Prepared for:

RWS | RIKZ

Monitoring and Modelling of a shoreface nourishment

VOP Short Term Morphology

Research Report

March 2008

WL | delft hydraulics
Monitoring and Modelling of a shoreface nourishment


Research Report

March 2008
Client: | RWS | RIKZ
---|---
Title: | Monitoring and Modelling of a shoreface nourishment
---|---
Abstract:
Within the VOP Short term morphology project an integrated approach was used to study the 2004 shoreface nourishment at Egmond in The Netherlands. The primary goal of the study was to increase our knowledge on the effects that shoreface nourishments have on the coast on time scales of weeks (storms) to years (cyclic bar behaviour). To achieve this research goal it is imperative to use a number of techniques/tools which together allow us to study the behaviour on all desired time scales. The adopted method aims at combining the results in such a way that an integral view on the behaviour of a nourished coast is obtained.

Work has focussed on five areas:
- Literature review
- Data analysis of the 2004 shoreface nourishment at Egmond.
- Application of Argus/Beach Wizard to obtain a high temporal resolution of the morphodynamic response.
- Calibration and Application of a Delft3D model on the Egmond shoreface nourishment.
- Physical experiment investigating various shoreface nourishment designs in WL | Delft Hydraulics’ Scheldt flume

The innovative part of the method is that the data analysis and the modelling are integrated so that a consistent and complimentary set of results form the basis of the study. This is especially important for the evaluation on the various time scales as a consistent integration enables us to put together analysis techniques that operate (or are valid) on different time scales.

<table>
<thead>
<tr>
<th>References:</th>
<th>Overeenkomst RKZ-1821A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ver</td>
<td>Author</td>
</tr>
<tr>
<td>1</td>
<td>D.J.R. Walstra</td>
</tr>
<tr>
<td>2</td>
<td>D.J.R. Walstra</td>
</tr>
<tr>
<td>3</td>
<td>D.J.R. Walstra</td>
</tr>
<tr>
<td>Project number:</td>
<td>Z4479</td>
</tr>
<tr>
<td>Keywords:</td>
<td>Shoreface Nourishments, Morphology, Argus, Beach Wizard, Delft3D, Data Analysis, Laboratory Experiments</td>
</tr>
<tr>
<td>Number of pages:</td>
<td>166</td>
</tr>
<tr>
<td>Classification:</td>
<td>None</td>
</tr>
<tr>
<td>Status:</td>
<td>Final</td>
</tr>
</tbody>
</table>
Contents

1 Introduction and Summary of Results ............................................. 1
  1.1 General ................................................................................. 1
  1.2 Summary of Results .............................................................. 4
    1.2.1 Literature review ............................................................ 4
    1.2.2 Field Data Analysis ......................................................... 5
    1.2.3 Laboratory experiment ..................................................... 7
    1.2.4 Beach Wizard – Argus ..................................................... 10
    1.2.5 Modelling a shoreface nourishment ................................. 11
  1.3 Synthesis ............................................................................... 13
    1.3.1 November 2004 ............................................................... 13
    1.3.2 Period 2004-2006 ......................................................... 16
  1.4 Recommendations .................................................................. 18
    1.4.1 Argus/Beach-Wizard ..................................................... 18
    1.4.2 Process based modelling (Delft3D) ................................. 19
    1.4.3 Field data analysis ....................................................... 20
    1.4.4 Laboratory experiment ................................................. 20

2 Literature Review ....................................................................... 21
  2.1 Introduction .......................................................................... 21
  2.2 Natural nearshore bar behaviour ............................................ 22
    2.2.1 Appearance ................................................................... 22
    2.2.2 Short-term variations (day – seasons) ............................ 24
    2.2.3 Long temporal scale (years – decades) .......................... 26
  2.3 Morphodynamic responses to shoreface nourishments ............ 28
    2.3.1 Response of nearshore bars ......................................... 29
    2.3.2 Beach response ............................................................. 30
  2.4 Physical mechanisms responsible for nearshore morphodynamics 32
  2.5 Discussion and conclusions ................................................... 33

3 Field Data Analysis .................................................................. 36
  3.1 Introduction .......................................................................... 36
    3.1.1 Project area ................................................................. 36
    3.1.2 Available data ............................................................. 36
  3.2 Data analysis ....................................................................... 37
    3.2.1 Expected effects, based on literature ............................. 37
    3.2.2 Morphological development ....................................... 38
    Profile development ........................................................... 38
    3.2.3 Volume development and sand balance ....................... 48
    3.2.4 Beach width development .......................................... 64
3.2.5 Surrounding area (Bergen aan Zee) ..............................................65
3.3 Conclusions .................................................................................65
4 Laboratory Experiment .................................................................67
  4.1 Introduction ..............................................................................67
  4.2 Measurements and instruments .................................................68
  4.3 Morphological development .....................................................70
  4.4 Sediment transports .................................................................78
  4.4.1 Sediment transport derived from verticals ..............................79
  4.4.2 Sediment transport derived from bed level change ..............82
  4.4.3 Third and fourth order velocity moments ............................85
5 Beach Wizard – Argus .................................................................88
  5.1 Introduction ..............................................................................88
  5.2 Model equations .....................................................................88
  5.3 Model Application .................................................................92
    5.3.1 Egmond, The Netherlands (1999-2001) .............................92
    5.3.2 Egmond, The Netherlands (2004-2006) ............................95
  5.4 Model improvements ...............................................................97
    5.4.1 Automatically characterizing the usability of Argus images ...97
    5.4.2 Pre-processing of time averaged intensity data ...............105
    5.4.3 Automatic detection of the intertidal bathymetry ..............109
    5.4.4 Model Improvement in the nearshore zone .......................114
6 Morphodynamic modelling of a shoreface nourishment ...............119
  6.1 Introduction ............................................................................119
  6.2 Model set-up ..........................................................................120
    6.2.1 Study area ......................................................................120
    6.2.2 Computational grids .........................................................120
    6.2.3 Boundary conditions .......................................................121
    6.2.4 Wave schematization ......................................................122
    6.2.5 Morphological set-up ......................................................122
    6.2.6 Parameter settings .........................................................123
  6.3 Profile modelling .................................................................125
    6.3.1 Tidal representation .........................................................125
    6.3.2 Wave schematisation .......................................................127
    6.3.3 Sensitivity analysis of main parameters ...........................128
    6.3.4 Validation .....................................................................132
  6.4 Area modelling .................................................................135
  6.5 Conclusions ...........................................................................139
  6.6 Application ............................................................................141
    6.6.1 Introduction ..................................................................141
    6.6.2 Profile modelling ..........................................................143
    6.6.3 Area modelling ..............................................................146
Figures

Figure 1.1 Location of Egmond. .............................................................................................................2
Figure 1.2 Schematic diagram showing the adopted method in the VOP Short Term morphology study. .................................................................................................................................3
Figure 1.3 Temporal scales on which data is available or can be provided. .........................3
Figure 1.4 Plan view of the nourished coast at Egmond. Left: November 2004 (just after nourishment was completed), Middle: April 2005, Right: May 2006. .................................6
Figure 1.5 Temporal volume development for various sub-areas with in study area. Line colours of the right plot correspond with the coloured areas in the top view in the left plot. ..............................................................6
Figure 1.6 Cross-shore profiles just after nourishment construction (Solid) and after two years (dashed), colours indicate transects. ..................................................................................................7
Figure 1.7 Initial profiles VOP Short Morphology experiment in Scheldt Flume. ...............7
Figure 1.8 Comparison of final profiles after 24 hours for the low wave condition case. T02: reference case, T04: Design #1 (low nourishment position), T06: Design #2 (high nourishment position). .............................................................8
Figure 1.9 Temporal development of sediment volumes for tests using the accretive wave condition. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach). T02: reference case, T04: Design #1 (low nourishment position), T06: Design #2 (high nourishment position). .................................................................8
Figure 1.10 Comparisons of wave height (top) and velocity moments (bottom) for erosive wave conditions.................................................................................................................................9
Figure 1.11 Comparison between observed (left) and Beach Wizard bathymetries (right) after 6 (upper) and 12 months (lower). ........................................................................................................10
Figure 1.12 Profile development (Transect 3700) for the period 04/11/04 – 30/11/04 induced by different schematisations of the tide. Initial profile is measured until 1029000 (just seaward of inner bar). ...............................................................12
Figure 1.13 Profile development for the period 04/11/04 – 30/11/04 induced by different schematisations of the wave climate ..................................................................................................................12
Figure 1.14 Plan view of sedimentation-erosion patterns over November 2004 as observed (left) and predicted with wave climate (middle) and predicted for storm wave condition only (right). ..................................................................................13
Figure 1.15 Hrms timeserie for the period 04/30 November 2004, and volume changes in a set of sub-sections of profile RSP 38.00. Solid lines and circles display the volume changes calculated by the profile model with boundary conditions specified as timeseries of water levels and waves, and observed, respectively. ..................................................................................................................14
Figure 1.16  Hrms timeserie for the period 04/30 November 2004, and volume changes in a set of sub-sections of profile RSP 39.00. Solid lines and circles display the volume changes calculated by the profile model with boundary conditions specified as time series of water levels and waves, and observed, respectively. .......................................................... 15

Figure 1.17  Cross-shore profiles at Transect 38 covering November 2004 computed by the area model, the Delft3D profile model and Beach Wizard. ...................... 16

Figure 1.18  Comparison of sand volumes based on Jarkus data (solid) and Beach Wizard (dashed). Top: Transect 37, middle: Transect 38, bottom: Transect 39. ................................................................. 17

Figure 2.1  Map of the Netherlands with references to the beach sections as listed in Table 2.1 ................................................................. 21

Figure 2.2  Temporal variation of bar shape characteristics as bar length and bar amplitude visible in the ARGUS images of Noordwijk from 28 February 2002 (a), 2 March 2002 (b) and 10 March 2002 (c). ....................................................... 23

Figure 2.3  Two models of bar generation: (a) breakpoint mechanism and (b) standing wave model (Masselink and Hughes, 2003). ........................................... 25

Figure 2.4  Temporal development of the cross-shore position of bar crest (a) and the bar crest depths (b) from 1965 to 1993 at Terschelling (Ruessink and Kroon, 1994). .......................................................... 27

Figure 2.5  ARGUS image from Noordwijk of 6 November 1996 showing the barswitching mechanism by the bifurcation of nearshore bars. The alongshore length is about 2 km and the cross-shore distance is 800 m (after van Enckevort, 2001). ....................................................... 28

Figure 2.6  Alongshore-averaged cross-shore position of the shoreface nourishment, the outer bar and the inner bar at Noordwijk aan Zee (after Ojeda et al., in prep). ................................................................. 30

Figure 2.7  Window-averaged cross-shore position $P_b$ of the middle bar vs. time (solid lines) for different nearshore stretches along the coast of Terschelling (A-F). The dotted lines indicate the projected net seaward migration of the middle bar estimated from the 28-year JARKUS-data of autonomous bar behaviour. The vertical dashed lines indicate the time of the nourishment implementation (Grunnet and Ruessink, 2005). ....................................................... 31

Figure 3.1  Location of nourishments at Egmond aan Zee ........................................... 37

Figure 3.2  Location of transects ............................................................................. 38

Figure 3.3  Cross-shore development of transect 3700 ............................................. 39

Figure 3.4  Cross-shore development of transect 3800 ............................................. 40

Figure 3.5  Cross-shore development of transect 3900 ............................................. 41

Figure 3.6  Bed level before nourishment .................................................................. 42

Figure 3.7  Bed level after nourishment .................................................................... 43

Figure 3.8  Bar separation ...................................................................................... 44
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.9</td>
<td>Flattening and shoreward movement</td>
<td>45</td>
</tr>
<tr>
<td>3.10</td>
<td>Placement of nourishment</td>
<td>46</td>
</tr>
<tr>
<td>3.11</td>
<td>Bar separation and nearshore accretion</td>
<td>47</td>
</tr>
<tr>
<td>3.12</td>
<td>Flattening and shoreward movement</td>
<td>48</td>
</tr>
<tr>
<td>3.13</td>
<td>Tightly fitting polygon</td>
<td>49</td>
</tr>
<tr>
<td>3.14</td>
<td>Volume development of nourishment</td>
<td>49</td>
</tr>
<tr>
<td>3.15</td>
<td>Alongshore transects</td>
<td>50</td>
</tr>
<tr>
<td>3.16</td>
<td>Volume development of several transects alongshore (0-1400m)</td>
<td>50</td>
</tr>
<tr>
<td>3.17</td>
<td>Egmond (Transect 3600), profile development (top), temporal volume development (bottom)</td>
<td>52</td>
</tr>
<tr>
<td>3.18</td>
<td>Egmond (Transect 3700), profile development (top), temporal volume development (bottom)</td>
<td>54</td>
</tr>
<tr>
<td>3.19</td>
<td>Egmond (Transect 3800), profile development (top), temporal volume development (bottom)</td>
<td>56</td>
</tr>
<tr>
<td>3.20</td>
<td>Egmond (Transect 3900), profile development (top), temporal volume development (bottom)</td>
<td>58</td>
</tr>
<tr>
<td>3.21</td>
<td>Egmond (Transect 4000), profile development (top), temporal volume development (bottom)</td>
<td>60</td>
</tr>
<tr>
<td>3.22</td>
<td>Analysis grid</td>
<td>61</td>
</tr>
<tr>
<td>3.23</td>
<td>Aggregated sections</td>
<td>61</td>
</tr>
<tr>
<td>3.24</td>
<td>Volume development of sections</td>
<td>62</td>
</tr>
<tr>
<td>3.25</td>
<td>Erosion/sedimentation at sections</td>
<td>63</td>
</tr>
<tr>
<td>3.26</td>
<td>Temporal development of beach width at Transect 3800. Dashed lines indicate nourishment construction. Line 1: Beach Nourishment May/June 1999, 0.300 Mm³; Line 2: Shoreface nourishment September 1999, 0.900 Mm³; Line 3: Beach nourishment September 2000, 0.207 Mm³; Line 4: Shoreface nourishment, June/November 2004, 1.8 Mm³; Line 5: Beach nourishment 2005 (unknown exact date), 0.5 Mm³</td>
<td>64</td>
</tr>
<tr>
<td>3.27</td>
<td>Depth maps of area north of Egmond (Bergen aan Zee)</td>
<td>65</td>
</tr>
<tr>
<td>4.1</td>
<td>Initial profiles VOP</td>
<td>68</td>
</tr>
<tr>
<td>4.2</td>
<td>From left to right: TSS, EMS, reference rod, WHM, ASTM, ADV</td>
<td>69</td>
</tr>
<tr>
<td>4.3</td>
<td>Profiler with three probes</td>
<td>70</td>
</tr>
<tr>
<td>4.4</td>
<td>Measured profiles (Top) and sediment transports derived from profile development (Bottom) for experiment T02: Reference profile using accretive wave condition</td>
<td>71</td>
</tr>
<tr>
<td>4.5</td>
<td>Temporal development of sediment volumes for experiment T02. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach)</td>
<td>71</td>
</tr>
</tbody>
</table>
Figure 4.6 Measured profiles (Top) and sediment transports derived from profile development (Bottom) for experiment T03: Reference profile using erosive wave condition.................................................................72

Figure 4.7 Temporal development of sediment volumes for experiment T03. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach). ..................................................72

Figure 4.8 Measured profiles (Top) and sediment transports derived from profile development (Bottom) for experiment T04: Deep shoreface nourishment profile using erosive wave condition .................................................................73

Figure 4.9 Temporal development of sediment volumes for experiment T04. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach). ..................................................73

Figure 4.10 Measured profiles (Top) and sediment transports derived from profile development (Bottom) for experiment T05: Deep shoreface nourishment profile using erosive wave condition .................................................................74

Figure 4.11 Temporal development of sediment volumes for experiment T05. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach). ..................................................74

Figure 4.12 Measured profiles (Top) and sediment transports derived from profile development (Bottom) for experiment T06: Shallow shoreface nourishment profile using erosive wave condition .................................................................75

Figure 4.13 Temporal development of sediment volumes for experiment T06. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach). ..................................................75

Figure 4.14 Measured profiles (Top) and sediment transports derived from profile development (Bottom) for experiment T07: Shallow shoreface nourishment profile using erosive wave condition .................................................................76

Figure 4.15 Temporal development of sediment volumes for tests using the accretive wave condition. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach). ..................................................76

Figure 4.16 Comparison of final profiles after 24 hours for the low wave condition case. .................................................................77

Figure 4.17 Temporal development of sediment volumes for tests using the accretive wave condition. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach). ..................................................77

Figure 4.18 Comparison of final profiles after 16 hours for the high wave condition case. .................................................................78
Figure 4.19  Temporal development of sediment volumes for tests using the erosive wave condition. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach). 78

Figure 4.20  Schematisation for velocity profile interpolation 79

Figure 4.21  Schematisation for concentration profile interpolation 81

Figure 4.22  Comparison of different integration methods 81

Figure 4.23  Comparison of different integration methods for all 5 positions and 6 experiments combined 82

Figure 4.24  Profile development and uncorrected transports derived from profile changes 83

Figure 4.25  Comparison of temporal erosion and sedimentation volumes for accretive wave conditions 84

Figure 4.26  Profile development and corrected transports derived from profile changes 84

Figure 4.27  Comparison of transports derived from profile development and process measurements for Test 02 85

Figure 4.28  Comparison of transports derived from profile development and process measurements for Test 07 85

Figure 4.29  Comparisons of wave height (top) and velocity moments (bottom) for accretive wave conditions 86

Figure 4.30  Comparisons of wave height (top) and velocity moments (bottom) for erosive wave conditions 87

Figure 5.1  Results of the Egmond application at a cross-shore array (y = 10 m) at five points in time during the model period when the bathymetry was measured (from top to bottom: 05/04/2000, 17/05/2000, 17/09/2000, 18/04/2001 and 18/06/2001). The blue line indicates the measured bathymetry, the red line indicates the computed bathymetry. Dashed lines indicate the initial situation of both. The model predicted errors are shown in red bars 94

Figure 5.2  Results of the Egmond application in the model domain on 15 June 2001. The left panel shows the measured bathymetry. The centre panel shows the computed bathymetries with the present model. The difference between the measured and computed bathymetries is shown in the right panel 95

Figure 5.3  Results of the Egmond 2004-2006 application at four points in time during the model period. The left panels show the measured bathymetry, the right panels the modelled bathymetry from Beach Wizard 97

