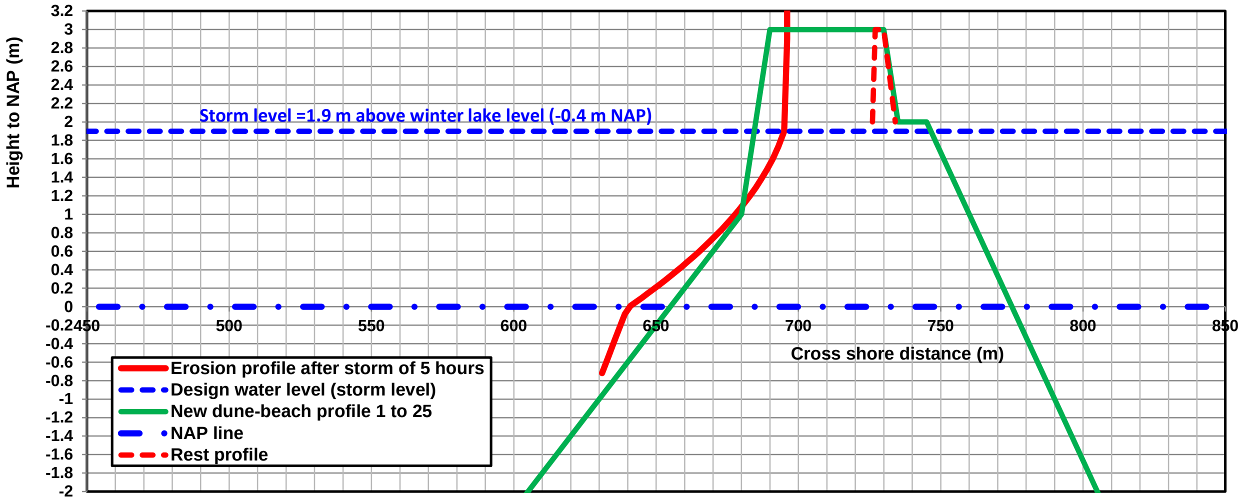


Figure 3.9.8 *Erosion profile based on DUROSPLUS-model; SW-beach*
Storm 1x per 4000 years; initial beach slope 1 to 25; d_{50}= 0.2 mm

Storm erosion based on CROSMOR-model

Figure 3.9.9 shows the computed beach profiles for a storm (H_s= 2.1 m and T_p= 6 s; water level = + 1.5 m NAP) with duration of 5 hours. The total volume of the dune erosion above the storm level is about 10 m^3/m for d_{50}= 0.2 mm. The total volume of beach and dune erosion is about 50 m^3/m for d_{50}= 0.2 mm. The maximum recession at the dune foot is about 10 m for d_{50}= 0.2 mm. The maximum recession at the water line is about 40 m for d_{50}= 0.2 mm. The outer slope of the dune front steepens to 1 to 1. In the case of a grain diameter of d_{50}= 0.35 mm, the erosion volume is less (30%) see **Figure 3.9.9**.

The erosion volume based on the CROSMOR model is considerably larger (factor 4) than that of the DUROSPLUS-model, because this latter model does not include beach erosion. It is noted that the empirical DUROSPLUS-model is developed for dune erosion under extreme storms with setup of 5 m along the coast. This model may not be applicable for minor storms on a lake.

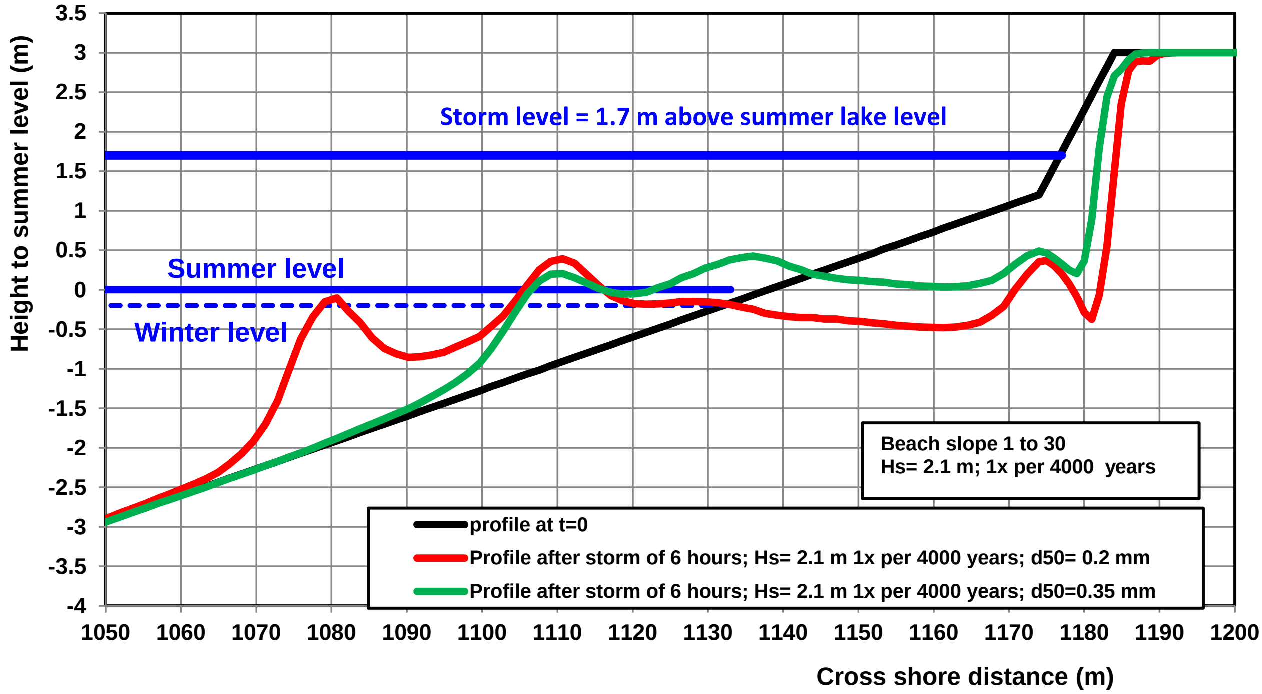


Figure 3.9.9 *Erosion profile of CROSMOR-model; SW-beach*
Storm 1x per 4000 years; d_{50}= 0.2 mm

3.10 Cross-shore erosion of NW-beach due to storm waves

3.10.1 Storm 1x per 50 years

Similar runs have been made using the CROSMOR-model. The results are given in **Table 3.10.1**.