Figure 5.4  CCD problem 101

Figure 5.5  Another CCD problem 101

Figure 5.6  Shifted image 102

Figure 5.7  Incorrect exposure (high gain, excessive noise) 102
Figure 5.8 Improper color balance ................................................. 103
Figure 5.9 Fog ........................................................................... 103
Figure 5.10 Clearly visible rain drops on housing glass ...................... 103
Figure 5.11 Streaks caused by particles on housing glass ...................... 103
Figure 5.12 Broken housing glass .................................................. 104
Figure 5.13 Ship ......................................................................... 104
Figure 5.14 Glare on the water surface (with refractions) ....................... 104
Figure 5.15 Cross-shore intensity profile at \( y = 0 \) m at 12:00 AM on 5 November 2004. The high intensity area caused by persistent foam is indicated with the red oval. .................................................................................. 105
Figure 5.16 A raw cross-shore intensity profile (in blue) and the resulting fitted and detrended intensity profile through the Alexander (2001) method (in red). .................................................................................. 106
Figure 5.17 Cross-shore profiles at two points in time (15 February and 7 April 2006) when a clear difference was visible between the modelled bathymetry with and without persistent foam. ........................................................................ 107
Figure 5.18 Results of the Egmond 2004-2006 application at four points in time during the model period. The left panels show the modelled bathymetry as shown earlier in paragraph 5.3.2, the right panels the modelled bathymetry from Beach Wizard with persistent foam reduction through Alexander (2001). 108
Figure 5.19 Interface of the Intertidal Beach Mapper tool. The user can define the area (region of interest – ROI, the area enclosed by the red line) in which the tool searches for the waterline (blue). The user can manually select the wrong shoreline points and delete these......................................................................... 109
Figure 5.20 Steps taken by the ASM to derive shoreline points. .................. 110
Figure 5.21 Bad definition of the region of interest on a rectified and merged timex image. The yellow line is the old region of interest that is too big; the blue line is the expected location of the waterline; the purple line is the landward extension of the blue line; the green line is the eventual region of interest, of which the lower line is the seaward extension of the blue line and the upper line is a cut off value to exclude buildings close to the dunes. The red line is an intermediate step in defining the green line......................................................... 111
Figure 5.22 Zigzagging region of interest (red) blocks part of the shoreline; this part of the shoreline will not be detected. The blue line is the expected shoreline location. The red line is extended towards the end of the image at the left. At the right, the region of interest is cut off to exclude the black pixels. The green line is an intermediate region of interest in which the black pixels were not yet eliminated................................................................. 112
Figure 5.23 Region of interest including the entire shoreline, both the continuous shoreline and the emerging sandbank. ......................................................... 112
Figure 5.24 Detected shoreline points. Many points are rejected because the bathymetry against which the points are checked contains not-a-number values at the location of the points.................................................. 113

Figure 5.25 Detected shoreline points checked against two bathymetries. Less points are rejected against NaN values.......................................................... 113

Figure 5.26 Schematic of a barred bathymetry (bottom solid line) and associated dissipation (top solid line), and the modelled bathymetry (bottom dashed line) and the modelled dissipation (top dashed line). The arrows indicate the direction of the adjustment of the modelled bathymetry.............................. 115

Figure 5.27 Measured bore speeds (Svendsen, 2003).............................................. 117

Figure 5.28 Design of the timestack arrays collected in Egmond from the Jan van Speijk lighthouse Argus station on 14 June 2006 – 31 December 2006. ............... 118

Figure 6.1 Computational grid for the profile model with bathymetry of 04 Nov. 2004 ........................................................................................................... 121

Figure 6.2 Profile development for the period 04/11/04 – 30/11/04 induced by different representations of the tide.................................................. 126

Figure 6.3 Wave climate for the period 04/11/04 – 30/11/04: significant wave height and peak direction.................................................. 126

Figure 6.4 Profile development for the period 04/11/04 – 30/11/04 induced by different schematisations of the wave climate.............................. 127

Figure 6.5 Profile development for the period 04/11/04 – 30/11/04 induced by different $\gamma$-expressions.................................................. 129

Figure 6.6 Profile at 04/11/04 with 2 sediment fractions: general diameter $d_{50}$ equal to 0.2 mm except on the nourished bar where $d_{50}$ equals to 0.4 mm.......... 130

Figure 6.7 Profile development for the period 04/11/04 – 30/11/04 induced by different settings .................................................. 131

Figure 6.8 Profile development for the period 04/11/04 – 30/11/04 induced by wave different settings.................................................. 131

Figure 6.9 Profile development for the period 04/11/04 – 30/11/04 obtained with different DELFT3D versions .................................................. 132

Figure 6.10 Wave climate (significant wave height) for the period 30/11/04 – 07/05/06 ........................................................................................................... 133

Figure 6.11 Profile development for the period 30/11/04 – 05/04/05 obtained adopting 1 and 2 sand fractions and using a morphological tide and a time series ... 133

Figure 6.12 Profile development for the period 05/04/05 – 28/07/05 obtained adopting 1 and 2 sand fractions and using a morphological tide and a time series .... 134

Figure 6.13 Profile development for the period 28/07/05 – 08/12/05 obtained adopting 1 and 2 sand fractions .................................................. 134

Figure 6.14 Profile development for the period 08/12/05 – 07/05/06 obtained adopting 1 and 2 sand fractions .................................................. 135
Figure 6.15  Computation grid area model.................................................................136
Figure 6.16  Initial bathymetry: 4 November 2004 (left panel) and observed final bathymetry: 30 November 2004 (middle panel) and erosion/sedimentation (right panel).................................................................137
Figure 6.17  Initial bathymetry: 4 November 2004 (left panel) and simulated final bathymetry using schematised wave climate: 30 November 2004 (middle panel) and erosion/sedimentation (right panel).................................................................................................................................137
Figure 6.18  Initial bathymetry: 4 November 2004 (left panel) and simulated final bathymetry only using the storm wave condition (middle panel) and erosion/sedimentation (right panel). ..........................................................138
Figure 6.19  Cross-shore profiles computed by the area model, the Delft3D profile model and Beach Wizard ..................................................................................................................140
Figure 6.20  Cross-shore volume changes computed by the area model, the Delft3D profile model and Beach Wizard..................................................................................................................141
Figure 6.21  Perspective plot of area model domain for Alternative 02: Nourishment height = -5 m, Length= 2000 m (Volume: 400 m$^3$/m) .........................................................142
Figure 6.22  Nourishment design Alternative 02: Nourishment height = -5 m (Volume: 400 m$^3$/m). .......................................................................................142
Figure 6.23  Profile development after 1 year for a representative profile (alternative case 0) and 1 nourishment design (alternative case 1). .........................................................144
Figure 6.24  Profile development after 1 year for 2 nourishment designs (alternative cases 2 and 4). .........................................................................................145
Figure 6.25  Volume changes in sub-sections defined from the Beach Pole position. Dark blue, light blue, yellow and red display results for Alternative cases 0, 1, 2 and 4, respectively..........................................................................................................................145
Figure 6.26  Initial bathymetry (left panel), computed final bathymetry (middle panel) and computed erosion/sedimentation (right panel) of schematised model without nourishment .........................................................................................146
Figure 6.27  Initial bathymetry (left panel), computed final bathymetry (middle panel) and computed erosion/sedimentation (right panel) of schematised model with nourishment (Alternative 2)..............................................................................................................................147
Figure 6.28  Initial and final computed beach profiles with and without nourishment...148
Figure 6.29  Absolute sedimentation-erosion for the case without a nourishment (left plot) and with a nourishment (central plot) and sedimentation-erosion relative to the reference situation (right) for Alternative 02. .........................148
Tables

Table 2.1 Definition of nearshore sections of the Dutch coastline and accompanying characteristics (after Wijnberg and Terwindt, 1995; Ruessink and Kroon, 1994; Ruessink et al., 2003) ......................................................................................................................22
Table 3.1 Available data ..................................................................................................................36
Table 3.2 Section description ..........................................................................................................62
Table 4.1 Wave conditions VOP .....................................................................................................67
Table 4.2 Overview of VOP tests ....................................................................................................67
Table 6.1 Harmonic components at the boundaries of the profile model for the year 2004. .................................................................................................................................122
Table 6.2 Reduced morphological 5 conditions wave climate applied for the period November 2004, ensuring identical offshore and onshore transports......122
Table 6.3 Summary of the main model parameters applied in the Delft3D area model and profile model ..........................................................................................................................124
Table 6.4 Wave climate from Walstra et al. (2004) ........................................................................143
1 Introduction and Summary of Results

This report describes the results from the VOP short term morphology study carried out in 2007. This chapter gives a short introduction to the project, summarises results and gives a synthesis of the various parts of the study. Focus was the 2004 shoreface nourishment at Egmond, The Netherlands. The measured morphological development over two years was, in combination with available hydrodynamic measurements, subject to detailed studies using various techniques such as modelling and data assimilation.

The project was carried out primarily at WL | Delft Hydraulics. However, a number of external team members from TU Delft and Utrecht University have made valuable contributions.

The team members were:
- Dirk-Jan Walstra: Project leader, modelling, synthesis
- Christophe Brière: Modelling
- Anna Cohen: Beach Wizard
- Ap van Dongeren: Beach Wizard
- Irv Elshoff: Beach Wizard
- Laura Unk: Beach Wizard (TU Delft)
- Maarten van Ormondt: Modelling
- Susanne Quartel: Literature Review (Utrecht University)
- Ben de Sonneville: Data Analysis Field
- Pieter Koen Tonnon: Data Analysis Laboratory
- Claartje Hoyng: Data Analysis Laboratory (TU Delft)

From RWS-RIKZ Marcel Taal, Sander van Rooij and John de Ronde were involved in supervising the project.

Leo van Rijn performed the Quality Assurance for this report.

Ad van der Spek is the project leader of the Kustlijnzorg project under which VOP resorts.

1.1 General

Within the VOP Short term morphology project an integrated approach was used to study the 2004 shoreface nourishment at Egmond in The Netherlands (see Figure 1.1). The primary goal of the study was to increase our knowledge on the effects that shoreface nourishments have on the coast on time scales of weeks (storms) to years (cyclic bar behaviour). To achieve this research goal it is imperative to use a number of techniques/tools which together allow us to study the behaviour on all desired time scales. The adopted method aims at combining the results in such a way that an integral view on the behaviour of a nourished coast is obtained.
The method is schematically shown in Figure 1.2 and is based on three concepts: modelling, data analysis and literature. The innovative part of the method is that the data analysis and the modelling are integrated so that a consistent and complimentary set of results form the basis of the study. This is especially important for the evaluation on the various time scales as a consistent integration enables us to put together analysis techniques that operate (or are valid) on different time scales.
The modelling part of the study is carried out with the Delft3D model (Lesser et al., 2004) in both profile and area mode (Roelvink and Walstra, 2004). The model is used in profile mode to perform a limited calibration and validation on the Egmond nourishment, subsequently an area model is applied which uses the parameter settings derived by the profile model (Brière and Walstra, 2006).

The data analysis uses the JARKUS dataset and additional surveys which have been incorporated into the UCIT system. In total 7 surveys covering a two period (July 2004 to May 2006) were considered to investigate the Egmond nourishment.

The Beach-Wizard data-model assimilation system, which derives the nearshore bathymetry by combining various remote sensing sources, is used to obtain a high temporal resolution estimate of the nearshore bathymetry. The video observations of the Argus system are used in surf zone, the intertidal zone is derived from mapping shoreline positions a number of times within a tidal cycle and radar derived properties are used to derive the bathymetry seaward of the surf zone.

The time scales on which these three methods are utilised in this project are shown in Figure 1.3. The Argus/Beach Wizard data provides results which can be used to analyse both the short term and long term response of the nourished coast. An important advantage of the system is its ability to monitor on a daily basis which, for example, allows us to investigate the storm response. This enables us to evaluate the development and select interesting storm periods of large morphological change during relative short periods. These storm periods are the focus of the modelling study as they allow us to study the behaviour of the coast with relative little computational effort. With this approach we can identify the relative importance of storm periods compared to calm periods.

![Diagram](image)

Figure 1.3  Temporal scales on which data is available or can be provided.

With a literature review the present knowledge on the behaviour of nourishments along the Dutch coast is summarised. This provides the knowledge framework for this study and gives an insight in the find mechanisms and processes which are not yet understood.

To increase our understanding of the physical processes that govern the behaviour of a nourished coast, a morphological experiment was carried out in the Scheldt flume at WL | Delft Hydraulics. In the experiment two shoreface nourishments were subjected to two
different wave conditions (average and storm). Detailed measurements of the developing morphology, as well as of the hydrodynamics (wave heights, water levels, velocities and sediment concentrations) provide important information which processes are affected by the presence of a shoreface nourishment. This is an important addition to the information obtained from the data analysis from the field which is based on morphological changes.

In the next section results of the individual parts of the study are discussed and this chapter is concluded with a synthesis of the results.

1.2 Summary of Results

1.2.1 Literature review

Several scientific studies have paid attention to the natural behaviour of nearshore bars and, although more limited, their response to shoreface nourishments. For the nearshore bar behaviour on longer timescales (years to decades), generally JARKUS data was used (e.g. Wijnberg and Terwindt, 1995). On shorter timescales (days to years), alongshore bar lines of the approximate cross-shore bar position derived from ARGUS-images were analysed. Such lines show the temporal and alongshore variations of nearshore bars (e.g. Van Enckevort and Ruessink, 2003). Small-scale processes forced by waves and currents thought to be relevant for cross-shore and alongshore sandbar behaviour are increasingly captured in numerical complicated models, which are used to understand and predict the generation and response of nearshore bars to time-varying or time-invariant forcing conditions (Roelvink and Braker, 1993; Van Rijn et al., 2003; Ruessink et al., 2007b). For this purpose, measurements of e.g. cross-shore profiles, hydrodynamic conditions and the associated sediment transport are exploited (e.g. Grunnet et al., 2004). Besides, the increasing amount of remote-sensed sandbar data now also allows for the use of data-driven model to explore sandbar behaviour (e.g., Plant et al., 2006; Pape et al., 2007). In contrast to process-models, data-driven models extract relations between forcing and sandbar response directly from observations and use limited, if any, process knowledge.

Along the Dutch coast, the differences in bar behaviour are pronounced, but also various consistent patterns in their behaviour were found. The literature review will summarise the available information on the natural short- and long-term behaviour of the nearshore bars. Subsequently, the morphodynamic response to the implementation of shoreface nourishments and the associated physical processes are described.

This literature study created an overview of the available information on natural behaviour of nearshore bars and the impact of shoreface nourishment. The daily behaviour of nearshore bars consists of onshore migration during calm wave conditions and offshore migration during energetic wave conditions. The integrated effect of the daily behaviour lead to long-term behaviour of bar cyclicity, but nearshore systems also contain additional boundary conditions which influence bar cycle characteristics as bar volume and cycle return period. The additional boundary conditions include the morphologic threshold function of the outer bar decay, which generally is postponed by implementation of a shoreface nourishment. The shoreface nourishment creates a feeder and lee effect, and
increases the contribution of wave-skewness processes, whereas it decreases the wave-induced return flow (i.e. undertow). These two cross-shore processes lead to a stable position or onshore migration of the natural nearshore bars for a period of several years. Alongshore processes as the wave-induced current, may entrap extra sediment when the alongshore flow field is retarded by the nourishment. However, variable alongshore behaviour and nourishments impact are expectable, because the strong oblique dominant wind directions stimulates the alongshore sediment transport. The impact of the shoreface nourishment will also depend on its design. Suggested is that long length scale nourishments would be more persistent than shorter length scale nourishment.

1.2.2 Field Data Analysis

For the field data analysis of the 2004 shoreface nourishment at Egmond the period from the summer 2004 to the summer of 2006 was considered. Within this period 7 surveys were available for the analysis. The basis of the analysis was a detailed examination of the observed changes in plan view in order to obtain a good synoptic overview. The next step was to select a number of cross-sections for which a detailed analysis of the observed changes was made. Data aggregation was based on standardised sections and areas for which sand volumes were determined. It was ensured that the areas and sections were based on the local characteristics of the study area and that they were as consistent as possible with previous studies (e.g. Witteveen en Bos, 2007).

Main results for the data analysis were:
- After 2 years of the nourishments construction (May 2006) most of the nourished sand (both on the shoreface and the beach) can still be found in the study area (a 7 km longshore and 1.2 km cross-shore study area encompassing the nourishments). In the northern part of the study area these findings are somewhat influenced by the placement of a shoreface nourishment at Bergen aan Zee (BaZ) in 2005. However the sand volume in the northern area associated with this BaZ nourishment are relatively low (less then 0.4 Mm³). By subtracting this volume from the nourishment volume at Egmond (2.5 Mm³) it can be concluded that, as a conservative estimate, after 2 years still 84% of the Egmond nourishment can be found in the study area.
- The dunes show a significant volume increase of nearly 0.5 Mm³ (which is 25% of the nourished volume). The inner surf zone (Section 4, cross-shore range -400 to -200, see Figure 1.5) has increased by more then 1 Mm³. The upper part of the profile thus contains an extra volume of sand equivalent to about 60% of the total nourishment volume (beach and shoreface). The overall steepening of the nourished section is primarily caused by the fact that the outer bar is still located shoreward from its position prior the placement of the shoreface nourishment (see Figure 1.6).
- In the first survey after construction of the shoreface nourishment was completed (November 2004) the nourishment had already merged with the natural bar system. The nourishment was at that time already acting as the new outer bar and stopped or had already partly reversed the natural offshore bar migration.
- In the following year the (November 2004 to August 2005) the shoreface nourishment itself detached from the former outer bar with a distinct trough forming between them. During this period the crest of the nourishment gradually decreased by about 0.5 m to 1 m. The former outer bar continued its onshore migration (about 100 m) whilst maintaining or slightly increasing its crest height. In the centre of the nourishment (Transect 38), the onshore migration was most pronounced (about 200 m) due to the formation of a boomerang shaped bar with its most onshore position at this transect (a
rip cell system is developing). It is noteworthy that this onshore migration primarily took place in the summer period (July to August 2005).

- In the final year of the analysis (August 2005 to July 2006) the system continues its adjustment to the shoreface nourishment. The former outer bar moves further onshore and the upper part of the profile (inner bar, beach and dunes) continue to gain sand.

Figure 1.4 Plan view of the nourished coast at Egmond. Left: November 2004 (just after nourishment was completed), Middle: April 2005, Right: May 2006.

Figure 1.5 Temporal volume development for various sub-areas with in study area. Line colours of the right plot correspond with the coloured areas in the top view in the left plot.
1.2.3 Laboratory experiment

In the Scheldt flume of WL | Delft Hydraulics three profiles were subjected to an average (accretive) and storm wave condition (erosive). Two shoreface nourishment designs, constructed at different water depths in the profile, were investigated. Both nourishment designs have the same volume which, on prototype scale, is approximately 400 m³/m. An undisturbed profile was also considered to act as a reference (see Figure 1.7).
In Figure 1.8 the initial and final profiles are compared. It is clear that both shoreface nourishment designs are not able to stop the erosion at the upper part of the profile. However the erosion rate is reduced significantly in this area. For the low shoreface nourishment (green lines) the erosion rate is reduced by about 20%. The high shoreface nourishment (red lines) results in a more substantial reduction of the erosion. For the low wave condition a reduction of 40% is found, whereas for the high wave condition the reduction is about 70%. This is illustrated in Figure 1.9 where the temporal volume development for various cross-shore sections are compared.

Figure 1.8  Comparison of final profiles after 24 hours for the low wave condition case. T02: reference case, T04: Design #1 (low nourishment position), T06: Design #2 (high nourishment position).

Figure 1.9  Temporal development of sediment volumes for tests using the accretive wave condition. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and...
beach). T02: reference case, T04: Design #1 (low nourishment position), T06: Design #2 (high nourishment position).

In the top plot of Figure 1.10 the wave height distributions for the erosive wave conditions are compared for the reference and nourishment designs. Both nourishments clearly results in an enhanced breaking and therefore act as a wave filter. Further inshore the observed wave heights for the deep nourishment (T05) are comparable to those of the reference case (T03). However, for the shallow nourishment (T07) the wave height decrease is present over the entire profile shoreward of the nourishment. The relative increase of the onshore transports associated with the wave asymmetry (bottom plot of Figure 1.10) will also contribute to a reductions of net offshore transport (or increase of net onshore transports). The results imply that the nourishments influence the transports in two ways: 1) reduced wave heights will result in a reduced undertow and hence reduced offshore transports, 2) relative increased wave asymmetry which results in an enhance onshore oscillatory sediment transport.

![Figure 1.10](image_url)  
Comparisons of wave height (top) and velocity moments (bottom) for erosive wave conditions.
1.2.4 Beach Wizard – Argus

This part of the study involved the application of the Beach-Wizard system on the 1999 and 2004 Egmond nourishments and improving various components of the system. Improvements are focussed on improving the operational state.

Application on the 1999 shoreface nourishment showed that the improved system in area mode has reduced the error range significantly compared to the original transect model (RMS-Error reduced from 1.5 m to about 0.5 m for the studied area). A detailed comparison showed that predictions were the most accurate in predicting the bar position and crest height. However, the outer areas, inner areas and the trough regions could not be reproduced accurately. Various reasons were identified which were primarily related to a reduced correlation of the observed intensity images and the local bathymetry. Many of these weak spots in the system have been analysed and alternative approaches (often alternative assimilation sources) have been identified and (partly) implemented to improve the performance of the system.

Figure 1.11  Comparison between observed (left) and Beach Wizard bathymetries (right) after 6 (upper) and 12 months (lower).

Application to the 2004 shoreface nourishment showed that Beach Wizard has especially difficulties representing the new outer bar (nourishment). The behaviour of the inner part of the surf zone is significantly better represented (Figure 1.11). The main causes of the relatively poor performance at the outer bar needs to be studied further. However, it is thought that with some modifications to the method and settings the system's performance can be improved considerably:
- The nourishment and outer bar are not covered well enough temporally by the Argus images as most of the time waves do not break there (and hence no bathymetry can be derived from the Argus time exposure images). The alternative assimilation source in this area would be the wave propagation speed from Argus time stack images or radar.
- The Argus image selection was focussed on covering a two year period which resulted in a maximum temporal resolution of one day. Increasing the resolution to e.g. 1 hour during storms has the potential to increase the performance of the system.
- Sensitivity runs have revealed that certain parameter settings regarding threshold levels for the acceptance of images was set too strict which caused the model to ignore images during storm periods.

1.2.5 Modelling a shoreface nourishment

The modelling of the Egmond nourishment is performed by first applying a profile model to investigate the models sensitivity to various boundary schematisations (tide and waves). Sub-sequentely this model is used to test various model parameters. The final model settings are used to set-up an area model.

Below some results of the sensitivity tests for different tidal and wave schematisations covering November 2004 are shown. Figure 1.12 shows the results for various tidal schematisations. The Beach Wizard profile is also added. The performance in the nearshore zone (offshore movement of the inner bar) can not be assessed because there is no survey data (4 November 2004) available in this region. Also, the offshore migration and generation of an pronounced outerbar bar are incorrectly predicted. However, the offshore movement of the (former) outer bar and its reduced crest height are predicted. The influence of the tidal schematisation is limited, only the new outer bar is influenced somewhat, which is caused by the exclusion of storm surge in the astronomic and harmonic tide schematisations. The storm surge will reduce the wave action on the outer bar and hence the transport capacity resulting in a slightly reduced offshore migration. It is especially promising to see that the harmonic tide (essentially one representative tidal cycle often referred to as the morphological tide) shows a large consistency with the astronomic tide (tidal hindcast using astro-nomical components).

In Figure 1.13 predictions for various wave schematisations are compared with observed development and a full hindcast (wave time series). The wave schematisation was based on either representing the longshore residual transport or the cross-shore residual transport. Although some differences are present the overall behaviour is very similar between the wave schematisations. This is a promising finding because the inclusion of a wave condition leads to a proportional increase in morphological simulation time.

Results of the application of the area model to the November 2004 period is summarised in Figure 1.14. The predicted sedimentation-erosion patterns are very similar to the observations. The absolute sedimentation and erosion values are however over-estimated in the bar region. The storm condition, representing the storm of 17 to 19 November seems to induce most of the changes in this period (compare right and middle plot).
Figure 1.12  Profile development (Transect 3/00) for the period 04/11/04 – 30/11/04 induced by different schematisations of the tide. Initial profile is measured until 1029000 (just seaward of inner bar).

Figure 1.13  Profile development for the period 04/11/04 – 30/11/04 induced by different schematisations of the wave climate
1.3 Synthesis

Main goal is to increase our knowledge on the effects shoreface nourishments have on the coast on time scales of weeks (storms) to years in order to make more efficient designs in the future. Here we are providing a synthesised analysis based on the three main components of the study. The analysis is first focussing on the storm time scale (November 2004) and combining survey data and modelling results. For the yearly time scale, a two year period (2004 – 2006) is considered in which we are using the survey data and the Beach-Wizard generated bathymetries.

1.3.1 November 2004

In Figure 1.15 and Figure 1.16 the derived volume changes per 200 m cross-shore section are shown. Both transects were simulated with identical model settings and forcing conditions. It is noteworthy that the initial profile has a large influence on the predicted morphology. For Transect 38 the 17 November 2004 storm does not induced an abrupt volume changes whereas for Transect 37 (not shown) and 39 most changes in the bar region occur during this period. The dissimilarity in (the modelled) response is most likely caused by the difference of the water depth above the crest and seaward slope of the nourishment. The relevance of storm response was also found in Ruessink et al. (2007b) which, at least qualitatively, confirms our findings. This difference in behaviour is also reflected in the
comparison of the final volume changes (dots in Figure 1.15 and Figure 1.16). For Transect 38 agreement is poor, whereas for Transect 39 and Transect 37 (not shown) is reasonable in the monitored sections (seaward of the inner bar, x = 200m). The Beach Wizard results are not shown because the system is unable to account for the storm response due to a too low temporal sampling resolution and the fact the systems performance is affected by spin up effects (the system starts at 4 November 2004). Because the Beach Wizard analysis focussed on covering the two year period a maximum temporal resolution of one day chosen which is probably insufficient (in hindsight) to capture the morphological storm response. Increasing the resolution to e.g. 1 hour during storms has the potential to increase the performance of the system.

Figure 1.15  Hrms timeserie for the period 04/30 November 2004, and volume changes in a set of sub-sections of profile RSP 38.00. Solid lines and circles display the volume changes calculated by the profile model with boundary conditions specified as timeseries of water levels and waves, and observed, respectively.
In Figure 1.17 the resulting profiles for Beach Wizard, Area and Profile model are compared for Transect 38. A striking difference between the area and profile model is the absence of the offshore migrating outer bar in the area model. This is probably caused by gradients in longshore transport which, by definition, cannot be accounted for by the profile model. The accumulation of sand in this transect is qualitatively well reproduced by the area model. However the onshore migration of the outer bar is not captured as it has flattened completely in the area model.

Although the different methods can not be compared directly it seems that the area model is best capable of reproducing the short term (storm) response of the system to the construction of a nourishment. Due to the high longshore variability the profile model is unable to capture the dominant processes on this short time scale. As the long term (years) nearshore morphology is predominantly governed by cross-shore processes, profile models are likely to be better applicable on such time scales. The area model was unable to make predictions on longer time scales due to the development of small scale alongshore undulations which after some time start to affect the entire surf zone domain.

The Beach-Wizard system is not yet reliably applicable on these short time scales so close at the beginning of the assimilation period (Beach Wizard starts at 4 November 2004). It is important that the system is developed and tested further to obtain better insight in the systems performance (and robustness) on short time scales.
1.3.2 Period 2004-2006

In Figure 1.18 a comparison between the three sections in the active profile is shown for Beach Wizard and Jarkus data. For most sections the temporal development as predicted by Beach Wizard compares reasonably well with the measurements. The high temporal resolution that Beach Wizard can provide reveals that especially the two upper sections (200-400 and 400-600) show relative large variations on short time scales (< weeks). This feature has the potential to increase our knowledge of the coastal system significantly as it can provide us with information that can link the occurring hydrodynamics with the morphological response on the time scale of storms, seasons and years (provided there is a Argus station for such long period). However, it is imperative that the performance and robustness of the predictions increase and that uncertainty ranges are incorporated in the predictions. In previous years considerable effort has been put into assessing uncertainty ranges of the individual and combined assimilation sources. The uncertainty range of predicted bathymetries requires further ground truthing. Furthermore, it needs to be investigated if other data aggregation methods (in stead of the volumetric aggregations applied in this study) are better suited for the Beach Wizard system.

The data analysis techniques used in this study show that a detailed examination of the data on various levels of (spatial) aggregation is imperative for obtaining a complete insight into the developments of the shoreface nourishment. The large alongshore variability on the considered time scales imply that the analysis is most benefitted by a spatial aggregation on a relative course grid analogous to the method applied in van Duin et al. (2004) which is also applied in this study (see e.g. Figure 3.16).
Figure 1.18  Comparison of sand volumes based on Jarkus data (solid) and Beach Wizard (dashed). Top: Transect 37, middle: Transect 38, bottom: Transect 39.
1.4 Recommendations

In this section recommendations are given for the individual components of the study.

1.4.1 Argus/Beach-Wizard

The present application of Beach-Wizard yielded somewhat disappointing results especially compared to the two previous (very) successful applications (Egmond 1999 nourishment and Duck). However the fact remains that, the Beach-Wizard tool has the capability to provide a high temporal resolution bathymetry which not only has the potential to increase our knowledge of coastal behaviour but also to provide us with valuable data for model calibration and validation purposes. Furthermore, ongoing research has revealed that recently introduced threshold conditions to accept or reject an image were the primary reason for the relative poor performance in capturing the behaviour of the outer bar.

The present application was aimed at providing bathymetries covering a two year period. This time period, in combination with a practical limit on maximum run times resulted in the use of Argus images with a temporal sampling resolution of one to two weeks. This image resolution is, in hindsight, probably too coarse to properly account for the effect of storms on the nearshore coastal morphology. To improve the capability of the Beach-Wizard system it is recommended to take the following steps:

- Focus on storm periods (e.g. 1 or 2 days) and vary the temporal image resolution. This will give information on the robustness of the system with respect to the availability of images and the associated time scales. Such a study can provide improved selection criteria and determine the smallest time scale for which the system still provides realistic results. This knowledge is vital for a further development of the Beach-Wizard system, as this knowledge is imperative for a further automisation (and operationalisation) of the system.

- Perform a detailed comparison between the 1999 and 2004 applications. It is expected that such a comparison will provide valuable information on which which issues (e.g. model parameters, initial conditions, wave conditions) influence the systems performance.

- Preliminary results indicate that the inclusion of remotely sensed wave celerity data as source in the system will increase the covered depth range significantly. It is expected that this source will extend the Beach-Wizards depth coverage to both deeper and shallower water.

The Beach-Wizard system will be of most use if the system can run autonomously. This requires a further operationalisation. Within the present study automatic image selection and water line detection software has already been developed. Further automation of the system comprises the following steps:

- Nesting of the system in large wave models which are coupled to meteorological models so that automatically is accounted for e.g. wind growth and storm surge.

- Increasing code robustness and efficiency. In the present version Delft3D is used to compute wave characteristics. It is suggested to extract the relevant part of the code (wave and roller energy balance solver) from Delft3D or Xbeach and implement that in Beach-Wizard.

- Dissemination of the results could be achieved by setting up public online databases.
Reformatting output files so that they are fully compatible with existing post-processing tools (e.g. Delft3D-Quickplot, Muppet and WL-Tools).

1.4.2 Process based modelling (Delft3D)

The application of Delft3D to investigate the morphological impact of a shoreface nourishment is only partially successful. This is to a certain extent due to well-known shortcomings in the model. However also a number of unexpected problems were encountered. This sub-section provides a summary of these shortcomings together with recommendations on how improve our capabilities in the nearshore zone.

Unrealistic formation of rip channels in shallow areas
In recent years, a lot of effort has been put in to implementing the TRANSPOR2004 sediment relations in the Delft3D code. Some very promising results have been obtained with these formulations in combination with the use of the roller model, in particular with respect to 3D bar behaviour. However application in the present project have also revealed a number of problems, which prevent us from running 3D morphodynamic simulations over periods longer than a few months. Large-scale, physically unrealistic, rip channels tend to develop at Egmond, also during severe storms. After a few months, these rip patterns have become so large that they start to influence the behaviour of the outer bars. Promising is the fact that the morphological response of the bar region prior to this seems to be simulated very well with the TR2004 formulations. A number of possible 'culprits' have been identified which may be responsible for this behaviour:

- Overestimation of bed roughness in shallow water with TR2004 bed roughness predictor.
- Underestimation of longshore wave-driven currents.
- Underestimation of entrainment/vertical mixing of sand under breaking waves.
- Lack of surf beat/swash in the model formulations.

3D vs. profile model
The combined application of a profile (2DV) and area model (3D) is very attractive as it has the potential to reduce the overall simulation effort of a coastal project considerably. It is however of the utmost importance that results between both approaches are entirely consistent. Within this project we have encountered a number of inconsistencies between the two approaches which need to be resolved. Part of the inconsistencies can originate from the difference in concepts (e.g. the profile model predicts a large bar offshore which is not found by the 3D model). However others (e.g. small, but noticeable, differences in longshore transports) are likely to be caused by coding errors. It is highly recommended to initiate research in which inconsistencies are resolved as far as coding errors are concerned and to assess differences in the predicted morphological behaviour which originate from the modelling concepts.

Hydrodynamic validation
In recent years there have been many morphological studies (amongst others the present study) on the one side and detailed studies using laboratory data on the other (development and implementation of TR2004 formulations). It is recommended to perform a hydrodynamic validation study using available field data (e.g. Coast3D and Duck). This study can form the basis of some of the recommendations mentioned above.
1.4.3 Field data analysis

The scope of the data analysis in the present study was limited in terms of both spatial and temporal coverage. Although we have learned more about the behaviour of the shoreface nourishment on small scales, relative little is known about the effects on longer term and larger scales. Furthermore it is vital to determine the autonomous behaviour before nourishments were constructed. This will enable a more objective judgement on the effects nourishments may have.

The analysis techniques used in this study have provided a solid framework for the evaluation of the nourishments. However, these techniques may need to be adjusted or improved if larger scales or other sites are considered. A database in which the applied algorithms are properly managed is a crucial part in obtaining consistent analysis results within different studies. Obviously this also applies to the datasets that are used in the analyses. Within WL | Delft Hydraulics such databases now exist (UCIT, Delft-Almighty), further improvement and extension of these systems is a long term commitment which should be entrenched in future research projects.

1.4.4 Laboratory experiment

The laboratory experiments have provided valuable information that will help us to improve our understanding of the morphological interaction of shoreface nourishments with the upper part of the beach profile. Within the present project the data is used to link the presence of a shoreface nourishment to observed hydrodynamics and sediment transports. However, it is recommended to perform additional studies in which the data is also used for model verification. A combined data-model study could help us to establish with more accuracy which processes are mostly affected.

Furthermore, the laboratory experiment has shown that we are able to partly mimic the cross-shore morphological response of nourished beach profile. It is recommended to establish whether this could be extended to include the longshore effects as well. This would involve a preliminary study to investigate whether a number of shoreface nourishment designs can be implemented in the Vinje basin.
2 Literature Review

2.1 Introduction

During the last decade, coastline maintenance along the Dutch coast frequently comprises the implementation of sand nourishments in the nearshore zone. Breaker bars are common subtidal nearshore features and are likely to be influenced by the nourishments.

Several scientific studies have paid attention to the natural behaviour of nearshore bars and, although more limited, their response to shoreface nourishments. For the nearshore bar behaviour on longer timescales (years to decades), generally JARKUS data was used (e.g. Wijnberg and Terwindt, 1995). On shorter timescales (days to years), alongshore bar lines of the approximate cross-shore bar position derived from ARGUS-images were analysed. Such lines show the temporal and alongshore variations of nearshore bars (e.g. Van Erckevort and Ruessink, 2003). Small-scale processes forced by waves and currents thought to be relevant for cross-shore and alongshore sandbar behaviour are increasingly captured in numerical complicated models, which are used to understand and predict the generation and response of nearshore bars to time-varying or time-invariant forcing conditions (Roelvink and Brørsker, 1993; Van Rijn et al., 2003; Ruessink et al., 2007b). For this purpose, measurements of e.g. cross-shore profiles, hydrodynamic conditions and the associated sediment transport are exploited (e.g. Grunnet et al., 2004). Besides, the increasing amount of remote-sensed sandbar data now also allows for the use of data-driven model to explore sandbar behaviour (e.g., Plant et al., 2006; Pape et al., 2007). In contrast to process-models, data-driven models extract relations between forcing and sandbar response directly from observations and use limited, if any, process knowledge.

Figure 2.1  Map of the Netherlands with references to the beach sections as listed in Table 2.1.
The central Dutch coast and 2 Wadden islands are divided into 7 nearshore sections (Table 2.1). The division of the central Dutch coast is based on the five Large Scale Coastal Behaviour (LSCB) sections defined by Wijnberg and Terwindt (1995). The nearshore bars in these LSCB-sections clearly prevail different long-term behaviour. In addition to these LSCB sections, two studied nearshore bar systems of the Wadden island Ameland and Terschelling were selected for the present study. Moreover the bar systems of these two Wadden islands reveal a mutual difference in natural behaviour, but also in comparison with the sections of the central Dutch coast (Table 2.1 and Figure 2.1). The defined nearshore sections differ in nearshore slope and natural bar behaviour (Table 2.1).

Along the Dutch coast, the differences in bar behaviour are pronounced, but also various consistent patterns in their behaviour were found. This literature review will first summarize the available information on the natural short- and long-term behaviour of the nearshore bars (Section 2.2). Subsequently, the morphodynamic response to the implementation of shoreface nourishments (Section 2.3) and the associated physical processes (Section 2.4) are described. Finally it will touch on the most notable findings in literature and ends with conclusions (Section 2.5). Throughout, emphasis is on subtidal sandbar behaviour in the regions listed in Table 2.1.

Table 2.1 Definition of nearshore sections of the Dutch coastline and accompanying characteristics (after Wijnberg and Terwindt, 1995; Ruessink and Kroon, 1994; Ruessink et al., 2003).

<table>
<thead>
<tr>
<th>Nearshore section</th>
<th>Region</th>
<th>Alongshore stretch [km]</th>
<th>Slope of nearshore (barred) zone [-]</th>
<th>Number of bars [-]</th>
<th>Cycle return period [yrs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Ameland</td>
<td>7</td>
<td>1:180 (1:225)</td>
<td>2 – 3</td>
<td>6.1</td>
</tr>
<tr>
<td>B</td>
<td>Terschelling</td>
<td>7</td>
<td>1:180 (1:205)</td>
<td>2 – 3</td>
<td>11.4</td>
</tr>
<tr>
<td>C</td>
<td>Den Helder</td>
<td>5</td>
<td>1:400 (small)</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Julianadorp</td>
<td>15</td>
<td>1:400 – 1:110</td>
<td>1</td>
<td>0 (stable)</td>
</tr>
<tr>
<td></td>
<td>Petten</td>
<td>32</td>
<td>1:110 (1:120)</td>
<td>2 – 3</td>
<td>15.1</td>
</tr>
<tr>
<td>D</td>
<td>Julianadorp</td>
<td>15</td>
<td>1:110 (1:120)</td>
<td>2 – 3</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>Petten</td>
<td>32</td>
<td>1:110 (1:120)</td>
<td>2 – 3</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>Ijmuiden</td>
<td>42</td>
<td>1:130 (1:170)</td>
<td>3 – 4</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>Scheveningen</td>
<td>20</td>
<td>1:130 – 1:400</td>
<td>0 – 2</td>
<td>-</td>
</tr>
</tbody>
</table>

### 2.2 Natural nearshore bar behaviour

#### 2.2.1 Appearance

The general environmental settings for nearshore bars comprise a semi-protected or open coastline with nearshore slopes varying between 1:33 – 1:200 (e.g. Short and Aagaard, 1993; Ruessink and Kroon, 1994). Gentle nearshore slopes seem to favour the number of bars, although a unique relation between slope and number of bars not (jet) found (e.g., Short and Aagaard, 1993; Wijnberg, 1995). Generally, the alignment of the bars is shore-parallel and their location with respect to the shoreline varies from shore-attached (0 m) up to several hundreds of meters. In case of multiple bars, the spacing between subsequent bars
is in the order of $10^1 - 10^2$ m and increases in the offshore direction. The bar height is in the order of $10^1 - 10^2$ m (Wijnberg and Kroon, 2002). In the alongshore direction, the shape of the bars may be uniform and straight (i.e. 2D-bars; Figure 2.2a); however, the bars may also appear as curved features (i.e. 3D-bars; Figure 2.2b and Figure 2.2c) with local seaward protrusions, which frequently correspond with the positions of rip channels. The cross-shore bar amplitude and alongshore bar length describe the 3D shape of the bar. The bar amplitude is defined as half the cross-shore distance between the most seaward and the most landward points of a 3D-bar (Figure 2.2c). The alongshore distance between two successive seaward protrusions is defined as bar length or rip spacing. The 3D character of the bars increases with a growing amplitude and a decreasing bar length. The bar shape can change in time in response to prevailing wave conditions (temporal variable). Additionally, the amplitude of bars also depends on spatial characteristics, because it is exponentially related to the mean water depth above the bar (Ruessink et al., 2003).