Beased on these results, the erosion after a period of 20 years with 20 storms of H_s= 1 m, 2 storms of H_s= 1.2 m and 1 storm of H_s= 1.3 m is estimated to be about 50 m^3/m between the -1 en +1 m NAP depth lines. The maximum recession at the dune foot is about 5 m after a period of 20 years.

Wave height H_s (m)	Wave period T_p (s)	Wave angle (°)	Wind setup above winter lake level (m)	Storm duration (hours)	Number of storms (-)	Sand d_{50} (mm)	Computed erosion volume beach+dune (m^3/m)
1.0 (1x year)	3.8	25	0.3	12	20	0.2	20
1.2 (1x 10 years)	4.4	25	0.5	12	2	0.2	15
1.3 (1x 50 years)	4.6	25	0.7	12	1	0.2	10

Tabel 3.10.1 *Input and output data of CROSMOR-model; NW-beach (initial slope of 1 to 20)*

3.10.2 Storm 1x per 4000 years

The wave height during a storm with frequency of 1 x per 4000 years is H_s= 1.6 m and T_p= 5.5 s.
The estimated water level = + 1.3 m NAP during an extreme storm from the North-Wwest.
The CROSMOR-model has been used to compute the erosion volume for a storm (H_s= 1.6 m and T_p= 5.5 s; water level = + 1.3 m NAP) with duration of 12 hours.
The total volume of the dune erosion above the storm level is about 7 m^3/m for d_{50}= 0.2 mm. The total volume of beach and dune erosion is about 20 m^3/m for d_{50}= 0.2 mm. The maximum recession at the dune foot is about 10 m for d_{50}= 0.2 mm. The maximum recession at the water line is about 10 m for d_{50}= 0.2 mm. The outer slope of the dune front steepens to 1 to 2.

3.11 Dune erosion of SW-beach due to windtransport

The beach and dune faces are subject to erosion by wind transport. This latter transport can be computed with the equations of Bagnold (1941, 1954), which are only valid for dry, loose sand grains at the end of a wide beach.
During storms with relatively high water levels, the beach is relatively narrow and wet by rainfall (grain interaction effects), which reduces the wind transport (factor 3 to 5). **Table 3.11.1** gives wind transport rates perpendicular to the SW-beach caused by wind from the sectors 180°-210°, 210°-240° and 240°-270° (South-West to North-West). The annual wind transport for dry, loose sediments is approximately 10 m^3/m for 0.35 mm up to 20 m^3/m for 0.2 mm sand. The annual wind transport for wet sand is estimated to be 3 to 5 m^3/m.
To reduce the wind-induced erosion, it is recommended to cover the dune front with grass-type plants, which can grow on sandy soils. This will reduce the erosion of the dune face and crest to about 0.05 to 0.1 m per year. Locally wind pits of 0.5 to 1 m deep can develop in the crest zone.

Wind speed (m/s)	Number of days (-)	Wind direction to North (degrees)	Coast normal to North (degrees)	Wind transport Bagnold d_{50}=0.2 mm (m^3/m/year)	Wind transport Bagnold d_{50}=0.35 mm (m^3/m/year)
9 (BF 5)	25	15°	45°	0.25	0
12 (BF 6)	7	15°	45°	2.15	0.35
15 (BF 7)	5	15°	45°	2.40	2.10
9	30	45°	45°	0.35	0
12	10	45°	45°	3.60	0.55
15	5	45°	45°	4.65	4.05
9	30	75°	45°	0.35	0
12	10	75°	45°	3.10	0.45
15	5	75°	45°	4.00	3.50
Total	**125**			**21**	**11**

Table 3.11.1 *Net annual wind transport perpendicular to SW-beach*

3.12 Estimation of required maintenance volume of beaches and dunes

The erosion of beaches and dunes is caused by several processes:

- long-term erosion of cross-shore profiles by small gradients of longshore transport due to daily wave conditions;
- erosion of the cross-shore profile due to extreme storms.

For example, the net longshore transport along the SW-beach can be of the order 10,000 m^3/year due to variations of the wave climate from year to year, which means that an amount of sand of about 200,000 m^3 can be carried from end of the beach to the other end over a period of 20 years (most likely from the South-East corner to the North-West corner). This is the most unfavourable situation assuming that the net longshore transport of 10,000 m^3/year for 0.2 mm-sand is always in the same direction for a period of 20 years.
In practice, there will be years with opposite net longshore transport due to variations in the wind and wave climate. Thus, the maximum erosion over half the length of the beach is about 200,000 m^3 after 20 years. The maximum corresponding erosion at the corner point South is estimated to be about 50 to 100 m after 20 years including the erosion by extreme storm waves.
The erosion by longshore and cross-shore transport processes can be partly mitigated by the an initial wear layer at the beach/dune face.

Table 3.12.1 provides an overview of the computed/estimated erosion volumes over a period of 20 years for all beaches (0.2 mm sand). The erosion values are based on quadratic summation of the longshore and cross-shore transport components, because both processes influence each other. For example, some of the sand eroded from the upper beach and dune (by cross-shore transport during storms) will serve as supply of sand for the longshore transport at the lower beach, reducing the erosion of sand at the lower beach.
The total maintenance volume for all beaches is estimated to be about **750,000** m^3 of sand over 20 years (60% for SW-beach; 25% for NW-beach; 15% for other beaches). This value is valid for a grain diameter of **0.2 mm** and gives an upper limit of the beach and dune erosion.
Most of the eroded sand will be deposited at very shallow water near the beach. In practice, some of the eroded beach sediments will be returned to the upper beach zone by waves and wind. In addition, the actual grain diameter will be significantly larger than 0.2 mm (about 0.35 mm), because the beach will be made of relatively coarse sand (see **Section 3.3.1**).

The most realistic estimate of the maintenance volume for all beaches is: **500,000 ± 250,000** m^3 for 20 years or 25,000 m^3 ± 12,500 m^3 per year.

The upper limit is about. 750,000 m^3 for beaches of 0.2 mm sand without wooden pile rows (open groins).

The lower limit is about 250,000 m^3 for beaches of 0.35 mm with wooden pile rows.

Process	**Model**	**SW-beach** **Length=3000 m**	**NW-beach** **Length=1500 m**	**Other beaches** **L= 3000 m**
Long term erosion over 20 years; **average wave climate (daily)**	LONGMOR	100,000 m^3	100,000 m^3	100,000 m^3
	CROSMOR	150,000 m^3 (50 m^3/m)	30,000 m^3 (20 m^3/m)	30,000 m^3 (10 m^3/m)
Total (20 years)		200,000 m^3	105,000 m^3	105,000 m^3
Average storm erosion over 20 years **(20 storms 1x per year)** **(2 storms 1x 10 years)** **(1 storm 1x 50 years)**	CROSMOR	250.000 m^3 (85 m^3/m)	50.000 m^3 (35 m^3/m)	30.000 m^3 (10 m^3/m)
TOTAL (20 years)		**450,000 m^3**	**155,000 m^3**	**135,000 m^3**
Maximum storm erosion in one year due to superstorm **(1x per 4000 years)**	CROSMOR	150,000 m^3 (50 m^3/m)	30,000 m^3 (20 m^3/m)	15,000 m^3 (5 m^3/m)
	DUROSPLUS	45,000 m^3 (low estimate) (15 m^3/m)	10,000 m^3 (low estimate) (10 m^3/m)	
Available sand volume above +0 m NAP		210 m^3/m	120 m^3/m	70 m^3/m
Wear volume (10 years) **Wear layer thickness** (between -2.5 m and 1 m NAP)		100,000 m^3 (30 m^3/m) 0.5 m	50,000 m^3 (30 m^3/m) 0.5 m	(20,000 m^3)

Table 3.12.1 *Overview of beach and dune erosion volumes; d_{50}= 0.2 mm*

On the long term there may be considerable erosion at the updrift beach ends (order 20 to 30 m every 10 years). The erosion due to small longshore transport gradients can be reduced by the construction of wooden pile rows (wooden posts between -2.5 m and + 1 m NAP depth lines; opening percentage of 30%), creating smaller compartments with a length of 300 to 500 m, see **Figure 3.1**. The pile rows will reduce the strength of the longshore currents and transport rates.
The erosion of about 200,000 m^3 (row 4 of **Table 3.12.1**) at the SW-beach over 20 years due to alongshore transport processes by daily waves gives an annual erosion of about 10.000 m^3/year and can be compensated by an initial wear layer. Assuming a wear layer for 10 years, the required volume is about 100.000 m^3.
The wear layer should be made at the SW-beach between -2.5 m and + 1 m NAP depth lines. The beach width is about 70 m and the total beach length is about 3000 m giving a wear layer thickness of about 100,000/(3000x70) = 0.5 m for 10 years. A similar layer should be made at the NW-beach.

The erosion of the beach and dune front at the SW-beach due to extreme storms is estimated to be about 75 ± 25 m^3/m above the mean water line (0 m NAP) over 20 years. The available sand volume above the mean water line (0 m NAP) is about 210 m/m.^{3}
The maximum erosion at the SW-beach during a super storm with frequency of 1 x per 4000 years is estimated to be about 50 m^3/m, which is much smaller than the available volume of sand. The damage must be repaired immediately, if more than 25% of the dune volume is eroded.
The minimum crest width (at + 3 m NAP) of the SW-beach is about 20 m to compensate the erosion over 20 years (including storm of 1 x per 50 years). It is recommended to cover the crest with grass-type plants to reduce the erosion by wind.

3.13 Groins

3.13.1 Corners West and South

At corner points W (West) and S (South) of the SW-beach (see **Figure 3.1**), the beach is protected by a rock protection with slope of 1 to 4 (rocks/stones of 60 to 300 kg; $d_{n,50} \cong$ 0,3 m), see **Figure 3.13.1.** The toe protection at corner point W can be made of a layer of rocks/stones of 0.02 to 0.05 m (layer thickness= 0.2 m; width=20 m).

Figuur 3.13.2 shows the rock/stone size as function of crest level and slope for a storm of 1x per 50 years (H_s = 1.5 m) using the tool Armour.xls with a safety factor of 1.2. This yields rock/stone sizes of 0.25 tot 0.3 m for a slope of 1 to 4 and crest level of 2 m.