![Figure 2.2](image)

**Figure 2.2** Temporal variation of bar shape characteristics as bar length and bar amplitude visible in the ARGUS images of Noordwijk from 28 February 2002 (a), 2 March 2002 (b) and 10 March 2002 (c).
The generation of nearshore bars is still under debate, but the following two hypotheses are most commonly used in the explanation of bar generation (e.g., Masselink and Hughes, 2003). The first hypothesis includes the generation of the nearshore bar near the breakpoint of short, incident waves (i.e. the breakpoint mechanism; Figure 2.3a). The nearshore bar results from the convergence of sediment, because wave skewness outside the surf zone induces onshore sediment transport and bed return flow in the surf zone induces offshore sediment transport. The second hypothesis associates the generation of a bar at the (anti-) nodes of standing infragravity wave (wave period = 20 – 300 s), which represent locations of sediment convergence (Figure 2.3b). When bedload sediment transport is dominant, the bar is formed at the node of the long wave. A bar is generated below an antinode of the long wave when suspended sediment transport is dominant. However, the second hypothesis is quite outdated. But there are also still no conclusive observations on the first hypothesis. However, it includes processes that also seem to be of importance for the (short-term) variations of the nearshore bars.

2.2.2 Short-term variations (day – seasons)

Short-term variations of nearshore bars include the daily cross-shore and alongshore migration in response to the prevailing wave conditions. Cross-shore migration comprises on- and offshore movement of the bar with rates in the order of one to tens m day⁻¹ (see for an extensive overview Van Enckevort and Ruessink, 2003a). Overall, the offshore migration rates of a nearshore bar on a daily to weekly timescale are larger than the onshore migration rates. Offshore bar migration happens during high-energetic wave conditions, whereas low-energetic wave conditions induce onshore bar migration (e.g., Sallenger et al., 1985, Van Enckevort and Ruessink, 2003a). More specifically, Ruessink and Terwindt (2000) described the conditions, which contribute most to the onshore sediment transport to vary between mainly breaking waves offshore of the bar zone to mainly non-breaking conditions on the beach. However, wave conditions contributing to the offshore sediment transport are restricted to breaking waves over the entire cross-shore profile. Perhaps because of their relatively large size, Dutch sandbars tend to be less responsive (i.e. lower migration rates) to individual storms than elsewhere.

The alongshore migration of the nearshore bars are generally measured by use alongshore changing position of rip channels. The alongshore migration rates are of the same range as the cross-shore migration rates, namely in the order of one to tens m day⁻¹ (see for an extensive overview Van Enckevort and Ruessink, 2003b). Wave conditions have proven their influence on the alongshore bar migration due to the correspondence in the direction of wave propagation and rip migration and the relation between the migration rates and the alongshore wave-induced current (e.g. Ruessink et al., 2000; Van Enckevort and Ruessink, 2003b; Holman et al., 2006).

Due to the cross-shore and alongshore migration of the nearshore bar, the location of the bar crest in a cross-shore profile changes continuously. During a 6-week study of the nearshore bars at Egmond, Ruessink et al. (2000) found that only 10% of the variation in the bar crest its cross-shore position was indeed due to cross-shore migration of the bar as a whole (i.e. uniform bar behaviour). On the contrary, 85% of the variations in the cross-shore position of the bar was related to alongshore migration, or to changes in the bar amplitude. Changes in
the bar amplitude are part of the bar shape changes that happen with changing wave conditions. Generally, bars tend to straighten (2D) during severe and prolonged wave breaking (Figure 2.2a). During the subsequent lower wave conditions develop 3D-shapes (Figure 2.2; e.g., Wright and Short, 1984; Wijnberg and Kroon, 2002). The duration before 3D-shapes are fully developed may vary between several days (Lippmann and Holman, 1990) and several weeks (Short, 1978). However, a relation between the prevailing wave height and the amplitude of the nearshore bars at Noordwijk was not established (Van Enckevort and Ruessink, 2003b).

Figure 2.3  Two models of bar generation: (a) breakpoint mechanism and (b) standing wave model (Masetlink and Hughes, 2003).

Other changes in bar shape include variations of the bar length, or in other words the spacing between rips. The bar length can also often be coupled to offshore wave energy (Short, 1985; Short and Brander, 1999) and tends to increase with growing wave energy. Nevertheless there remains uncertainty about this relation (Ranasinghe et al., 1999; Lafon et al., 2005). Computed from aerial images from the whole central Dutch coast, Short (1992) found an alongshore averaged bar length of 595 m (range = 355 - 909 m) for the inner bar and 900 m for the outer bar. However, the temporal resolution of the aerial images was limited and especially the outer bar length is questionable due to rare sampling. From daily Argus images, Van Enckevort and Ruessink (2003b) derived bar lengths varying between 380 and 2760 m for the inner bar and between 970 and 2730 m for the outer bar at Noordwijk. Here, the changing bar lengths over weekly timescales was associated with the alongshore variable grow of the bar amplitude.
Morphologic changes of the nearshore bars are generally explained as a response to variations in forcing wave conditions. In case of a multiple bar systems, the presence of an outer bar affects the behaviour of the inner bar(s), because the outer bar influences the wave field approaching the inner bar(s). Previous studies described the possible influence of the outer bar on inner bar(s) as morphologic coupling that is a similarity in shapes of two bar lines. Frequently no direct spatial relation is found between two bar systems (e.g. Sonu, 1973, Van Enckevort and Ruessink, 2003b). However, Ruessink et al. (2007a) showed an inner and outer bar system in a swell-dominated setting at the Australian east-coast to change from an initially uncoupled to a coupled system in response to the onshore propagating, increasingly 3D outer bar.

Generally, the amplitude and the degree of 3D-shape of the nearshore bars of the storm-dominated, Dutch coast are smaller compared to nearshore bars along some well-studied, swell-dominated coasts of e.g. Australia or North America. Besides, the Dutch nearshore bars contain more sediment than the swell-dominated nearshore bars. Storm-dominated, nearshore bars seem to have a more robust character, just as the intertidal beaches are more robust along a storm-dominated coast than along a swell-dominated coast (Quartel et al., accepted). Therefore note that some (quantitative) results on short-term, nearshore bar behaviour may not be exchangeable between these two types of coasts.

2.2.3 Long temporal scale (years – decades)

Many short-term variations (storm-recovery sequences) lead to long-term bar behaviour. However, long-term nearshore bar behaviour is not just simply the sum of daily changes. Long-term behaviour of bars seems to be an integrated effect of short-term variations with concepts as relaxation time and morphologic feedback (Wijnberg and Koon, 2002). Frequently, long-term bar behaviour incorporates bar cyclicity, which is recognized for bars along major parts of the Dutch coast (Table 2.1; Ruessink and Koon, 1994; Wijnberg and Terwindt, 1995) as well as along various coastlines around the world (Lippman et al., 1993; Shand and Bailey, 1999).

The bars cycle is built up by three stages. Initially, the nearshore bar is generated in the inner nearshore zone (stage I). After a certain period, the bar migrates net offshore from the inner to the outer nearshore zone (stage II) and subsequently the bar decays at the outer boundary of the nearshore zone (stage III) (Ruessink and Koon, 1994; Wijnberg and Terwindt, 1995). Various bar parameters, besides the cross-shore position (Figure 2.4a) change in time and during these stages. The bar crest depth, bar height, bar width and bar volume increase with the cross-shore distance to the shoreline during stage I and II, and all reduce to zero during stage III, with exception of the bar crest depth (Figure 2.4b; Ruessink and Koon, 1994).

Within the bar cyclicity, Ruessink and Koon (1994) defined three different morphologic feedback mechanisms between the behaviour of the individual bars in a multiple bar system: (1) the stage of a bar changes when the outer bar degenerates; (2) prevention of the change from stage I to stage II from the inner bar due to the alongshore appearance from a new outer bar having a small crest depth; and (3) alongshore difference in mean annual seaward migration rate caused by the possible presence of a more seaward positioned bar
(comparable findings by Lippmann et al., 1993; Kroon, 1994, Wijnberg and Wolf, 1994). Therefore, Ruessink and Kroon (1994) hypothesized that the crest depth of the outer bar regulates the relative importance of processes inducing shoreward and seaward migration in the inner nearshore bar zone and therefore controls the behaviour of the nearshore bar zone on the timescale of years.

Mechanism 1 functions as a morphologic threshold on the bar cyclicity and leads to understanding of the bar degeneration. Wijnberg and Kroon (2002) stated the decay of a nearshore bar to be possible by highly asymmetric, non-breaking wave (after Larson and Kraus, 1992; Wijnberg, 1995; Ruessink, 1998). This statement is in conformance with the nearshore bar morphology being a function of breaker height (after Short and Aagaard, 1993), which suggests nearshore bars do not decay under breaking waves (Wijnberg and Kroon, 2002). However, the exact bar decay mechanism remains uncertain. The outer bar crest depth determines the amount of reduction of short wave energy entering the inner nearshore zone. For the Terschelling nearshore bars, a critical water depth above the outer bar crest of 5.5 m was found (Ruessink and Kroon, 1994). Higher wind waves propagated into the inner nearshore zone when the water depth is larger than the critical water depth. This leads to stronger offshore-directed currents that enable the inner bar to migrate offshore (stage 2).

The bar cycle may be disturbed by the alongshore migration of the bars (mechanism 2). This has been observed at Terschelling (beach section B in Figure 2.1; Ruessink and Kroon, 1994), but can occur at every site where bars net migrate alongshore. The net alongshore migration rates are larger along the Wadden islands than along the central Dutch coast, namely in the order of hundreds m yr\(^{-1}\) and several to tens m yr\(^{-1}\) respectively (Short, 1992; Grunnet and Hoekstra, 2004).
Mechanism 3, the local and temporal lag in net offshore bar migration, leads to bar switching (Van Enckevort, 2001; Shand et al., 2001). The morphologic threshold of the depth of the outer bar (mechanism 1) may contribute to this mechanism, because bar switching may appear when an inner bar opposite of a low outer bar receives more energetic wave conditions than an inner bar shoreward of a high outer bar. The net offshore migration of the former inner bar will be larger than the net offshore migration of the latter inner bar (e.g., Grunnet and Hekstra, 2004). The resulting alongshore difference in bar migration leads to bar switching and prevails as bar bifurcations (Figure 2.5).

Figure 2.5  ARGUS image from Noordwijk of 6 November 1996 showing the bar-switching mechanism by the bifurcation of nearshore bars. The alongshore length is about 2 km and the cross-shore distance is 800 m (after Van Enckevort, 2001).

Some nearshore bars along the Dutch coast do not reveal any cyclic behaviour and remain at an identical cross-shore position in the long run (e.g. nearshore section D; Table 2.1). However, most Dutch nearshore bars do experience cyclicity, but the return period of the bar cycle is spatially variable (Table 2.1). The return period varies between about 4 up to 15 years (Wijnberg and Terwindt, 1995; Ruessink et al., 2003). Cycle return period is related to the bar zone depth range: the smaller the range, the shorter the cyclicity (slope of relation is 4 yr/m; Ruessink et al., 2003). Besides the cycle return period, also the alongshore coherence of the cross-shore migration can be variable. For example, nearshore section F shows more coherence in the offshore bar movement than nearshore section E (Wijnberg and Terwindt, 1995). However, a reason for this variation is indistinct.

With respect to the coastal maintenance issue, the bar cycle is a cross-shore redistribution of sand without significant loss of sand to the offshore region. Wijnberg (1995) found this with computations on the sediment budget derived the JARKUS profiles. However, the bar cycle seems to play a role in the long-term fluctuations of the shoreline position. Namely, similarity was found between the temporal and alongshore scales between behaviour of the shoreline and the nearshore bar in nearshore section E (Figure 2.1). On the contrary though, less than 10% of the variation in the cross-shore bar position is correlated to the cross-shore position of the shoreline. In this weak relation, retreat of the shoreline correlates to a landward position of the nearshore bars (Wijnberg and Terwindt, 1994).

2.3  Morphodynamic responses to shoreface nourishments

The Dutch shoreface nourishments are generally implemented as alongshore berms in the nearshore zone. During the shoreface nourishment at Terschelling (nearshore section B;
Figure 2.1) of 1993 though, the dredged sand was placed in the outer trough of the present multiple bar system. The supplemented nearshore berms may have two different effects, namely the lee and feeder effect (e.g., Van Duin et al., 2004; Grunnet et al., 2005; Ojeda et al., in prep). The lee effect refers to the berm ability to increase wave dissipation with a corresponding reduction of the shoreward wave-induced alongshore current, which leads to increased deposition of sediment by alongshore sediment transport (Grunnet et al., 2005). Besides the nourished berm may also partially block the wave-induced current (Van Duin et al., 2004). The feeder effect comprises the onshore movement of nourished sand by wave non-linearity and slow onshore currents, which are inherent to cell-circulation patterns induced by the nourishments (Ojeda et al., in prep).

Depending on the water depth where the shoreface nourishment is implemented, the berm is referred to as stable or active. The intention of a stable berm is not to migrate shoreward, but to retain its position and volume, and to function as a wave filter dissipating the energy of the larger breaking waves (lee effect; Grunnet, 2004). The water depth varies between 10 and 15 m, whereas the water depth above active berms remains below 8 m (Van Rijn, 2005 in Van Duin, 2004). Active berms lead to the feeder effect on the nearshore zone (Grunnet, 2004), but may also have the lee effect. An increase in the feeder effectiveness supposes to coincide with decreasing distance to the shoreline (Van Rijn, 2005 in Van Duin, 2004). Both the effectiveness of the lee and/or feeder purpose of the shoreface nourishment supposedly depend on its accompanying lifetime, which varies between 2 to 8 years.

2.3.1 Response of nearshore bars

When implementing the shoreface nourishment as an alongshore berm, the nourishment reshapes itself into a bar with a landward trough within a few months and eventually may migrate landward (e.g. Witteveen+Bos, 2006). The newly formed outer bar influences the nearshore bar behaviour by the morphologic threshold mechanism (Section 2.2.3). Consequently, the nearshore bar stops its net offshore migration, and even sometimes starts migrating shoreward. During the stop of the offshore migrating bars, the bar parameters as bar depth, height and volume maintain the pre-nourishment values (Grunnet and Ruessink, 2005). Obviously the duration of the interference on the bar cyclicity depends on the lifetime of the shoreface nourishment and may even exceed this lifetime. At Noordwijk, the nourishment was detectable by wave breaking patterns in Argus-images up onto 5 years after the nourishment, whereas the halted offshore migration lasted at least over 5.8 years (Figure 2.6; Ojeda et al., in prep). Additionally, the shoreface nourishment leads to an increase of the 3D bar shape including the development of shallow horns which ultimately connect to the shore (Spanhoff et al., 2006). However, this increase in 3D is not found to be a consistent response (Ojeda et al., in prep).

Grunnet and Ruessink (2005) showed that the Terschelling-nourishment, which was implemented by filling the outer trough, also halted the autonomous net offshore migration of the bars for a period of 6 to 7 years (Figure 2.7). The development of the nourishment comprised deepening of the infilled trough due to onshore sediment transport. An intensification of the 3D shape as a consequence of the nourishment was found as well, although only specifically for the middle nearshore bar.
Besides the direct influence on bar behaviour, an indirect result may be steepening of the nearshore profile. Namely, nearshore profiles of section D (Figure 2.1) showed the new trend of steepening after the implementation of a shoreface nourishment, whereas the trend was profile flattening during the decades previous to the nourishment implementation (Wijnberg and Terwindt, 1995). However, flattening of the nearshore profile would be more rational when locally the water depth increases in response to depositing sediment at the outer part of the nearshore zone.

All above-described responses of the nearshore bars associate to the impact shoreward of the nourishment, but at the same time the nearshore bars at the flanks of the nourishment are differently affected. While the nourishment leads to a stop or an inverse of the net offshore migration of the shoreward located nearshore bars, the bars at the flanks maintain their natural behaviour and net migrate offshore. This leads to formation of forked shapes (bifurcations; Figure 2.5) and subsequent bar switching. This flank effect is found along various nourished areas within nearshore sections E and F (e.g. Keijzer, 2004; Spanhoff et al., 2006; Witteveen+Bos, 2006; Ojeda et al., in prep).

2.3.2 Beach response

Grunnet (2004) summarizes all studies done on ‘experimental’ shoreface nourishments, and concludes that as long as the berms are placed at the right water depth, the berm may indeed function as a feeder berm and consequently restores the beach profile. However, more detailed studies on Dutch shoreface nourishments report that the effect on beach evolution remains uncertain (e.g. Witteveen+Bos, 2006; Quartel and Grasmeijer, 2007). In general, the studies apply a similar definition for the beach i.e. the coastal zone between the dunefoot (+3 m NAP) and the mean low water line (about −1 m NAP).
For the shoreface nourishment at Egmond of 1999 is concluded that it did not directly affected the beach (Van Duin et al., 2004). However, this supposed to be caused by the relative short lifetime (2 years) of the shoreface nourishment, which started to disappear before the sediment could reach the beach. Van Duin et al. (2004) suggested that a timescale in the order of 5 – 10 years is needed for sediment to feed the beach zone. On the contrary, the shoreface nourishment almost instantaneously, positively affected the sediment volume of both the intertidal as the supratidal beach of Terschelling (nearshore sections B; Grunnet and Hoekstra, 2003). A morphodynamic coupling between the beach and inner bar behaviour was found in several decades of Jarkus-data obtained before the implementation of the Terschelling nourishment. The beach shoreward of a high inner bar accreted while the same beach shoreward of a lower inner bar retreated (Grunnet and Hoekstra, 2003). This specific behavioural relation was not found at sites as Egmond and Noordwijk (nearshore sections E and F, respectively; Quartel and Grasmeijer, 2007). At Noordwijk, the beach volume indeed tended to increase within a period of 3 years after the shoreface nourishment. Subsequently the beach volume was the same after 7 years as when the nourishment was implemented. However, reservations remain about the direct relation between the volumetric beach changes and the nourishment, whereas the range remains within the natural annual variation of the beach volume (Quartel and Grasmeijer, 2007).

Figure 2.7 Window-averaged cross-shore position $P_b$ of the middle bar vs. time (solid lines) for different nearshore stretches along the coast of Terschelling (A-F). The dotted lines indicate the projected net seaward migration of the middle bar estimated from the 28-year JARKUS-data of autonomous bar behaviour. The vertical dashed lines indicate the time of the nourishment implementation (Grunnet and Ruessink, 2005).