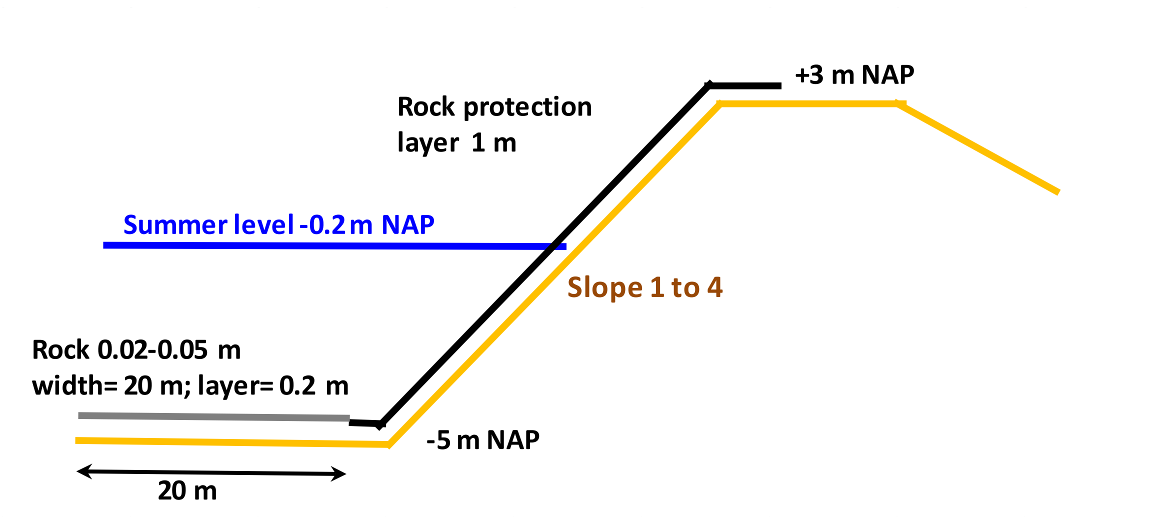
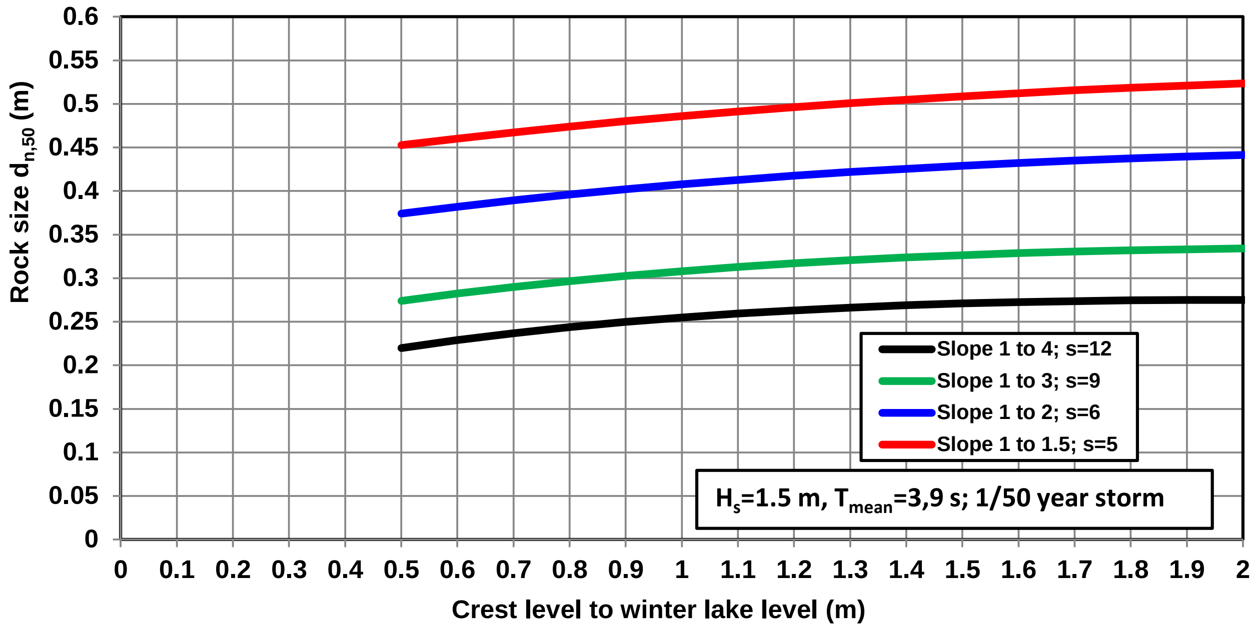


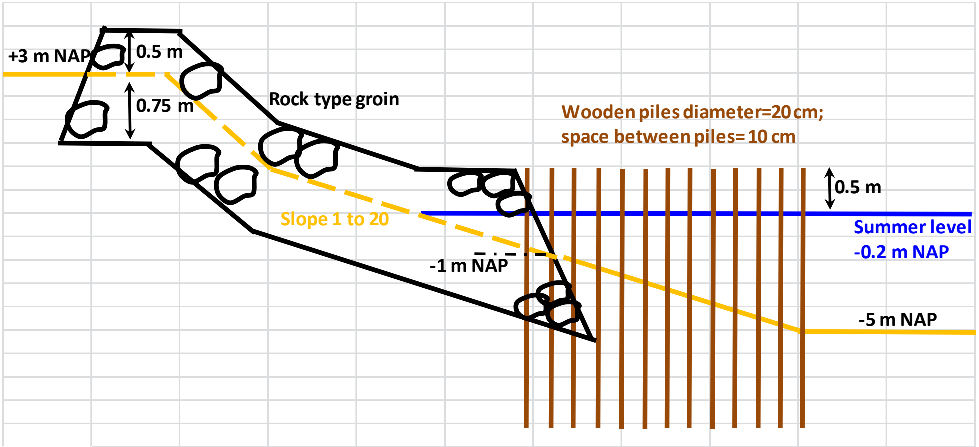
Figure 3.13.1 *Rock protection at corner West*



Figurer 3.13.2 *Rock/stone size as function of crest level and slope (s= damage level)*

3.13.2 Corner North

The beach ends in lee areas can be protected by short groins made of rocks combined with wooden pile rows, see **Figure 3.13.3**.



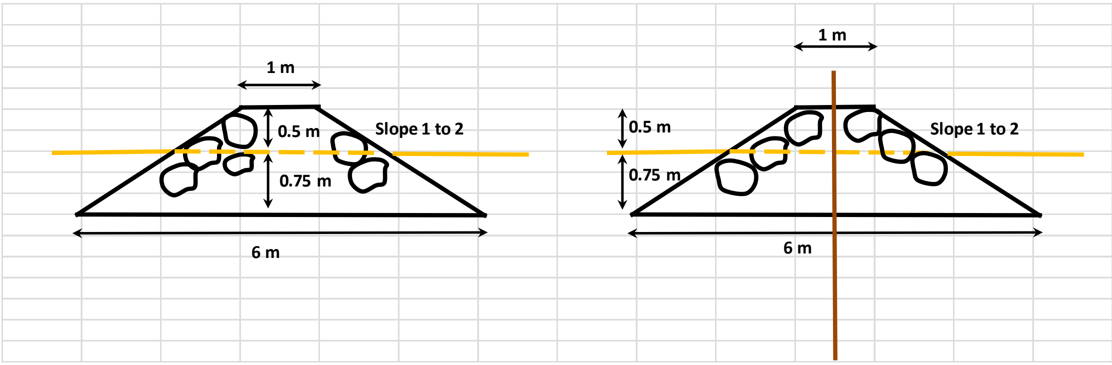


Figure 3.13.3 *Groins at lee corners (North and East)*

3.13.3 Wooden pile rows

To reduce beach erosion due to longshore transport gradients as much as possible, wooden pile rows between the -2.5 m and +1 m NAP depth contourlines can be made at regular spacings of 500 m (see **Figure 3.13.4**).

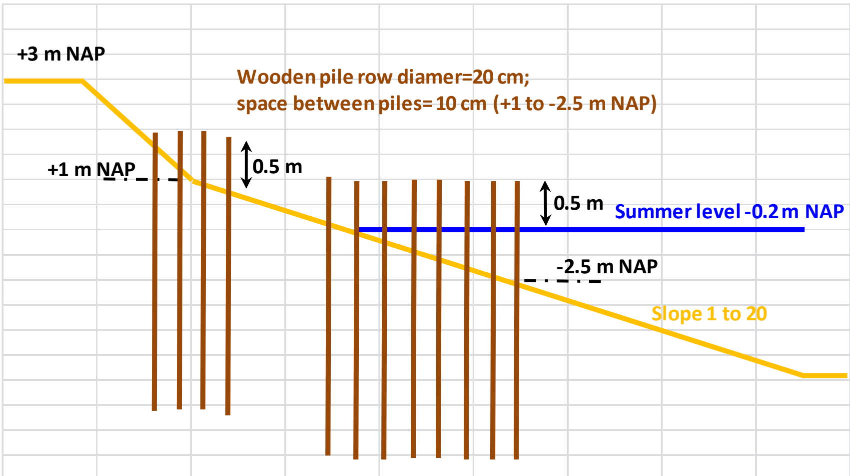


Figure 3.13.4 *Wooden pile rows at beaches*

Annex A LONGMOR-model

Basically, the accretional and erosional processes along the coastline are the result of differences in onshore/offshore transport and gradients of longshore sand transport, induced by:

- changes of shoreline orientation (gradual or abrupt due to presence of bays and headlands);
- changes of shoreface topography (local steep slopes, hollows, scarps, canyons);
- changes of wave-current conditions and mean sea level conditions;
- changes of sediment supply (sources like cliff erosion).

Shoreline changes can be simply understood by considering the sediment continuity equation for the littoral zone (roughly the surf zone) with alongshore length Δx, cross-shore length Δy and vertical layer thickness (h), see Figure 4.5.15. The sand volume balance reads:

$$h\,(\Delta y_s/\Delta t) + \Delta Q_{LS}/\Delta x - q_S = 0 \qquad (4.5.1)$$

with: y= cross-shore coordinate, x= longshore coordinate, y_s= shoreline position, h= thickness of active littoral zone layer, Q_{LS}= longshore transport rate or littoral drift (bed-load plus suspended load transport in volume including pores per unit time, in m^3/s) and q_S= source, sink or cross-shore transport contribution (in m^2/s).

Basically, Equation (4.5.1) states that: **a coastal section erodes if more sand is carried away than supplied; vice versa coastal accretion occurs if there is a net supply.**

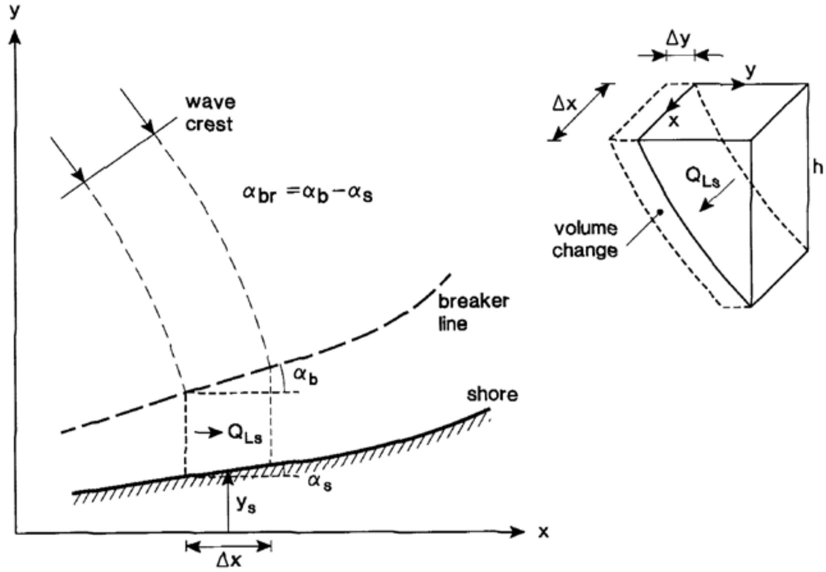


Figure 4.5.15 Definition sketch of shoreline configuration and sand volume balance

The longshore sand transport (Q_{LS}) under wave-dominated conditions can be estimated by the CERC-formula **(Van Rijn, 1993)**:

$$Q_{LS} = 0.025\, g^{0.5}\, \gamma^{-0.5}\, (H_{br})^{2.5} \sin(2\alpha_{br}) \qquad (4.5.2)$$

with γ= breaker coefficient=H_{br}/h, H_{br}= significant wave height at breaker line and α_{br}= angle between breaker line and local shoreline.

4.281

Waves arriving from deep water are transformed in shallow water according to the laws of refraction (Snell's law for gradually varying bathymetry; $\sin\alpha_{br}= L_{br}/L_0 \sin\alpha_0$) and shoaling, yielding $H_{br}= k_{r,br}\ k_{s,br}\ H_0$ with $k_{r,br}$= refraction coeficient at breaker line and $k_{s,br}$= shoaling coefficient at breaker line. For gradually varying bathymetry these values are:
$k_{r,br}= (\cos\alpha_0/\cos\alpha_{br})^{0.5}$ and $k_{s,br}= (n_0c_0/n_{br}c_{br})^{0.5}$ with c= wave propagation velocity, n= coefficient, α= wave angle, index br= at breaker line and index 0= at deep water. The wave height at the breaker line $H_{br}= \gamma h_{br}$ can be computed if the breaker depth h_{br} and the breaker coefficient γ (roughly 0.6) are known. Generally, this procedure requires iterative computations. An estimate of the breaker depth can be obtained by applying:
$h_{br}= ((H_0^2\ c_0 \cos\alpha_0)/(1.8\ \gamma^2\ g^{0.5}))^{0.4}$; see **Van Rijn (1990)**.
Thus, wave refraction largely controls the orientation of the shoreline, when relatively smooth and regular depth contours are present (neglecting cross-shore contributions).