Following Witteveen+Bos (2006), the beach width remains unaffected by the implementation of shoreface nourishments, but sand is transported in shoreward direction and eventually leads to the seaward migration of the dunefoot position. This implies a simultaneous growth in dune sand volume and thus a positive influence by the nourishment
on the beach as a natural coastal defence mechanism. It should be noted though that the above-mentioned seaward migration was found for individual cross-shore profile(s) at, for example, the Noordwijk beach. Nevertheless, the alongshore-averaged dunefoot position of the same beach varied little (Quartel and Grasmeijer, 2007), which suggests that results derived from individual profiles may be biased by local variations. Besides, positive effects may be found on the beach stretch shoreward of the nourishment, negative effects are found within several hundreds of meters outside this beach stretch where the beach width decreases and the dunefoot even retreats sometimes (Witteveen+Bos, 2006).

2.4 Physical mechanisms responsible for nearshore morphodynamics

Hydrodynamic processes caused by tides, wind and waves contribute to the transport of nearshore sediment, and thus also to the redistribution of nourished sand. Generally in the nearshore zone, the flow field induced by waves is assumed to be dominant, whereas tides and winds only act as modifiers on this flow field. Modifications of the flow field comprise i) changes in the water level by e.g. tidal cycle, wind set-up/set-down, ii) an additional alongshore-current vectors or iii) the effect of winds on wave breaking (Wijnberg and Kroon, 2002). Besides different shapes of the nearshore bars will have their own process signature (Wright and Short, 1984). The straight bars will be associated with an alongshore more uniform flow field. Weak to moderate horizontal circulation will prevail when the nearshore bars obtain a 3D shape. Ultimately, when bars even become shore-attached, strong rip currents develop and the horizontal circulation dominates the flow field (e.g., Wright and Short, 1984).

The transport of sediment in the cross-shore direction is essentially due to wave skewness and undertow (e.g., Kroon, 1994; Grunnet et al., 2004; Ruessink et al., 2007b; Van Leeuwen et al., 2007). The net sediment transport in cross-shore direction needs to be shorewards for the nourishment to be effective. This objective is accomplished due to the larger waves, which break at the seaward side of the nourishment. Consequently, the remaining shoaling waves induce an onshore transport of the nourished sediment due to the wave skewness (feeder effect; Section 2.3). In addition, the calmer wave climate induces a wave-induced return flow (i.e. undertow), which leads to a decrease in the offshore sediment transport (lee effect; Van Duin et al., 2004).

Remarkably, reproduction of onshore bar migration under relatively calm wave conditions by coupled process-based models remains difficult suggesting that relevant processes in onshore bar migration are still missing (Roelvink and Brøker, 1993; Van Rijn et al., 2003). However, Ruessink et al. (2007b) found this onshore migration due to feedback between the (near-bed) wave skewness, bedload transport and the sandbar. A sandbar was found to remain its position under small waves and conditions, when breaking and non-bearing waves alternate with low and high tide, respectively. During periods of extreme low water levels (i.e. ebb at spring tide or set-down in water level), water above the inner nearshore bar may be shallow to possibly absent. Then also swash-backwash processes influence the cross-shore (onshore) migration of the inner nearshore bar (Kroon, 1994).
The net sediment transport in the alongshore direction results mainly from alongshore currents and horizontal circulation (i.e. rip cells; e.g., Grunnet et al., 2004; Van Leeuwen et al., 2007). Because waves break on the shoreface nourishment, the resulting calmer wave climate behind the nourishment leads to a reduction of the alongshore current (i.e. lee-effect; Section 2.3). This reduction in flow velocity causes a reduction of the sediment transport capacity (e.g., Van Duin et al., 2004). In addition, the wave-induced alongshore current generated downrift of the nourishment is blocked by the shoreface nourishment, which leads to updrift sedimentation (feeder-effect) and downrift erosion. Although the dominant direction of the wave-driven alongshore current along the central Dutch coast is in northern direction, erosion dominated north and south flank of the Egmond-nourishment (Van Duin et al., 2007).

Van Leeuwen et al. (2007) focussed in a numerical, linear model-study on the effect of the horizontal circulation for the development of nourished berms. In this model the waves approach perpendicular to the coast and these waves initiated gradients in wave energy and wave set-up due to breaking waves seaward of the nourishment and shoreward at the channels in between. These gradients lead to sediment transport initiated by the horizontal flow field. This study concluded that long length scale nourishments decay more slowly than shorter length scale nourishments and that the long length scale nourishments migrated shoreward.

A process-based model study of the Terschelling-nourishment (nearshore section B, Figure 2.1) pointed out that the strong obliquity of the dominant wind direction indeed led to alongshore wind-driven currents increasing the net alongshore sediment transport (Grunnet et al., 2005). The wind-induced increase in sediment transport could explain stronger alongshore migration of the bar systems at the Wadden islands compared to the central Dutch coast (Section 2.2.3), because the dominant wind direction of the central Dutch coast is not as oblique as the dominant wind direction at e.g. Terschelling. The tide along the straight parts of the Dutch coast practically has no net transport capacity. Although when the vertical tide was removed from the model of the Terschelling-nourishment, the cross-shore migration of the shoreline was incorrectly predicted (Grunnet et al., 2005). So wind and tides may not dominate the flow field, they are not negligible either.

2.5 Discussion and conclusions

Nearshore bars appearance and their behaviour prevail longer as an objective in research studies than shoreface nourishments. Obviously more (detailed) information is available on the natural behaviour of the nearshore bars than their behaviour in response to shoreface nourishments. Hindcasting on the nourishment and the response of the nearshore bars turns out as feasible, but the predictability of the effect and impact of the nourishment remains difficult.

The nearshore berm created by the implementation of shoreface nourishment induces a lee and feeder effect that maintains for varying time periods (i.e. lifetime of the nourishment). The supplemented sediment is redistributed over the nearshore profile by net onshore sediment transport, but eventually the nourishment decays (Section 2.3) meaning sediment ‘disappears’ into offshore or alongshore direction. The flank effects of nourishments usually incorporate erosion suggesting the nourished sediment does not disappear to alongshore-
adjacent nearshore zones. The nourished sediment apparently is lost to the offshore zone. However, a characteristic of the natural bar cycle is that no sediment is lost to the offshore zone and the bar cycle just comprises cross-shore redistribution of sediment. This suggests the nearshore sediment volume to be a characteristic of the bar cycle, but little is known about the existence of this relation.

The natural bar volume depend the depth of the bar zone and may also be influenced by the steepness of the nearshore profile (Section 2.2.1). Presumably it is impossible to change the natural bar zone depth meaning that the implemented extra bar always disappears because the nearshore zone tends to this equilibrium between the amount of bars and the bar zone depth. Whereas the slope of the nearshore zone is changed simultaneously with the implementation of the nourishment, the nearshore slope seems better adjustable to maintain this extra bar. Unfortunately, a clear direct relation between the nearshore slope and bars volume is not (yet) found (e.g., Short and Aagaard, 1993; Wijnberg, 1995).

Although the presence of an extra outer bar decreases the amount of energy affecting the beach and thus possibly prevents ongoing beach erosion, the ideal effect of the nourishment is shoreline progression. However, the response of the beach and the accompanying beach volume are ambiguous (Section 2.3.2). The difficulty in separating natural beach behaviour from the beach response to nourishment plays a significant part in this. Pre-nourishment trends are based on decades of annual JARKUS-data, whereas post-nourishment trends are established on (bi-annual) data collected over only several years. Besides, the uncertainties exist about the nourishment having a slow or an instantaneous effect on the beach (Van Duin et al., 2004 or Grunnet and Hoekstra, 2003, respectively).

Whereas the lee effect of the nourishment explains the movement of nourished sediment to the inner nearshore zone, it also provides an explanation for the halted autonomous net offshore migration. Firstly high waves break on the seaward side of the nourishment and the reduced wave energy cannot engender strong undertow, which are generally forcing bars to migrate offshore during storm conditions (Section 2.2.2). Less moments of daily offshore migration prevail resulting in a more stable position of the nearshore bars on the longer timescale. Secondly, the reduction in wave energy leads to small waves that shoal on the natural bars. Ruessink et al. (2007b) demonstrated the onshore migration of bars to prevail during energetic, weakly to non-breaking conditions and due to a feedback between nearbed wave skewness, bedload transport and the bar itself. By these two ways the lee effect leads to the general response of the natural bars to the shoreface nourishment to temporarily stop or inverse the net cross-shore migration.

This literature study created an overview of the available information on natural behaviour of nearshore bars and the impact of shoreface nourishment. The daily behaviour of nearshore bars consists of onshore migration during calm wave conditions and offshore migration during energetic wave conditions. The integrated effect of the daily behaviour lead to long-term behaviour of bar cyclicity, but nearshore systems also contain additional boundary conditions which influence bar cycle characteristics as bar volume and cycle return period. The additional boundary conditions include the morphologic threshold function of the outer bar decay, which generally is postponed by implementation of a shoreface nourishment. The shoreface nourishment creates a feeder and lee effect, and increases the contribution of wave-skewness processes, whereas it decreases the wave-
induced return flow (i.e. undertow). These two cross-shore processes lead to a stable position or onshore migration of the natural nearshore bars for a period of several years. Alongshore processes as the wave-induced current, may entrap extra sediment when the alongshore flow field is being blocked by the nourishment. However, variable alongshore behaviour and nourishments impact are expectable, because the strong oblique dominant wind directions stimulates the alongshore sediment transport. The impact of the shoreface nourishment will also depend on its design. Suggested is that long length scale nourishments would be more persistent than shorter length scale nourishment. Still the design aspect needs more attention within research.
3 Field Data Analysis

3.1 Introduction

3.1.1 Project area

At the end of the nineties Egmond aan Zee was identified as one of the main erosional hotspots of the Dutch coast. As a result, shore- and beach nourishments were designed to improve the coastline stability. Two major nourishment projects were carried out. In 1999 a combined beach and shoreface nourishment was implemented with a total volume of 1.4 Mm$^3$ (shoreface 0.9 Mm$^3$; between RSP 39.124-36,875 and beach 0.5 Mm$^3$, between RSP 38,750-37,250 and RSP 38,000-38,800). From June to November 2004 a shoreface nourishment of 1.8 Mm3 was constructed between RSP 36.2-40.2 and in 2005 (exact date unknown) a beach nourishment of 0.5 Mm$^3$ was applied between RSP 37.0-39.5. Directly North of the Egmond nourishment, at Bergen aan Zee, a shoreface and beach nourishment were placed in 2005. Especially the shoreface nourishment (1.5 Mm$^3$, between RSP 31.5-35.0) is expected affect the behaviour of the coast near Egmond. The beach nourishment (0.3 Mm3, RSP 32.5-33.5) is much smaller and located in the centre of the shoreface nourishment. Figure 3.1 gives an overview of the location of the 1999 and 2004 shoreface nourishments at Egmond, respective to the alongshore RSP beach poles (JARKUS transects).

This chapter focuses on the morphological behaviour of the 2004 shoreface nourishment. The analysis is performed with the UCIT coastal analysis toolbox. Different aspects of the behaviour are considered. First the profile development is examined for a set of transects. Then depth maps and sedimentation/erosion figures are studied, followed by an analysis of the volume and beach width development. Finally the area north (‘downstream’) of the nourishment is considered.

3.1.2 Available data

Apart from the standard JARKUS and Vaklodingen measurements a few extra monitoring measurements were performed after the placement of the nourishment. Table 3.1 gives and overview of the data used in this analysis.

Table 3.1 Available data

<table>
<thead>
<tr>
<th>Number</th>
<th>Date of measurement</th>
<th>Data type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8 July 2004</td>
<td>JARKUS measurement</td>
</tr>
<tr>
<td>2</td>
<td>4 November 2004</td>
<td>Final survey (Only covers nourishment area)</td>
</tr>
<tr>
<td>3</td>
<td>30 November 2004</td>
<td>Extra monitoring measurement</td>
</tr>
<tr>
<td>4</td>
<td>24 April 2005</td>
<td>Vaklodingen measurement</td>
</tr>
<tr>
<td>5</td>
<td>28 July 2005</td>
<td>JARKUS measurement</td>
</tr>
<tr>
<td>6</td>
<td>8 December 2005</td>
<td>Extra monitoring measurement</td>
</tr>
<tr>
<td>7</td>
<td>7 May 2006</td>
<td>JARKUS measurement</td>
</tr>
</tbody>
</table>
3.2 Data analysis

3.2.1 Expected effects, based on literature

The hydrodynamic and morphodynamic effects of submerged structures have been studied in previous studies. The following general conclusions are stated in van Duin et al. (2004):

- Dissipation of wave energy on top of the submerged structure
- Reduction of wave-driven longshore currents in the lee of the structure
- Generation of set-up currents at end sections
- Generation of low-frequency waves in the lee of the nourishment
- Trapping of sand in the lee, updrift of the nourishment by blocking of longshore sediment transport and downdrift erosion
- Diffusion of the nourished sand

The effects can also be subdivided into longshore and cross-shore effects:

- A decrease of longshore transport
• Updrift sedimentation
• Downdrift erosion

• Increase in onshore sediment transport
• Reduction in offshore sediment transport

### 3.2.2 Morphological development

First, the behaviour of the nourishment is analysed by studying the cross-shore development in three transects in the nourishment area. Then the behaviour is analysed by studying the nourishment from a top view.

**Profile development**

Each year the Dutch coast is sounded at several cross-sections along the coast. The transects are identified by their distance from a certain reference point in Northern Holland. Figure 3.2 shows the transects at the nourishment location. Transect 3700, 3800 and 3900 lie within the nourishment area and are therefore chosen for the analysis.

**Profile 3700**

Figure 3.3 gives the profile development of the most northern transect (number 3700). The profile shows typical features often observed at Egmond aan Zee: two breaker bars in the surf zone with a swash bar near the coastline. The blue line represents the profile before the 2004 nourishment (summer 2004), the green line the profile a month after nourishing (winter 2004) and the red line the profile at the final measurement, after 1.5 years. All heights are relative to NAP.

![Figure 3.2 Location of transects.](image-url)
Figure 3.3  Cross-shore development of transect 3700.

The nourishment was placed against the outer breaker bar in the surf zone, at a depth of approximately NAP -5 m to -7 m. After four months (the black line) the nourishment transforms into a separate bar, seaward of the original outer bar. In the meantime, the original outer bar moves shoreward slightly and becomes more pronounced. In between the two bars a trough develops. At the shoreline slight accretion is observed.

During the summer of 2005 the location of the bars hardly change (cyan line). This indicates a seasonal effect: during summer, storms occur less frequently and therefore induce little morphological change. Towards the end of summer 2005, the original outer bar moves further landward. In the summer of 2006 the nourishment bar has flattened slightly, while the former outer bar moves even further landward. Two years after the nourishment, most of the nourished sand seems to still be in place.
Figure 3.4 Cross-shore development of transect 3800

Figure 3.4 shows profile number 3800, located in the centre of the nourishment. Here, the nourishment was placed on both sides of the outer bar. Similar developments are observed here as in profile 3700: forming of a separate bar, followed by shoreward movement of the original outer bar and eventually slightly flattening of the ‘new’ nourishment bar. Accretion is observed near the shoreline, even more than in the previous profile 3700. A likely first reason for this phenomenon is blocking of longshore transport, or the so-called ‘shadow effect’. Profile 3800 lies at the centreline of the nourishment. The decrease of wave energy behind the nourishment results in a lower longshore transport capacity. This, on return, causes sand to accumulate behind the nourishment. A second reason could be that sand from the nourishment is transported onshore by wave-asymmetry. It is however also influenced by the beach nourishment of 2005. The individual contributions of the three sources are hard to evaluate.
Figure 3.5  Cross-shore development of transect 3900.

The third profile had a double outer bar in 2004 (see Figure 3.5). The nourishment was constructed on top of these bars. After the winter of 2004 the nourishment divides back into two bars that move shoreward while the nourishment bar flattens slightly. Accretion takes place at the shoreline, while the system seems to return to the single outer bar equilibrium. All the profiles show a significant erosion in the upper part of the profile. There is a considerable longshore variability in this zone which is often linked to the bar morphology.

**Three dimensional behaviour**

The next step in this analysis is to examine the three dimensional behaviour. The results confirm the developments observed earlier in the profile analysis. Four stages are clearly distinguished: (1) Before nourishment, (2) One month after nourishment, (3) Nourishment bar formation, (4) Flattening of seaward bar and shoreward movement of outer bar.
(1) Seabed level before nourishment

Figure 3.6 Bed level before nourishment

Figure 3.6 shows the seabed level before the nourishment in summer 2004. The outer bar is indicated by the dotted line and the transects by red lines. The inner and swash bar are located (less clearly visible) in the orange and red area. The second outer bar in transect 3900 could possibly be the remainder of the 1999 nourishment.

1. The x-axis of this figure is stretched out for a better vision of the bathymetry features
Figure 3.7   Bed level after nourishment.

The nourishment is clearly visible in the depth zone of NAP -5m to -7m (Figure 3.7). The outer bar is more pronounced than in summer 2004, forming an clearly visible bar, now extending from north to south throughout the domain. The outer bar has clearly been fed by the nourishment, since the nourishment was finished one month earlier.
Figure 3.8  Bar separation.

Figure 3.8 shows the next phase: nourishment trough bar formation. The nourishment has (after around six months) effectively been absorbed by the system and has taken over the role of outer bar. A trough is clearly developing in between the two bars. The former outer bar furthermore seems to be developing into a rounder boomerang-like shape behind the nourishment area. Sediment accumulates near the coastline of transect number 3800. The beach area indicated in orange is clearly more pronounced, indication seaward extension of the beach. These are the morphologic effects of the nourishment, combined with a beach nourishment. Their effects are therefore hard to distinguish.
(4) Flattening and shoreward movement

Figure 3.9  Flattening and shoreward movement.

Finally, in the last phase the original outer bar migrated further shoreward (caused by wave asymmetry) while the new outer bar flattens slightly, reducing its function as a reef. The nourishment, although smoother and less distinct, is still observed in the nearshore zone. The shore line and upper shoreface area seem to contain more sand than halfway 2004.

Erosion and sedimentation

In the following step of the analysis the previously considered depth maps are subtracted from each other, to have a better view on the differences between the subsequent periods.
Figure 3.10 Placement of nourishment

Figure 3.10 shows a difference map of the period from 08 07 2004 to 30 11 2004. It clearly shows the nourishment placement as an orange bar with a height of around 2 m. The more pronounced outer bar is also visible as a stretched out orange patch. Other zones of sedimentation and erosion are also observed, but these are smaller and more irregular. Seaward of the nourishment little change is observed.
(3) – (2) : Bar separation and nearshore accretion

Figure 3.11  Bar separation and nearshore accretion.

Figure 3.11 shows the difference map of the 30th of November 2004 to the 24th of April 2005, the period of bar separation. The large blue zone indicates the area where the sand disappears (the through forms – see Figure 3.8). At both sides of the trough accretion is observed, with relatively more at the shoreward side. Much sedimentation is observed nearshore and at the beach, at mainly the 3800 and 3900 transects. The nearshore zone behind the nourishment is fed by the shoreward bar movement, the reef effects (blocking longshore transport) and the 2005 beach nourishment.
(4) – (3): Flattening and shoreward movement

Figure 3.12  Flattening and shoreward movement

Figure 3.12 shows the difference map of the period 08 12 2005 to 07 05 2006. The flattening of the seaward bar causes a patch of erosion, indicated to the left in the figure. Towards the coast, elongated patches of erosion and sedimentation are observed, indicating that sediment fills the trough (figure 3.11) while the remaining bar shifts forward. The erosion just North of the Egmond nourishment can primarily be attributed to the Bergen aan Zee shoreface nourishment.