The longshore transport rate along a specific coastal section depends on the angle α_0 between the shoreline and the deep-water wave direction. If the shoreline orientation varies and the wave direction is constant, the longshore transport rate can be expressed as a function of α_0. This curve (including refraction and shoaling effects) is shown for a specific case in Figure 4.5.16. The transport rate is maximum for a shoreline orientation of about α_0= 40° to 45° (depending on refraction effects) and zero for angles of 0° (wave crests parallel to coast) and 90° (wave crests normal to coasts). The longshore transport will be in opposite direction (negative Q_{LS}) for $\alpha_0<0°$. The longshore transport can also be expressed as a function of the shoreline angle α_s ($\alpha_s=\alpha_n-\alpha_o$, α_n= constant if wave direction is constant and shoreline is varying, α_n=45° in the example of Fig. 4.5.16) with respect to the x-axis. In case of a wave climate with various wave classes, directions and probabilities of occurrence the net longshore transport rate can be expressed as a function of shoreline orientation.
Equation (4.5.2) is valid for wave-induced longshore transport in the absence of tide- or wind-driven currents. The effect of quasi-steady currents superimposed on the wave-induced longshore current will result in a vertical shift of the transport curve in Fig. 4.5.16.

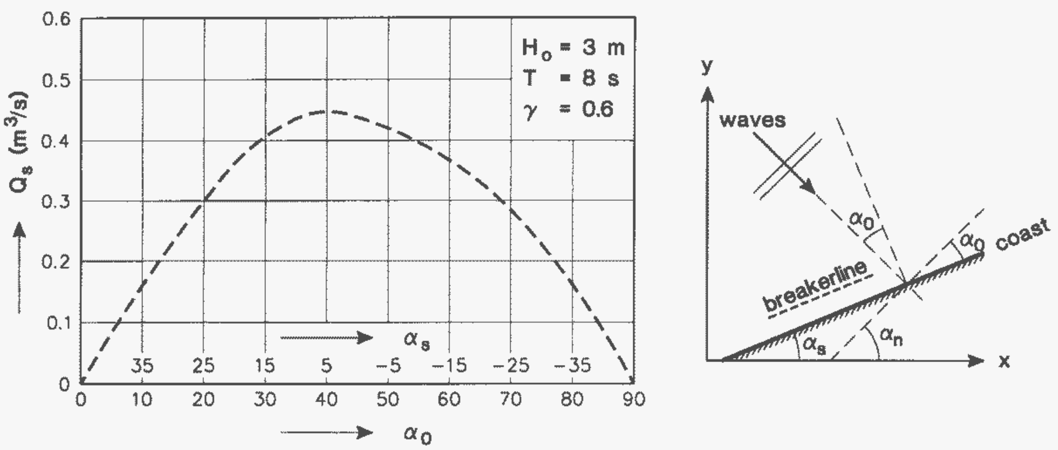


Figure 4.5.16 *Longshore transport rate as a function of shoreline orientation (α_o= angle between deep-water wave direction and shoreline, α_s= angle between shoreline and x-axis)*

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Longshore transport equation Van Rijn 2014

The simplified formula for the longshore sand transport (incl. all effects) of Van Rijn (2002) reads as:

$$Q_{t,mass}= 0.00018\ \rho_s\ g^{0.5}\ (\tan\beta)^{0.4}\ (d_{50})^{-0.6}\ (H_{s,br})^{3.1}\ \sin(2\theta_{br}) \quad (1)$$

Q_t= total longshore sediment transport (in kg/s), ρ_s =sediment density (kg/m^3), d_{50}= median grain size (m), $H_{s,br}$= significant wave height at breakerline (m), θ_{br} = wave angle at breakerline, g= acceleration of gravity (m/s^2), $\tan\beta$= slope of beach/surf zone.

Equation (1) does not account for the effect of the wave period on the longshore transport rate. However, low-period swell waves in the range of 1 to 2 m produce significantly larger transport rates compared to wind waves of the same height (H_{rms}=H). This effect can to some extent be taken into account by using a correction factor to the longshore transport rate, if the percentage of swell waves (in terms of wave height) of the total wave height record is known. Herein, it is proposed to use a swell factor, as follows:

$$K_{swell}=1.5(p_{swell}/100) + 1\ (1-p_{swell}/100) = 0.015p_{swell} + (1-0.01p_{swell}) \quad (2)$$

with: p_{swell}= percentage of low-period swell wave heights of the total wave height record (about 10% to 20% for sea coasts and 20% to 30% for ocean coasts). Some values are: K_{swell}=1.05 for p_{swell}=10%; K_{swell}=1.1 for p_{swell}=20% and K_{swell}=1.5 for p_{swell}=100%. If swell is absent (or unknown), then K_{swell}= 1.
Using this approach, the longshore transport rate increases slightly with increasing percentage of swell. The swell factor is based on computations with grain sizes in the range of 0.2 to 50 mm.
Based on this, Equation (1) reads, as:

$$Q_{t,mass}= 0.00018\ K_{swell}\ \rho_s\ g^{0.5}\ (\tan\beta)^{0.4}\ (d_{50})^{-0.6}\ (H_{s,br})^{3.1}\ \sin(2\theta_{br}) \quad (3)$$

Equation (3) can also be expressed, as:

$$Q_{t,mass}= 0.0006\ K_{swell}\ \rho_s\ (\tan\beta)^{0.4}\ (d_{50})^{-0.6}\ (H_{s,br})^{2.6}\ V_{wave} \quad (5)$$

$$V_{wave}= 0.3\ (gH_{s,br})^{0.5}\ \sin(2\theta_{br}) \quad (6)$$

with: V_{wave}= wave-induced longshore current velocity (m/s) averaged over the cross-section of the surf zone.

ANNEX B CROSMOR-model

The CROSMOR-model has been used to compute the cross-shore profile development as function of time. The CROSMOR2007-model is an updated version of the CROSMOR2004-model (Van Rijn, 1997, 2006, 2007d). The model has been extensively validated by Van Rijn (2008) and Van Rijn et al. (2003).

The propagation and transformation of individual waves (wave by wave approach) along the cross-shore profile is described by a probabilistic model (Van Rijn and Wijnberg, 1994, 1996) solving the wave energy equation for each individual wave. The individual waves shoal until an empirical criterion for breaking is satisfied. The maximum wave height is given by $H_{max}=\gamma_{br}$ h with γ_{br}= breaking coefficient and h=local water depth. The default wave breaking coefficient is represented as a function of local wave steepness and bottom slope. The default breaking coefficient varies between 0.4 for a horizontal bottom and 0.8 for a very steep sloping bottom. The model can also be run a with a constant breaking coefficient (input value). Wave height decay after breaking is modelled by using an energy dissipation method. Wave-induced set-up and set-down and breaking-associated longshore currents are also modelled. Laboratory and field data have been used to calibrate and to verify the model. Generally, the measured $H_{1/3}$-wave heights are reasonably well represented by the model in all zones from deep water to the shallow surf zone. The fraction of breaking waves is reasonably well represented by the model in the upsloping zones of the bottom profile. Verification of the model results with respect to wave-induced longshore current velocities has shown reasonably good results for barred and non-barred profiles (Van Rijn et al., 2003; Van Rijn and Wijnberg, 1994, 1996).

The complicated wave mechanics in the swash zone is not explicitly modelled, but taken into account in a schematized way. The limiting water depth of the last (process) grid point is set by the user of the model (input parameter; typical values of 0.1 to 0.2 m). Based on the input value, the model determines the last grid point by interpolation after each time step (variable number of grid points).

The cross-shore wave velocity asymmetry under shoaling and breaking waves is described by the semi-empirical method of Isobe and Horikawa (1982) with modified coefficients (Grasmeijer and Van Rijn, 1998; Grasmeijer ,2002). Near-bed streaming effects are modelled by semi-empirical expressions based on the work of Davies and Villaret (1997, 1998, 1999). The velocity due to low-frequency waves in the swash zone is also taken into account by an empirical method.

The depth-averaged return current (u_r) under the wave trough of each individual wave (summation over wave classes) is derived from linear mass transport and the water depth (h_t) under the trough. The mass transport is given by $0.125\ g\ H^2/C$ with $C= (g\ h)^{0.5}$ = phase velocity in shallow water. The contribution of the rollers of broken waves to the mass transport and to the generation of longshore currents (Svendsen, 1984; Dally and Osiecki, 1994) is taken into account.

The sand transport of the CROSMOR2007-model is based on the TRANSPOR2004 sand transport formulations (Van Rijn, 2006, 2007a,b,c,d). The effect of the local cross-shore bed slope on the transport rate is taken into account (see Van Rijn, 1993, 2006).

The sand transport rate is determined for each wave (or wave class), based on the computed wave height, depth-averaged cross-shore and longshore velocities, orbital velocities, friction factors and sediment parameters. The net (averaged over the wave period) total sediment transport is obtained as the sum of the net bed load (q_b) and net suspended load (q_s) transport rates. The net bed-load transport rate is obtained by time-averaging (over the wave period) of the instantaneous transport rate using a formula-type of approach.

The net suspended load transport is obtained as the sum ($q_s= q_{s,c} + q_{s,w}$) of the current-related and the wave-related suspended transport components (Van Rijn, 1993, 2006, 2007). The current-related suspended load transport ($q_{s,c}$) is defined as the transport of sediment particles by the time-averaged (mean) current velocities (longshore currents, rip currents, undertow currents). The wave-related suspended sediment transport ($q_{s,w}$) is defined as the transport of suspended sediment particles by the oscillating fluid components (cross-shore orbital motion). The oscillatory or wave-related suspended load transport ($q_{s,w}$) has been implemented in the model, using the approach given by Houwman and Ruessink

(1996). The method is described by Van Rijn (2006, 2007a,b,c,d). Computation of the wave-related and current-related suspended load transport components requires information of the time-averaged current velocity profile and sediment concentration profile. The convection-diffusion equation is applied to compute the time-averaged sediment concentration profile based on current-related and wave-related mixing. The bed-boundary condition is applied as a prescribed reference concentration based on the time-averaged bed-shear stress due to current and wave conditions.

ANNEX C DUNE EROSION RULE

The erosion of sand dunes (see Figure 7.1) can be estimated by the following expression (Van Rijn, 2009):

$$A_{d,t=5}= A_{d,ref}\,(d_{50,ref}/d_{50})^{\alpha1}\,(S/S_{ref})^{\alpha2}\,(H_{s,o}/H_{s,o,ref})^{\alpha3}\,(T_p/T_{p,ref})^{\alpha4}\,(\tan\beta/\tan\beta_{ref})^{\alpha5}\,(1+\theta_o/100)^{\alpha6} \quad (1)$$

with:
$A_{d,t=5}$ = dune erosion area above storm surge level after 5 hours (m^3/m),
$A_{d,ref}$ = dune erosion area above S storm surge level after 5 hours in Reference Case= 170 (m^3/m),
S = storm surge level above mean sea level (m),
S_{ref} = storm surge level above mean sea level in Reference Case= 5 (m),
$H_{s,o}$ = offshore significant wave height (m),
$H_{s,o,ref}$ = offshore significant wave height in Reference Case= 7.6 (m),
T_p = peak wave period (s),
$T_{p,ref}$ = peak wave period (s) in Reference Case= 12 (s),
d_{50} = median bed material diameter (m),
$d_{50,ref}$ = median bed material diameter in Reference Case= 0.000225 (m),
$\tan\beta$ = coastal slope gradient defined as the slope between the -3 m depth contour (below mean sea level) and the dune toe (+3 m),
$\tan\beta_{ref}$= coastal slope gradient defined as the slope between the -3 m depth contour and the dune toe (+3 m) for the Reference Case= 0.0222 (1 to 45),
θ_o = offshore wave incidence angle to coast normal (degrees),
α_1 = exponent=1.3,
α_2 = exponent=1.3 for $S<S_{ref}$ and α_2=0.5 for $S>S_{ref}$,
α_3 =α_4=α_6=0.5 (exponents),
α_5 = exponent=0.3.