3.2.3 Volume development and sand balance

After having analyzed the morphodynamic behaviour of the nourishment, the next topic to consider is the associated volume change. First the volume development of the nourishment itself is discussed. Then, volume developments of several transects along the coast are analysed, followed by an analysis of several cross-shore subsections. Finally the sediment budget of the area is discussed.

Nourishment volume

Figure 3.13 shows the location of the nourishment with a tightly fitted polygon. The figures to the right show the volume development within this polygon. Towards the end 2004 the nourishment placement leads to a volume increase of around 1,16 Mm³. This means only 63% of the nourished volume is found in the polygon. This can be caused by two factors: (1) some of the sand was dumped outside of the polygon, and (2) the nourishment is already being absorbed in the morphological system during construction causing sediment to be transported outside the polygon. After the placement erosion continues and slowly
decreasing with time. Figure 3.14 indicates that about 42% of the volume is left after one year. In the following six months erosion is gradually decreasing.
Transects along the coast

Figure 3.15  Alongshore transects

Figure 3.16  Volume development of several transects alongshore (0-1400m)

Figure 3.16 shows the volume development of several transects in the nourishment area. The first observation is that erosion dominates at two transects, while sedimentation is observed at the other four.

The blue and purple line of the northern transects show erosion directly after the nourishment is placed, with maximum erosion halfway 2005. This erosion is probably caused by lee side effects of the nourishment. As the prevailing longshore sediment transport is oriented from South to North, partly blocking of sediment behind the nourishment interrupts the supply of sediment to the North, causing erosion North of the nourishment. Towards winter 2005 the volume increases again. This peak is however not (primarily) related to this nourishment though; another nourishment was placed at Bergen aan Zee halfway 2005 which extended to Transect 3600. Transect 3700 to 4000 initially show accretion for the first period. This increase is caused by the nourishment volume itself. At transect 4000 the sedimentation continues. This indicates that for the first six months after construction the longshore sediment transport is effectively reduced behind the nourishment (lee-side effects), leading to accumulation of sediment at the south, however possibly also influenced by the beach nourishment. This seems to end one year after construction when erosion takes over at transect 4000. The more northern located transects still show accretion after 1,5 years. The sediment budget that follows later will further elaborate on the volume development involved.
Subsections in cross-shore direction

The following figures zoom in on the volume development of a few characteristic transects in cross-shore direction. Transects 3600, 3700, 3800, 3900 and 4000 are subdivided into strips of 200m.

Profile 3600

Figure 3.17 shows the volume development in transect 3600, that lies directly north (or downstream) of the nourishment. This is one of the transects characterised by erosion. Based on Figure 3.17, the following conclusions can be drawn:

- The observed erosion mainly occurs nearshore, near the beach (0-200m). After a half a year the erosion decreases.
- The 200-400 zone shows a fluctuating pattern, probably due to sand bar dynamics.
- The 400-600 zone benefits from the nourishment temporarily (see more pronounced bar, figure 3.7).
- Much sedimentation occurs in the 600-800m range. The nourishment at Bergen however also influences these results.
- The developments further offshore are significantly less.
Figure 3.17  Egmond (Transect 3600), profile development (top), temporal volume development (bottom).
Profile 3700

Figure 3.18 shows the volume development in transect 3700 in which the shoreface nourishment can be distinguished clearly. The volume development of the nourished section (600-800) is comparable to that of transect 3800. Apart from sections 200-400 and 400-600, the temporal development has similar trends. The difference in the 200-400 and 400-600 sections is due to the fact that the outer bar only shows a limited shoreward migration induced by the presence of the shoreface nourishment whereas for transect 3800 it migrates from section 400-600 to 200-400.
Figure 3.18  Egmond (Transect 3700), profile development (top), temporal volume development (bottom).
Profile 3800

Figure 3.19 shows the volume development at the centreline of the nourishment, exactly in front of Egmond aan zee. Here, the following conclusions are drawn:

- Accretion dominates at the nearshore zone (0-400m) for a considerably long time (until 2006) after the nourishment placement. This is caused by the combined effect of the beach nourishment, lee effects and feeder effects.
- Erosion is observed in the 400-600 zone. This is where the trough develops, when the nourishment is absorbed by the natural bank system.
- The nourishment is placed in the 600-800m zone, where it erodes initially, but stabilises after about one year.
- Slight erosion takes place further offshore.
Figure 3.19  Egmond (Transect 3800), profile development (top), temporal volume development (bottom).
Profile 3900

Also in transect 3900 (Figure 3.20) the shoreface nourishment induces a shoreward migration of the outer bar. The trends for the nourished region are comparable for all transects. However the shoreward migration of the outer bar from 2005 to 2006 is not observed in the other transects. This explains the increase of volume in section 200-400 in this period.
Figure 3.20  Egmond (Transect 3900), profile development (top), temporal volume development (bottom).
Profile 4000

Transect 4000 lies in the southern part of the nourishment. This transect was characterized by much sedimentation within the first half year. Figure 3.21 shows its volume development.

- Directly after placement of the nourishment sedimentation dominates in the whole profile (except 400-600). This is a clear sign of blocking of longshore sediment transport.
- This accretive trend changes into an erosional trend halfway 2005, when the longshore transport increases again behind the nourishment.
- After a year, mainly most of the zones still show a positive sediment balance.
Figure 3.21  Egmond (Transect 4000), profile development (top), temporal volume development (bottom).
**Sediment budget**

The analysis until now described the morphodynamic development and volume development of several transects. The following analysis aims to evaluate where the sediment moves to, based on a sediment budget.

![Figure 3.22  Analysis grid.](Image)

![Figure 3.23  Aggregated sections.](Image)

The approach for the sediment budget is to define a grid at the nourishment area with several sections. The grid and sections are given in Figure 3.22 and Figure 3.23. The longshore size of the aggregated sections is 250 m and correspond with the transect locations. The cross-shore size is 200 m and matches the sections as they are used to analyse the transects.
Table 3.2  Section description

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 1</td>
<td>Southern section far</td>
</tr>
<tr>
<td>Section 2</td>
<td>Southern section close</td>
</tr>
<tr>
<td>Section 3</td>
<td>Nourishment section</td>
</tr>
<tr>
<td>Section 4</td>
<td>Shoreface and beach section in front of nourishment</td>
</tr>
<tr>
<td>Section 5</td>
<td>Northern section close</td>
</tr>
<tr>
<td>Section 6</td>
<td>Northerm section far</td>
</tr>
<tr>
<td>Section 7</td>
<td>Dune section (&gt;N.A.P. +3 m)</td>
</tr>
</tbody>
</table>

Figure 3.24 shows the volume development of the different sections, as well as the total volume development.

1: South far

2: South close

3: Nourishment

4: Shoreface/beach

5: North close

6: North far

7: Dunes  

Figure 3.24  Volume development of sections.

The nourishment is clearly visible in section three, where it erodes initially and stabilizes after a year, as observed in Figure 3.24. Section 4, the upper shoreface gains sediment throughout all 1.5 years. An amount of 0.5 Mm$^3$ accumulates in the area towards the end of 2005 (after subtraction of the beach nourishment: 0.5 Mm$^3$). During 2006 sedimentation continues in the nearshore zone (section 4). The dunes (section 7) gain sediment too, starting from half a year after the placement. Thus it seems that part of the sand is transported to the
beach and upper shoreface, where it may later be transported into the dunes. The sections located to the north and south show smaller developments. For these sections, a better insight is obtained when considering the average bed level change (see Figure 3.25). The black line of total volume development shows that (in contrast to the nourishment polygon) all of the nourished volume (1.8 Mm$^3$) is found back in the total section area. The balance reaches 2.4 Mm$^3$ towards May 2006, which means that all of the beach nourishment (0.5 Mm$^3$) is also accounted for. The dune volume has increased with an amount that equals 25% of the nourishment volume (2.3 Mm$^3$). The fact that more sand is available in nearshore zone has most likely increased the sand drift from the beach to the dunes.

In Figure 3.25 the temporal development of the average bed level changes are shown. The developments are similar to those in Figure 3.24, but there is a marked difference in the changes. Especially the northern sections (5 and 6) show a large adjustment which is due to the aforementioned BaZ nourishment.

1: South far

2: South close

3: Nourishment

4: Shoreface/ beach

5: North close

6: North far

7: Dunes

Figure 3.25 Erosion/sedimentation at sections

The figure shows that the nourishment leads to an elevation of 0.5 m in the nourishment area (section 3) and the shoreface area (section 4). The northern sections (sections 5 and 6) show about 20 cm of erosion after the nourishment placement, followed by sedimentation (due to the Bergen aan Zee nourishments constructed in 2005). It is further interesting to mention that the dunes show a remaining elevation of 30 cm halfway 2006. The level of the upper shoreface and beach (section 4) still show an increase of on average 58 cm.
3.2.4 Beach width development

The following plot shows the beach width development in front of Egmond aan Zee, relative to RSP.

![Beach width development graph](image)

Figure 3.26 Temporal development of beach width at Transect 3800. Dashed lines indicate nourishment construction. Line 1: Beach Nourishment May/June 1999, 0.300 Mm$^3$; Line 2: Shoreface nourishment September 1999, 0.900 Mm$^3$; Line 3: Beach nourishment September 2000, 0.207 Mm$^3$; Line 4: Shoreface nourishment, June/November 2004, 1.8 Mm$^3$; Line 5: Beach nourishment 2005 (unknown exact date), 0.5 Mm$^3$.

Figure 3.26 shows that the beach width has been steadily increasing in the past ten years (e.g. increasing distance between the dune foot and MLW position in Figure 3.26), probably as a result of the nourishments along the coast since 1990. Both the 1999/2000 and 2004/2005 nourishments induce a seaward migration of the beach, especially around the NAP level and the HWL. The beach width sharply increases by about 60-70 m halfway 2005 due to the placement of the beach nourishment. The dune foot shows a similar development, only slightly later (towards the end of 2006) and less pronounced. Towards 2006 sediment is redistributed over the nearshore zone; the MHW and MLW move back landward, while the NAP level moves seaward. On the short term the benefit of the nourishment is relatively large. Based on the discussed data it can not be concluded that the nourishments induce a systematic seaward trend. However, the long term influence of nourishments can only be determined if longer time series (prior to nourishments) are considered in combination with larger study areas and different nourishment sites.
3.2.5 Surrounding area (Bergen aan Zee)

The longshore sediment transport is generally northward directed along the Holland coast (Van Rijn, 1997). Therefore, this paragraph shortly deals with the area North of Egmond aan Zee, to analyse the downstream effect of the Egmond nourishment. Figure 3.25 shows bathymetric maps of the Bergen aan Zee area.

![Depth maps of area north of Egmond (Bergen aan Zee)](image)

The main observations are:

- One month after the nourishment at Egmond, the outer bar near Bergen aan Zee is more pronounced, probably caused by the storms occurring in the autumn of 2004.
- In 2005 (exact date not known) the nourishment at Bergen aan Zee is applied (1.5 Mm$^3$ against the outer bar and 0.3 Mm$^3$ on the beach). This also implies that the effects of the two nourishments are hard to distinguish.
- Halfway 2006 (after about a year) the Bergen aan Zee nourishment has largely eroded whereas the upper part of the profile experiences significant sedimentation.

3.3 Conclusions

Based on the previous analyses the following conclusions are drawn:
Morphological behaviour

- After the placement the nourishment is quickly absorbed by the bar system; a trough forms in the middle of the nourishment during winter 2004/2005, redistributing the nourished sand: the original outer bar grows slightly and a new ‘outer’ bar is formed further offshore.
- Relatively little changes during the summer of 2005 (seasonal effect).
- During autumn 2005 the original outer bar migrates shoreward and sediment accumulates in the nearshore zone. The bars temporarily take on boomerang like shapes.
- During the winter and spring of 2005/2006 the ‘new outer bar’ flattens slightly, while the original outer bar moves further shoreward. The nourishment, although smoother and less distinct, is still observed in the nearshore zone.
- Blocking of longshore transport is indicated by erosion north (downstream) of the nourishment, mainly near the beach in the first year.

Volume development

- 63% of the nourishment volume is found in a polygon around the nourishment one month after the placement. All of it is found in the larger area. After around 1.5 years all of the sediment (including the beach nourishment volume) still seems to remain in the area.
- The nearshore zone benefits significantly from the shoreface nourishment. After subtraction of the beach nourishment volume, 0.5 Mm³ of sand (28% of the shoreface nourishment volume) accumulates behind the nourishment after approximately one year, caused by feeder and lee effects. This causes an average bed level rise of 0.5 m.
- The dune volume increases with around 25% of the beach and shoreface nourishment volume after 1.5 years, leading an average increase in dune elevation of 30 cm.

Beach width

- The beach width and dune foot position behind the nourishment increase sharply after placement of the nourishments. The contribution of the shoreface nourishment is however hard to evaluate, because of the simultaneously applied beach nourishment.
- On the longer term, the nourishment policy seems to contribute to an increasing trend of beach width.
4 Laboratory Experiment

4.1 Introduction

Within the EU-sands project, experiments to investigate scale effects were carried out in WL Delft Hydraulics' the Scheldt Flume. These experiments were carried out with plane sandy profiles of three different slopes (1:10, 1:15 and 1:20) which were subjected to an erosive and an accretive wave condition (see Table 4.1). In the VOP project this experimental set-up was used to investigate two shoreface nourishment designs using the same wave conditions.

<table>
<thead>
<tr>
<th>Scheldt flume</th>
<th>Hs</th>
<th>Tp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jonswap1</td>
<td>0.10 m</td>
<td>3.0 s</td>
</tr>
<tr>
<td>Jonswap2</td>
<td>0.17 m</td>
<td>2.3 s</td>
</tr>
</tbody>
</table>

Table 4.1 Wave conditions VOP

The initial profile was obtained by using the final profile of an experiment carried out by Bosboom and Koopmans (2000) which was subjected to an additional eight hours of waves according to the high wave condition (Jonswap2). The obtained profile was used as the basis for all the designs. Reference tests for both wave conditions are done and subsequently two nourishment designs are implemented. Two wave spectra are run, first the accretive condition (Jonswap1) and secondly after restoring the profile the erosive wave condition (Jonswap2). The first test T01 was used to obtain a reference profile as close to equilibrium as possible. Overview of VOP tests are shown in Table 4.2. The designs are shown in Figure 4.1.

<table>
<thead>
<tr>
<th>Test nr</th>
<th>Hs</th>
<th>Tp</th>
<th>Profile</th>
<th>Profile measurement (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T01</td>
<td>0.17 m</td>
<td>2.3</td>
<td>initial</td>
<td>0 / 8</td>
</tr>
<tr>
<td>T02</td>
<td>0.10 m</td>
<td>3.0 s</td>
<td>reference</td>
<td>0 / 1 / 3 / 8 / 16 / 24</td>
</tr>
<tr>
<td>T03</td>
<td>0.17 m</td>
<td>2.3 s</td>
<td>reference</td>
<td>0 / 1 / 3 / 8 / 16</td>
</tr>
<tr>
<td>T04</td>
<td>0.10 m</td>
<td>3.0 s</td>
<td>design1</td>
<td>0 / 1 / 3 / 8 / 16 / 24</td>
</tr>
<tr>
<td>T05</td>
<td>0.17 m</td>
<td>2.3 s</td>
<td>design1</td>
<td>0 / 1 / 3 / 8 / 16</td>
</tr>
<tr>
<td>T06</td>
<td>0.10 m</td>
<td>3.0 s</td>
<td>design2</td>
<td>0 / 1 / 3 / 8 / 16 / 24</td>
</tr>
<tr>
<td>T07</td>
<td>0.17 m</td>
<td>2.3 s</td>
<td>design2</td>
<td>0 / 1 / 3 / 8 / 16</td>
</tr>
</tbody>
</table>

Table 4.2 Overview of VOP tests

The designs are shown in Figure 4.1. The blue line indicates the reference profile (end of test T01) which was used as the basis for the shoreface nourishment designs. Both nourishment designs have the same volume which, on proto type scale, is approximately 400 m³/m.
4.2 Measurements and instruments

SANDS tests as well as VOP tests focus on measuring bed profiles, water level variations, flow velocities, sediment concentrations and sediment transport. Following instruments are used:

Transverse Suction System (TSS)
Tubes with different elevations are connected to several pumps, which generate a velocity of the water in the nozzles of the tubes. The pumps extract water and sediment. The extracted volume of water is read from the volume scale on the buckets in which the water and sediment are collected. The suspended sediment samples are flushed in a volume meter tube and this reading can be converted to the concentration of sediment in the water.

Electric Magnetic Velocity (EMV)
This instrument is based on the principle that a conducting fluid will generate a voltage proportional to the flow velocity as it passes through the magnetic field created by the sensor.

Wave Height Meters (WHM)
Several wave gauges along the flume measure the water elevation. The free surface elevations, with respect to still water level, are recorded with resistance type twin-wire wave height meters. The output signal range from -10 to 10 V, corresponds to a water elevation measuring range of -0.25 m to 0.25 m.

Acoustic Sediment Transport Measurement (ASTM)
ASTM is an acoustic instrument for measuring the flow and the sand concentration. The Acoustic Sand Transport Monitor is based on the transmission and scattering of ultrasound waves by the suspended sand particles in the measuring volume. Using the amplitude and frequency shift of the scattered signal, the concentration and velocity and hence the transport of the sand particles can be determined simultaneously and continuously.
Acoustic Doppler Velocimetry (ADV)
ADV is based on the Doppler principle to measure three components (u, v and w) at a single point.

Figure 4.2 From left to right: TSS, EMS, reference rod, WHM, ASTM, ADV

Bed Profiler
Three probes with a mutual distance of 25 cm are constructed on a carriage that moves along the flume. The probes move up, forward and down again. The distance between two measured points is variable. The results of the three parallel measurements give the average bed profile, which is used in the analyses.
4.3 Morphological development

In Figure 4.4 to Figure 4.15 an overview is given of the temporal development of the bottom profile for the tests listed in Table 4.2. In addition, the sediment transports and the temporal sand volume development for various parts of the profile are shown.

The effect of the different wave conditions can be seen clearly for the lower part of the profile (in the vicinity of the bar at x~25 m) for the reference tests (tests T02 and T03). The accretive wave condition (Test T02) results in sedimentation landward of the bar, whereas for the erosive wave condition (Test T03) deposition occurs on the seaward slope of the bar. From the transport plots it becomes clear that this is not due to a difference in onshore and offshore transports, as for both wave conditions the transports tend to be offshore for almost the entire profile. Only at the swash zone small onshore transports are present. The deposition seems to be primarily be determined by extend the waves can transport the sand offshore. Erosion at the upper part of the profile is very similar for both cases. This is partly caused by the fact that the reference profile was obtained using the high wave condition. This implies that the profile is closer to equilibrium for the high wave condition, resulting in relative lower transports.

In Figure 4.16 to Figure 4.19 the profiles and volumes are combined. Both shoreface nourishment designs are not able to stop the erosion at the upper part of the profile. However the erosion rate is reduced significantly in this area. For the low shoreface nourishment the erosion rate is reduced by about 20%. The high shoreface nourishment results in a more substantial reduction of the erosion. For the low wave condition a reduction of 40% is found, whereas for the high wave condition the reduction is about 70%.
Figure 4.4  Measured profiles (Top) and sediment transports derived from profile development (Bottom) for experiment T02: Reference profile using accretive wave condition.

Figure 4.5  Temporal development of sediment volumes for experiment T02. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach).
Figure 4.6  Measured profiles (Top) and sediment transports derived from profile development (Bottom) for experiment T03: Reference profile using erosive wave condition.