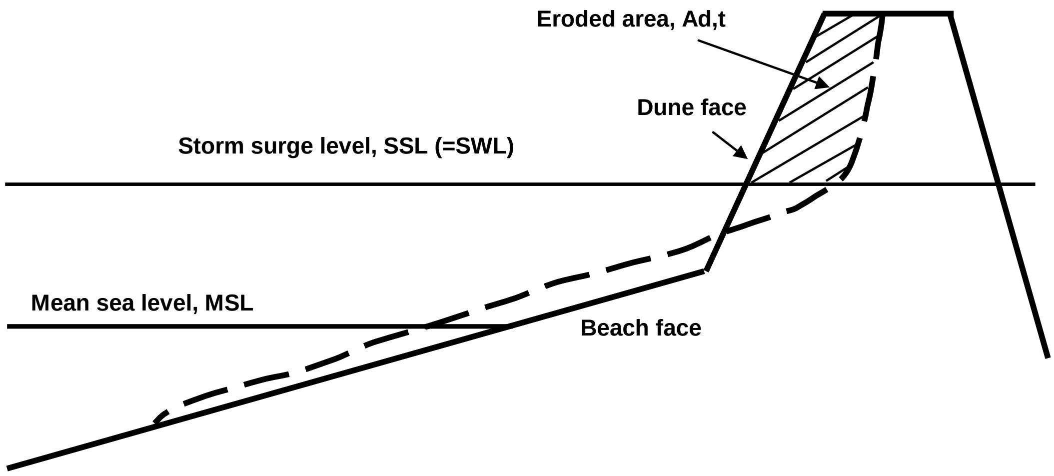

Figure 1 *Sketch of dune erosion*

Equation (6.1) yields zero erosion for S=0 (no storm surge set-up).

The average horizontal dune recession (R_d) can be estimated from:

$$R_d=A_d/(h_d-S) \quad (2)$$

The maximum horizontal dune recession ($R_{d,max}$) at storm surge level can be estimated from:

$$R_{d,max} \cong 1.5\ R_d \qquad (3)$$

with:
R_d = average horizontal dune recession (m),
$R_{d,max}$ = maximum horizontal dune recession at storm surge level (m),
h_d = height of dune crest above mean sea level (m).

The time development over 100 hours can be estimated from:

$$A_{d,t}=A_{d,t=5}\ (t/t_{ref})^{\alpha 6} \qquad (4)$$

with:
t = time in hours (t_{ref}= 5 hours),
α_6 = exponent= 0.5 for $t<t_{ref}$ and 0.2 for $t>t_{ref}$.

Basically, the proposed method produces dune erosion values with respect to a defined Reference Case (storm with a constant storm surge level, wave height and duration of 5 hours). According to the CROSMOR-model, the dune erosion area above storm surge level in the Reference Case is approximately $A_{d,ref}$= 170 m^3/m.
The storm surge level (S) above mean sea level and the bed material diameter (d_{50}) are the most influencial parameters.

As an example, the following storm values are used:
S=4 m, $H_{s,o}$=5m, T_p=10 s, d_{50}=0.0002 m, α_o=20°, h_d=15, tanβ=0.02 yielding:
A_d= 170 $(0.000225/0.0002)^{1.3}$ $(4/5)^{1.3}$ $(5/7.6)^{0.5}$ $(10/12)^{0.5}$ $(0.02/0.0222)^{0.3}$ $(1+20/100)^{0.5}$ = 115 m^3/m after 5 hours.
A_d= 82 m^3/m after 2.5 hours and 135 m^3/m after 10 hours.
R_d= 115/(15-4)=10.5 m after 5 hours; 7.5 after 2.5 hours and 12.5 m after 10 hours.
$R_{d,max}$= 16 m after 5 hours; 11 m after 2.5 hours and 19 m after 10 hours.

Equation (1) yields realistic results for minor storm events. Data are taken from the storm erosion field database summarized by Birkemeier et al. (1988) and Larson et al. (2004). The data have been clustered into 10 cases, shown in Table 1. The bed material diameter at these beaches varies in the range of d_{50}=0.3 to 0.5 mm. The coastal slope is taken as tanβ=0.0222.

Equations (1) and (4) have been used to predict the dune erosion volumes at these beaches.
The wave incidence angle is assumed to be zero (normal to coast).
The bed material diameter is set to 0.4 mm for all cases. As an example the dune erosion at Nauset Beach is computed by using Equation (1):
$A_{d,t=5}$ =170 $(0.225/0.4)^{1.3}$ $(2.5/5)^{1.3}$ $(3.6/7.6)^{0.5}$ $(1)^{0.3}$ $(9.5/12)^{0.5}$ =20 m^3/m after 5 hours.

Equation (4) yields the dune erosion volume after 12 hours: $A_{d,t=12}$ =20 $(12/5)^{0.2}$ = 24 m^3/m. The measured value is 27 m^3/m.
The predicted dune erosion is within the variation range for 6 cases; systematically too large for 2 cases and systematically too small for 2 cases.

Field site	Wave height (m)	Wave period (s)	Surge level (m)	Surge duration (hours)	Measured dune erosion volume (m^3/m)	Predicted dune erosion volume (m^3/m)
LBI	2.6	9	1.5	14	15±7	**10**
AC,LB	2.6	8	1.5	14	6±5	**10**
LB	3.4	8	1.4	24	8±4	**11**
LBI	1.9	8	1.5	36	27±7	**10**
LB	2.1	7	1.5	36	10±3	**9**
NB	2.4	8	2	10	25±3	**15**
NB	3.6	9.5	2.5	12	27±10	**24**
MB,WB,JB	3.8	10.5	2	11	10±5	**18**
AC,LB	3.0	8	1.8	10	5±3	**12**
LB	**1.8**	**10**	**1.5**	**12**	**7±4**	**9**

NB= Nauset Beach, MB=Misquamicut Beach, WB=Westhampton Beach, JB= Jones Beach, LBI=Long Beach Island, AC=Atlantic City, LB=Ludlam Beach

Table 1 *Dune erosion volumes during minor storm events along various USA-beaches*

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