Figure 4.7  Temporal development of sediment volumes for experiment T03. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach).
Figure 4.8 Measured profiles (Top) and sediment transports derived from profile development (Bottom) for experiment T04: Deep shoreface nourishment profile using accretive wave condition.

Figure 4.9 Temporal development of sediment volumes for experiment T04. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach).
Figure 4.10  Measured profiles (Top) and sediment transports derived from profile development (Bottom) for experiment T05: Deep shoreface nourishment profile using erosive wave condition.

Figure 4.11  Temporal development of sediment volumes for experiment T05. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach).
Figure 4.12  Measured profiles (Top) and sediment transports derived from profile development (Bottom) for experiment T06: Shallow shoreface nourishment profile using accretive wave condition.

Figure 4.13  Temporal development of sediment volumes for experiment T06. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach).
Figure 4.14 Measured profiles (Top) and sediment transports derived from profile development (Bottom) for experiment T07: Shallow shoreface nourishment profile using erosive wave condition.

Figure 4.15 Temporal development of sediment volumes for experiment T07. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach).
Figure 4.16  Comparison of final profiles after 24 hours for the low wave condition case.

Figure 4.17  Temporal development of sediment volumes for tests using the accretive wave condition. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach).
Figure 4.18 Comparison of final profiles after 16 hours for the high wave condition case.

Figure 4.19 Temporal development of sediment volumes for tests using the erosive wave condition. Top-Left: entire profile; Top-Right: Lower part of profile (lower shoreface). Bottom-Left: middle part of profile (surf zone); Bottom-Right: Upper part of profile (saturated surf zone, swash zone and beach).

4.4 Sediment transports

This section focuses on the sediment transports as they are derived from the measured profile development and the velocity and concentrations measurements. First the transports derived from the process measurements are derived, next the sediment transports are obtained from the measured bed level change are discussed. Furthermore, both methods are compared to provide insight into the accuracy of the measurements. This section is finalised with a comparison of wave height and velocity moments in a first attempt to identify the physical processes that are affected by the nourishment designs.
4.4.1 Sediment transport derived from verticals

Sediment transport is derived from velocity and concentration profiles applying the integral method according to Van Rijn (1991). This method gives the total suspended load transport between the bed and the water surface by fitting a distribution to the measured velocity and concentration profiles.

Velocity

The velocities between bed and first measuring point is described by:

\[ v = v_1 (z / z_1)^{0.25} \quad \text{for} \quad 0 < z < z_1 \]  

(4.1)

in which:

- \( v_1 \) = fluid velocity in first measuring point above the bed
- \( z_1 \) = height above bed of first measuring point

The velocities between the last measuring point (\( z_L \)) and water surface can be taken equal to the velocity in the measuring point.

\[ v = v_L \quad \text{for} \quad z_L < z < h \]  

(4.2)

![Figure 4.20 Schematisation for velocity profile interpolation.](image)

Concentration

The sediment concentrations between last measuring point and water surface are given by a linear function according to:

\[ c = [(h - z) / (h - z_L)]c_L \quad \text{for} \quad z_L < z < h \]  

(4.3)

in which:

- \( c_L \) = concentration in last measuring point
- \( z_L \) = height above bed of last measuring point
Three different extrapolation methods are used to represent the concentration profile between bed and lowest measuring point.

**Method 1:**

Applying the first method the sediment concentrations between bed and lowest measuring point are assumed to be equal to the concentration in the first measuring point:

\[
c = c_1 \quad \text{for } 0 < z < z_1
\]  

(4.4)

**Method 2:**

The second method computes the sediment concentrations according to:

\[
c = A Y^B \quad \text{for } 0 < z < z_1
\]

(4.5)

in which:

- \( Y = (h-z)/z \) (dimensionless vertical coordinate)
- \( z \) = vertical coordinate above bed
- \( h \) = water depth
- \( A, B \) = coefficients

**Method 3:**

Sediment concentrations between bed and first measuring point are represented by:

\[
c = e^{AZ+B} \quad \text{for } 0 < z < z_1
\]

(4.6)

in which:

- \( z \) = vertical coordinate above bed
- \( A, B \) = coefficients

The coefficients in method 2 and 3 are determined by a regression method applying the measured concentrations in the first three measuring points above the bed.
Figure 4.21  Schematisation for concentration profile interpolation.

Figure 4.22  Comparison of different integration methods.

**Suspended load transport**

Computation of the depth-integrated suspended sediment transport requires measurements of velocities and concentrations at equal elevations. Depth-integrated suspended sediment transport ($S_z$) is calculated as follows:

$$S_z = \sum_i^N [0.5(v_i c_i + v_{i-1} c_{i-1}) (z_i - z_{i-1})]$$  \hspace{1cm} (4.7)

in which:

- $v_i$ = fluid velocity at height $z$ above the bed (m/s)
- $c_i$ = sediment concentration at height $z$ above the bed (kg/m3)
- $N$ = total number of points
Three different methods result in three different results for the depth-integrated suspended sediment transport (see Figure 4.23). Method 1 and method 3 are quite similar. Method 2, on the other hand, deviates considerably and is, therefore, omitted in the computation of the sediment transport. The average of method 1 and method 3 is considered.

![Graph showing comparison of different integration methods](image)

**Figure 4.23** Comparison of different integration methods for all 5 positions and 6 experiments combined.

Standard deviation of the mean values of method 1 and method 2 is 0.0072 kg/sm.

### 4.4.2 Sediment transport derived from bed level change

Besides the estimation of the sediment transport from the verticals, a mean sediment transport is derived from the change in bed level between the different subtests. The mean sediment transport over the entire profile is calculated from the bed level change according to:

\[
S_{xx} = \int_{0}^{end} \frac{dz}{dt} \, dx
\]

(4.8)
Figure 4.24  Profile development and uncorrected transports derived from profile changes.

As a zero transport at the beginning and at the end of the profile is assumed. The integration using Eq. (4.8) can therefore start at both distal ends of the profile. Here the integration starts at the lower (seaward) side of the profile. In case of a perfect measurement the resulting transport is zero on the dry beach. The deviation is a measure of the accuracy of the measured profile. Furthermore, the sediment transport should remain zero (i.e. zero gradient) on the upper part of the beach which has not been affected by waves. Especially the initial estimate for each experiment consistently shows a loss of sediment (e.g. blue line in Figure 4.24). The reason for this could not determined. It is thought that the procedure in which the initial profile is measured before any waves have been active plays a role. The profile measured after 1 hour of wave action is settled somewhat causing a small deviation in the derived transports. Other reasons that have been mentioned in other studies are the occurrence of a transverse curvature of the bottom profile or the presence of ripples. However, detailed analysis of the three tracks measured by the bed profiler did not show a transverse curvature.

The initial profile of T02 contained ripples (it is the resulting profile of Test T01 after 8 hours of wave action). So the derived transports after 1 hour are a good test to see if the ripples indeed have an effect. In Figure 4.25 it can be seen that the initial volume change over the entire profile after 1 hour is much larger for T04 and T06 in comparison with T02. This implies that the non-closed sediment balance after 1 hour could largely be attributed to the presence of ripples.
Figure 4.25  Comparison of temporal erosion and sedimentation volumes for accretive wave conditions.

Erosion and sedimentation volumes indicate a small loss or gain of sediment along the entire profile. Assuming a zero transport at the beginning and at the end of the profile, this volume should be zero. This difference is evenly distributed over the profile between the start of the profile and point of no bed level change. This imposes a nearly closed sediment balance as illustrated in is nearly closed. (see Figure 4.26).

Figure 4.26  Profile development and corrected transports derived from profile changes.
Difference between two methods

Both methods are compared in Figure 4.27 and Figure 4.28 for Tests 02 and 07 respectively. The agreement between both methods is reasonable at best (Test 07 is the experiment with best agreement, TO2 is more representative for other experiments). Part of the deviation is due to the fact that the bed load is not taken into account. However, especially in the saturated surf zone the suspended sediment transport is dominant. This implies that that the uncertainty in the derived transports is relatively high which, for example, is (very) important for model validation purposes.

![Graph showing transports comparison](image)

Figure 4.27  Comparison of transports derived from profile development and process measurements for Test 02.

![Graph showing transports comparison](image)

Figure 4.28  Comparison of transports derived from profile development and process measurements for Test 07.

4.4.3 Third and fourth order velocity moments

The third and fourth statistical moments give insight into the non-Gaussianity of the wave process. Skewness is indicative for third order velocity moment and is characteristic for asymmetry in the wave profile, with systematically larger peaks and shallower troughs. A positive skewness implies a landward bed load transport. Kurtosis is indicative for fourth order velocity moment.

Skewness and kurtosis are computed applying:
\[
\text{Skewness} = \frac{1}{N} \sum_{i=1}^{N} (x - \bar{x})^3
\]
\[
\text{Kurtosis} = \frac{1}{N} \sum_{i=1}^{N} (x - \bar{x})^4
\]

(4.9)

Initial results of the comparison (Figure 4.29 and Figure 4.30) reveal that the nourishments have a significant impact on both the wave height distribution and the velocity moments. The results imply that the nourishments influence the transports in two ways, reduced wave heights will result in a reduced undertow and hence reduced offshore transports. The relative increase of the onshore transports associated with the wave asymmetry will also contribute to a reductions of net offshore transport (or increase of net onshore transports).

Figure 4.29  Comparisons of wave height (top) and velocity moments (bottom) for accretive wave conditions.
Figure 4.30  Comparisons of wave height (top) and velocity moments (bottom) for erosive wave conditions.
5 Beach Wizard – Argus

5.1 Introduction

This chapter describes a data-model assimilation method called Beach Wizard with which the nearshore subtidal bathymetry can be accurately estimated based on video-derived observations of wave roller dissipation and variation of the intertidal shoreline, and radar-derived observations of wave celerity. Using many consecutive images, these observed properties are compared with numerical model results, and through a simple optimal least-squares estimator approach the computational bathymetry is adjusted gradually for each image in order to improve the fit between model output and observations. The key advantages of the technique are that it is based on multiple sources of information (i.e., video and radar products), depends on only a few free parameters (to which the model results are insensitive), shows good skill and is therefore robust. The method can deliver coastal state information (i.e., simultaneous updates of bathymetry, waves, and currents) with high temporal and spatial resolution and can be used in conjunction with or instead of in-situ measured data.

The outline of this Chapter is as follows: In Section 2 the model equations of the Beach Wizard system are described. Section 3 describes two longer-term validations for Egmond Beach (the first one 1.5 years and the second xx years). Section 4 describes the model and data improvements that have been made this year, in the framework of the VOP project but also by other means, and include the automated pre-processing of data, improvement of estimation of intertidal bathymetries, nearshore subtidal bathymetries and persistent foam. The integral of the progress is presented in this report.

5.2 Model equations

[This work has also been submitted in journal form as Van Dongeren et al. (2007), submitted to Coastal Engineering.]

The model formulation uses an optimal least-squares estimator (Bouttier and Courtier, 1999) to update the bathymetry. It utilizes the prior state about the bathymetry (and its uncertainty) as well as new estimates of bathymetry derived from remote sensing observations (and their uncertainty). After obtaining new remote sensing data and estimating the bathymetry from this new information, the updated bathymetry is

\[ h_{\text{update}} = h_{\text{prior}} + \alpha (h_{\text{obs}} - h_{\text{prior}}) \]  \hspace{1cm} (5.1)

where \( h_{\text{obs}} \) is the estimate based only on the remote sensing data (an “image” in our case) and \( h_{\text{prior}} \) is the estimate of the bathymetry before the new information was utilized. All quantities are functions of space unless otherwise noted. The updated uncertainty is then

\[ \sigma_{\text{update}}^2 = \frac{T}{\Delta t} \sigma_{\text{obs}}^2 \]  \hspace{1cm} (5.2)

Here
\[ \alpha = \frac{\sigma_{\text{prior}}^2}{T_s \left( \sigma_{\text{obs}}^2 + \sigma_{\text{prior}}^2 \right)} \]  

(5.3)

is a weighting term (with values between 0 and 1) between the uncertainties in the prior bathymetry (\( \sigma_{\text{prior}} \)) and in the observations (\( \sigma_{\text{obs}} \)). While the formulation is clearly similar to Kalman's (1960) weighting, this equation is to be used in a time-update scheme, which means that the same observation is used for every time step in the simulation. Since these observations are not statistically independent, the value of \( \sigma_{\text{obs}}^2 \) needs to be multiplied by a factor \( T_s / \Delta t \), where \( T_s \) is the simulation duration for a given image and \( \Delta t \) the numerical time step.

As mentioned above, we do not have direct observations of the bathymetry. Instead, we have remote sensing observations of wave celerity and time-averaged image intensity, and we have prior estimates of these quantities obtained from a forward model and the prior estimate of the bathymetry. Thus, we must use an inverse model to relate the remotely sensed observations to the bathymetry. Using the chain rule

\[ h - h_{\text{obs}} = \left( \frac{df}{dh} \right)^{-1} \left( f - f_{\text{obs}} \right) \]  

(5.4)

where \( f_{\text{obs}} \) is an observed (measured) local quantity and \( f \) is a computed quantity. The time update scheme (5.1) then becomes

\[ h(t + \Delta t) = h(t) - \alpha \frac{df}{dh} \left( f - f_{\text{obs}} \right) \]  

\[ + \delta^2 \]  

(5.5)

where variables in Eqs. (5.1)-(5.3) with subscript “update” are at time level \( t + \Delta t \) and all variables with subscript “prior” are at time level \( t \), and we have used an inverse transfer function (Menke, 1989) with a noise level \( \delta \). Note that we are not inverting the co-variance matrix that describes the sensitivity of variables at one location to variables at other locations, but instead we only consider the main diagonal terms which describe co-located data inputs and model outputs. Continuous results are enforced through the forward wave modelling with Delft3D. Using the above formulation the update scheme will initially converge slowly, due to an arbitrarily large model-data mismatch until the correct bathymetry is approached.

The error in the observations \( \sigma_{\text{obs}}^2 \) will be defined as the ratio of the sum of measurement error and the difference between the modelled and observed quantity, and the gradient with respect to depth, or

\[ \sigma_{\text{obs}}^2 = \frac{e^2 + (f - f_{\text{obs}})^2}{\left( \frac{df}{dh} \right)^2 + \delta^2} \]  

(5.6)
where \( \varepsilon \) is the measurement error for a given source (in units of the quantity of that source). This equation states that the uncertainty is large when the difference between the modelled and observed quantities are large (i.e. the computational bed level must deviate considerably from ground truth) or the gradient is small (the quantity is not dependent on the local depth; hence, it gives no reliable information about the bed level).

This assimilation model (5.5) is generalized for multiple sources as

\[
h(t + \Delta t) = h(t) - \alpha \sum_{i=1}^{S} \frac{df}{dh} \left( f_i - f_{i,\text{obs}} \right) ^2 + \delta^2
\]  

(5.7)

where the index \( i \) indicates the source. For the present application we have limited the number of sources to three: wave roller energy dissipation, wave celerity, and intertidal bathymetry. These sources may be extended with any measurable quantity that can be expressed as a differentiable function of depth, such as percentage of breaking or wave height.

The uncertainty per source \( \sigma_{\text{obs},i}^2 \) is Eq. (5.6) with subscript \( i \) on all variables, and the total uncertainty in observations (in units of bed level) is the ensemble of the uncertainties of the individual sources or

\[
\sigma_{\text{obs}}^2 = \frac{1}{\sum_{i} \left( \frac{1}{\sigma_{\text{obs},i}^2} \right)}
\]

(5.8)

where the double reciprocal is applied so that the source with the smallest uncertainty is locally dominant. Eqs. (5.1) and (5.3) remain the same for multiple sources.

The assimilation scheme is applied to consecutive (in time) sources, e.g. a sequence of video or radar images from which the observed wave properties and their uncertainties are derived. Initial values of \( h_{\text{prior}} \) and \( \sigma_{\text{prior}} \) at the start of the first simulation are also required, which can be derived from a previous assimilation run, a recent bathymetric survey, or a best guess. The simulation for a source at a given time uses the updated bathymetry from a previous simulation as a starting value. The uncertainty in this bathymetry is also taken from the previous run, except that the uncertainty is increased as a function of the (calendar) time that has elapsed between images because of possible morphological changes. The uncertainty increase between the end result of one simulation and the start of another is heuristically modelled as

\[
\sigma^2(t_j) = \sigma^2(t_{j-1}) + \left( \sigma_{\text{evo}}^2 - \sigma_{\text{obs}}^2(t_{j-1}) \right) \tanh^2 \left( \frac{3}{T_e} (t_j - t_{j-1}) \right)
\]

(5.9)

where \( j \) is the index of the run (image), and \( t_j \) the julian day. The time scale \( T_e \) reflects a physical interpretation that a previously computed uncertainty is invalidated due to morphological changes over a period of days and evolves into the natural uncertainty \( \sigma_{\text{evo}} \). The time scale constant must depend on the magnitudes of sediment transport rates that are responsible for beach evolution and, hence, must vary with the wave height or currents. For
instance, near the region with sand bars, $T_r$ is on the order of days, while offshore it may approach zero if there is no expected bathymetric change over the analysis time period. However, we will attempt to use a constant value of 5 days, which is representative of the average conditions. We have chosen $\sigma_{eio}$ to be identical to the initial prior bathymetry ($\sigma_{\text{prior}}$) at 1 (m), which eliminates one parameter and corresponds to an upper limit in the beach variability at Duck (Plant et al., 1999).

The method has only one free parameter, the simulation length $T_s$, as opposed to the scheme proposed by Aarrinkhof et al. (2005a,b), which involved two free parameters per source. The present method also needs the measurement error field $e_m$, which is dependent on the measurement technique and also not a freely tuneable parameter. As and mentioned above, the model needs an initial (best guess) bathymetry and an initial uncertainty. We will vary these inputs in the Discussion section. We have in the present implementation done away with the concept of a virtual buffer layer of suspended sediment as used in Aarrinkhof et al. (2005a,b). This choice implies that the present model does not necessarily conserve mass; although this constraint could be included straightforwardly by forcing incremental updates to have zero mean value. Moreover, if there is a known change in mass due to a beach nourishment, this could be imposed on the solution.

The assimilation model is implemented in the Delft3D morphodynamic model and can be run alone or in parallel with a physics-based morphology model. For the present purpose, this is turned off to focus on the assimilation routines. Delft3D computes the spatial distribution of the roller energy dissipation and wave celerity (the properties $f$), as well as the derivatives $df/dh$ across the model bathymetry using the observed wave and tide conditions (water level, wave height, peak period and wave angle). This is done in the wave roller model (Roelvink, 1993; Reniers et al., 2004), which concurrently solves the energy equations of the organized wave motion and the roller motion using expressions for the wave and roller energy dissipation by Baldock et al. (1998) and Reniers et al. (2004), respectively. We refer to Reniers et al. (2004) for details of the model equations.

Each of the simulation runs in stationary mode, which means that the water level and offshore wave conditions are assumed constant for the duration of the simulation (about 2 hours maximum). The boundary conditions therefore consist of tidal elevation, offshore $H_{rms}$ wave height, peak period, and mean direction. In hindcast mode these quantities can be derived from nearby gauges and buoys. A stationary run is carried out for each point in time that data from a remote source is available. Each stationary computation has a fixed simulation time and all available remote data in that simulation time is combined in one simulation. So depending on data availability, for some simulation runs data from only a single source are used, while in other runs concurrent data from multiple sources are used. The time resolution of a complete Beach Wizard computation is thus not equidistant, but dependant on the availability of data. In order to properly compute the bed evolution, it is necessary to perform a large number of sequential simulation runs (on the order of 50 to 100 in our applications) for a diverse set of combinations of wave conditions and water levels so that the driving force for the bed update can be applied all along the sub- and intertidal bathymetry.
5.3 Model Application

5.3.1 Egmond, The Netherlands (1999-2001)

The first application involves the assessment of the evolution of subtidal bathymetry along a 2 km coastal stretch at Egmond (The Netherlands) over an 18 month period starting December 1999 (Aarninkhof et al., 2005b). Egmond Beach is situated on the northern part of the central Dutch coast and is characterized by two shore-parallel subtidal nearshore sandbars. The meso-tidal (ranging between 1.4 and 2 m) beach is exposed to a wave climate with a yearly mean wave height $H_m$ of 1.2 m and a mean period $T_m$ of about 5 s, showing considerable seasonal fluctuations.

During the 18 month period from December 1999 to July 2001, the bathymetry was surveyed twice per year, typically along 50 cross-shore profiles with 100 m spacing alongshore. The measured depth is estimated to have an error of less than 15 cm. Offshore wave conditions were measured with a directional wave buoy at IJmuiden, located approximately 15 km to the south. Approximately 15% of the data was missing, of which half could be replaced by values from an identical buoy approximately 75 km to the north. Offshore tidal levels are found from interpolation in water level data collected at tidal stations located 15 km north and south of Egmond.

At this location two assimilation sources are available for the modelled period: dissipation and intertidal bathymetry from video. We use the 100 wave dissipation maps (non-equidistant time resolution) as generated and used in Wijnberg et al. (2004), collected from 13/12/1999 until 20/07/2001. Intertidal bathymetry files are constructed from the intertidal bathymetries derived from video, using two sets generated by Caljouw (2000) and Nipius (2022). Due to variations in the spatial extent of the two datasets, only the overlapping area of a 1360 m coastal strip centered around the Egmond light house and enclosed by the elevation contours at 0 m NAP and +0.9 m NAP could be used. The overall Egmond dataset obtained consists of 27 intertidal beach bathymetries over the period 15/06/1999 until 22/09/2001.

A model was set up similar to Wijnberg et al. (2004). The flow model grid spans from -1400 to 1400 meters in y-direction (alongshore) and from -100 to 1200 meters in x-direction (cross-shore) in the local Argus coordinate system. The grid sizes $\Delta x$ and $\Delta y$ are 5 and 20 m respectively. The model is run for each 2hr period where remote-sensing information is available. The simulation starts with a bathymetry measured on 14 and 15 September 1999. At the offshore boundary, short wave energy and peak period (group speed) are imposed, the lateral boundaries are prescribed by the Neumann boundary condition. Wave directions are calculated by a SWAN model, which is laterally extended with respect to the flow grid, to avoid boundary disturbances on the flow grid. The model and instrument error settings were the same as in the Duck hindcast.

Figure 5.1 shows the results of the Egmond application for one cross-shore array (at $y = 10$ m in the local coordinate system and corresponding to JARKUS (e.g. Wijnberg and Terwindt, 1995). The actual bathymetry was measured only five times during the simulation period. The measured bathymetry is indicated in blue (solid line) and the computed
bathymetry in red (solid line). Initial values of both are shown with dashed lines. The computed uncertainty estimates are shown as the red error bars.

The assimilation approach yields bathymetric updates that converge toward the independently measured values (Figure 5.1). In the deeper regions (seaward of $x = 700$ m) the bathymetry is less dynamic. No useful assimilation data in this region is available, so the model does not update the bathymetry. The model predicted errors (Figure 5.1) vary in a manner similar to that seen in the Duck example. The error is smallest around the bar tops. Errors in the deeper regions (troughs and offshore) remain larger, because of the lack of sensitivity to the data in these areas. In order to decrease these errors, inclusion of a third data source (for instance wave celerity) would be needed. For the model period, unfortunately no such data were available.

The 2-D results (Figure 5.2) show that the rms error over the entire model domain is about 0.5 m. The largest differences between the measured and computed bathymetry occur seaward of the shoreline, where the depth is overpredicted. The former approach (Aarninkhof et al., 2005b, not shown) resulted in an rms error of about 1.5 m in the same model domain, which was due to much larger deviations in the deeper regions and just seaward of the shoreline. This shows that the current assimilation method has improved the performance near the shoreline by including intertidal bathymetry as an assimilation source in the model. Also, the performance near the shoreline is improved because the overall performance in the bar-trough region is improved and the accumulation of errors towards the beach has decreased. Still, the model skill is lowest in these shallow areas, a point that will be addressed in the next Section.
Figure 5.1 Results of the Egmond application at a cross-shore array ($y = 10$ m) at five points in time during the model period when the bathymetry was measured (from top to bottom: 05/04/2000, 17/05/2000, 17/09/2000, 18/04/2001 and 18/06/2001). The blue line indicates the measured bathymetry, the red line indicates the computed bathymetry. Dashed lines indicate the initial situation of both. The model predicted errors are shown in red bars.
Figure 5.2 Results of the Egmond application in the model domain on 15 June 2001. The left panel shows the measured bathymetry. The centre panel shows the computed bathymetries with the present model. The difference between the measured and computed bathymetries is shown in the right panel.

5.3.2 Egmond, The Netherlands (2004-2006)

Using the same model settings as for the first application, the model was applied to data from a two-year period just after application of a foreshore nourishment in Egmond aan Zee in 2004. The computation starts in December 2004 en runs until December 2006. The assimilation dataset used as input data for the assimilation model in this computation consists of 28 intertidal beach bathymetries and 286 wave dissipation maps over the period 05/11/2004 until 29/12/2006. (both from video, non-equidistant time resolution) The data are selected based on good visibility and sufficient wave energy to obtain a visible signal on the sea surface. A 2D filter was applied on the computed bathymetry to reduce noise.

From Figure 5.3 it can be seen that the bar, that exists at a cross-shore location of 450m from shore, moves shoreward during the months after the nourishment. In the year after that the bar remains stable at its more shoreward position (approx. x_{surf}=350m). The outer bar (foreshore nourishment) at x=750m flattens slightly in the model during the model period. This flattening cannot be seen in the measured bathymetries, which are available for 4 instants during the model period. This artificial flattening in the model may be caused by the lack of good assimilation data in this area. Improvement may be possible by including wave celerity information from video in the computation. On the dry beach, the bathymetry should be linearly interpolated for each cross-shore grid line between the most shoreward wet point and a set vertical position of the dune at the most shoreward grid point in the model domain. In the model results presented in this paragraph, this post shoreward grid
point did not have a fixed vertical position. This is why the dry beach erodes very much in the model computation, whereas the measured bathymetries do not show this. In future computations it is thus advised to use a fixed point at the most shoreward point of each cross-shore grid line.
5.4 Model improvements

5.4.1 Automatically characterizing the usability of Argus images

The Argus archive contains images that may not be suitable for automated analysis tools such as Beach Wizard. Images taken on a foggy day or during hours with excessive solar glare on the water surface generally have a low information content. The human eye can identify these at a glance; the challenge is to automatically qualify large numbers of images before they are used.

Everyone that looks at an Argus image can say whether or not it’s a good photograph. Bad photographs may be usable for downstream processing, however. An image with good contrast but unrealistic colours would be fine for edge detection but not for spectrographic analysis. The notion of usability depends on the application that uses the images. A simple, binary good-bad answer is not enough.

Near real-time image characterization can be used to warn station maintainers of problems that might require manual, on-site intervention. Here it is important to differentiate between transient and inevitable problems like solar glare or visible raindrops on the housing glass and serious, lasting problems like a broken housing glass or camera defects.

Our goal is to develop a system that rates an Argus image on one or more metrics. What these metrics represent depends on the needs of (anticipated) downstream applications. The ratings could be computed shortly after the image arrives in the archive and stored in a database. Each application can then specify a set of minimums for each metric to select sets of images.

**Present pre-selection**

Presently we are selecting images for use in Beach Wizard manually. The selection criteria are:

1. Images should not be contaminated with sunlight (rising or setting sun). Rising and setting sun is dealt with by excluding all images before 1000 local and after 1700 local. We may release this restriction somewhat if we are east facing or west facing. This does not always solve the problem though.
2. Images should not be contaminated with raindrops. Rain drops could be detected by looking at the longshore standard deviation of the signal or doing an fft longshore to detect "blobs". This is work in progress.
3. All cameras in the merged view area should be active and give a picture. Since we are scaling the whole area with the incoming wave energy, there cannot be any missing sectors in the merged view.
4. Likewise, offshore (incoming) wave information should be available, otherwise picture is useless.
5. Images should not be contaminated with raindrops. Some smoothing is already carried out which solves some of the problems, but still some 'funny' images appear sometimes due to this problem. Rain drops can be detected by looking at the longshore standard deviation of the signal or doing an fft longshore to detect "blobs"
6. Human selection with respect to contamination of the merged image with bright sunlight in one of the cameras is carried out. If we see very high intensities in one camera which do not occur in the other cameras, we exclude the image.
7. We may also want to exclude images where the wind direction is too different (>60 degrees) from the wave direction, and cases where the wave direction is more than 45 degrees off normal.
8. We would like to use images when the wave height is high, so that much dissipation occurs in the image (strong signal). Also, in storm periods we expect large morphological change to occur.
9. The number of images that will be used in the computation is dependent on the timescale of interest. An optimum has to be found between the computation time and the extent to which morphological changes will be solved. The computation time is largely dependent on the size of the computation grid.
   - For a timescale of one and a half years we have used approximately 60 dissipation images (in addition to ibathy), the computation time is approximately one and a half weeks (so approximately 1 image per week)
   - For a timescale of three weeks we have used approximately 60 dissipation images (in addition to cx and ibathy), the computation time is approximately two days (so approximately 3 images per day)

The selection process is still a very time consuming part of running the Beach Wizard model. This is why effort is put in developing automated characterization of Argus images for analysis purposes, such as Beach Wizard.

**Causes of unusable images**

Before techniques for identifying unusable images can be developed, the mechanisms that result in an unusable image need to be identified. Without regard for the probability of occurrence, a fairly comprehensive list of possible causes is:

- **Camera defects**: Argus cameras consist of a:
  - Sensor, typically a charged-coupled device (CCD).
  - Digital signal processor (DSP) that takes care of the shutter, gain and color balance.
  - Communication protocol, now IEEE-1394 (Firewire) but in the past analog video.
  - Each of these components can create faulty images if they fail. Examples of this broad category are shown in Figure 5.4, Figure 5.5 and Figure 5.6.

- **Improper camera settings**: Argus cameras are under control of external image acquisition software. An improper setting by the user or a bug in some control function may result in unusable images. Figure 5.7 and Figure 5.8 illustrate this.
• **Obstructions**: Light from the scene in view passes though the atmosphere protective housing glass, housing atmosphere and lens before it reaches the camera. Potential obstructions or distortions are:
  - Fog (e.g., Figure 5.9).
  - Falling rain or snow.
  - Raindrops or other transparent material on the housing glass (e.g., Figure 5.10).\(^2\)
  - Discrete, translucent spots on the housing glass (e.g., bird excrement).
  - Evenly spread, fine dried matter such as salt spray or dust that attenuate, reflect or refract light (e.g. Figure 5.11).
  - Broken housing glass (e.g., Figure 5.12).
  - Humidity or condensation within the camera housing.
  - Close-by moving objects such as birds, kites, balloons, aircraft or ships (e.g. Figure 5.13).

• **Lighting conditions**
  - Glare on the water surface that causes (local) overexposure (e.g. Figure 5.14).
  - Early morning or late evening images that are under exposed.
  - Night time with artificial illumination.\(^3\)
  - Fast-moving (cumulus) cloud cover that causes rapidly changing lighting conditions and perhaps frustrates auto-exposure algorithms.

• **Orientation changes**: External forces cause the camera housing to move and thus the observed scene to change, such as:
  - Extreme winds that cause the camera to sway or vibrate
  - Loose mounting bolts on the camera housing that cause it to move downward under influence of gravity, either gradually or abruptly.

• **Incorrect file names**: The Argus archive relies heavily file names that contain the date and time, site name and camera number. Software bugs, operator error, or an incorrect time or time zone on the acquisition computer could result in an image being stored in a file with the wrong name.

Each of the above conditions results in artefacts in the image. It is not always possible, given a particular artefact, to determine the cause. For example, a very dark image could be caused by natural low light conditions, an improper camera setting, or a camera defect. Images may have more than one defect. Artefacts can be grouped as follows:

- Incorrect exposure
- Low contrast
- Unexpected edges or other features
- Lack of detail (in certain parts of the image, even after contrast enhancement)
- Everything else.

**Qualification strategies**

Broadly speaking, qualification methods can be considered intrinsic or extrinsic. Intrinsic methods use only the image in question; extrinsic methods employ other images or auxillary

\(^2\) The effect of a raindrop depends on the lens being used. A wide-angle lens has a large depth of field and can "see" a raindrop on the housing glass, whereas a narrow-angle lens looking through the same raindrop will result in a distorted image.

\(^3\) WL Argus image acquisition software senses "nighttime" based on intensities in a small rectangular box within the full image. An unexpected light source in this box might generate unusable nighttime images.
information. Qualification also depends on the image type. A seagull that flew right in front of a camera as a snapshot was being taken will affect the usability of the snapshot, but not of many types of time exposure. A slowly moving ship in the foreground would affect time exposures in a different way.

**Intrinsic Methods**

Intrinsic methods are based only on the image in question. A histogram of a single image can identify under- and overexposed images, as well as low contrast. Comparing the size of a compressed image with the uncompressed size can expose bad images that have a good histogram (e.g., random noise would not compress very much, "color bars" would compress to almost nothing). Intrinsic tests could ultimately be done by the image acquisition software, before the image arrives in the archive.

**Extrinsic Methods**

Extrinsic methods judge an image using other images from the same camera, images from other cameras from the same station, or non-video information such as the time of day, tide level, or local meteorological measurements. Some methods compare actual pixels; others are based on processed images.

The Argus "autogeom" procedure is an excellent example of an extrinsic filter using actual pixels. Autogeom is meant to detect small camera movements using a previous image from the same camera and is based on auto-correlation between small patches in the two images. Autogeom is designed for relatively permanent movements - e.g. gravity-induced sag or wind-induced lateral movements of the camera mounts - and recalculates the extrinsic camera parameters (primarily the orientation angles of the camera). If autogeom has a problem with an image pair it is good indication that the subject image might be unusable and deserves more scrutiny.

Spatial transforms can be applied to images before comparison. One approach is to use a set of "good" reference images to compute a mean histogram (perhaps with fewer bins than the number of intensity values) and compare the subject image to this. If it deviates more than a certain amount it deserves further scrutiny. Any function that reduces dimensionality in a meaningful way can be used. The key is to discard information that is not needed to judge suitability and would only complicate comparison.

Frequency domain (e.g., the discrete Fourier transform (DFT)) and multiresolution processing (e.g., wavelets) can also be used to compare and discriminate images.

Extrinsic methods can be based on a collection of images that are known to be suitable. These are often chosen by manual inspection. A tool that presents many image thumbnails - perhaps after intrinsic filtering - to a user familiar with local conditions to identify the bad images could result in a large enough training set for neural network (NN) techniques. For NN it is especially important to condense the information content of an image.

---

4. In Argus terminology a "timex" image is a pixelwise arithmetical mean of all video frames captured in a certain period. A "var" image represents the standard deviation. There are also pixelwise minimum (darkest) and maximum (brightest) time exposures in which moving objects leave a very definite trail.

5. The number (or percentage) of pixels in an image as a function of discrete pixel intensity (range 0-255).

6. Most Argus images are compressed at the station using JPEG with a quality of 80 out of 100.

7. Fog and other meteorological conditional will affect all cameras in a station. If an image appears foggy, but another camera at the same station and time produces a clear and sharp image, the "fog" on the first camera may be moisture on the inside of the housing.

8. Mathematically, an image can be considered a 2D surface in a 3D space. A histogram effectively removes two dimensions (pixel coordinates) and replaces them with another (pixel count).

9. Most Argus images are fine, so its easier to manually choose the bad ones than the good ones.
Deploying special pixel time series ("stacks") on the Argus station can help identify problems like excessive camera movement, lighting changes and excessive noise. This cannot be used retroactively.

**Erroneous images**

![Figure 5.4 CCD problem](image)

![Figure 5.5 Another CCD problem](image)
Figure 5.6  Shifted image

Figure 5.7  Incorrect exposure (high gain, excessive noise)
Figure 5.8  Improper color balance

Figure 5.9  Fog

Figure 5.10  Clearly visible rain drops on housing glass

Figure 5.11  Streaks caused by particles on housing glass
Figure 5.12  Broken housing glass

Figure 5.13  Ship

Figure 5.14  Glare on the water surface (with refractions)
5.4.2 Pre-processing of time averaged intensity data

In past applications of the Beach Wizard model, a problem occurred with persistent foam remaining on the water surface after breaking. This foam appears on the time exposure images as a high intensity area just landward of the breaker bar (see Figure 5.15). The Beach Wizard model sees this high intensity area as an area of wave dissipation, thus telling the model that a breaker bar should be present in this area (driving the model bathymetry upward). This may cause the erroneous flattening of the breaker bars in the previous Beach Wizard computations.

![Cross-shore intensity profile at y = 0 m at 12:00 AM on 5 November 2004. The high intensity area caused by persistent foam is indicated with the red oval.](image)

A possible solution to this problem would be to remove the persistent foam (i.e. high intensity area behind the breaker bar) from the time exposure image that is fed into the model. Earlier work on a 1-D version of the Beach Wizard model (Aarninkhof, 2003) has shown that this improves model performance. The technique developed for the 1-D model by Aarninkhof (2003) is now applied to the 2-DH Beach Wizard model we are describing in this report.

**Noise reduction**

A first step is taken to reduce the noise in the time averaged intensity image. This is done by a technique developed by Alexander (2001), where a Gaussian type curve of intensity is fitted to each cross-shore intensity profile in the time exposure image. The procedure developed by Alexander (2001) results in a smooth approximation of the cross-shore intensity profile and is found to effectively filter noise from the raw intensity data. Also, the technique filters part of the high intensity area just landward of the breaker bar, caused by persistent foam. An example of the application of this technique is shown in Figure 5.16.
Figure 5.16 A raw cross-shore intensity profile (in blue) and the resulting fitted and detrended intensity profile through the Alexander (2001) method (in red).

**Persistent foam scaling**

Aarninkhof (2003) has developed a technique to filter the persistent foam by scaling the intensity data. To be able to relate the intensity profile to the model-predicted wave dissipation, the roller induced contribution to the intensity is isolated from the intensity contribution of persistent foam. This last contribution is removed through application of a reduction factor \( f_{\text{red}}(x) \) to the intensity \( I(x) \), which reflects the relative importance of roller induced pixel intensities as a fraction of the combined intensity impact of the wave roller plus persistent foam, as a function of the cross-shore location \( x \). Although successfully applied in a 1-D application (Aarninkhof, 2003), application of this method (with the same model settings as applied by Aarninkhof (2003) for the 1-D Duck case) has shown to be unfit for the 2-DH Egmond case. Almost the entire intensity profile was reduced to zero, which led to a weak input signal for the Beach Wizard model.

**Application to 2DH model computation of Egmond data 2004-2006**

Because of the disappointing results from the persistent foam reduction scaling, only the 2-DH version of the reduction of noise method by Alexander (2001) was applied to the Egmond 2004-2006 data.

Results show that the difference with the computation without persistent foam reduction is very small. In Figure 5.18, the results with and without persistent foam are shown at four points in time when measured data are available. Almost no difference is visible, except for the fact that the outer bar (foreshore nourishment) disappears from the bathymetry in the
situation without persistent foam. Due to the Gaussian fit, the signal is entirely removed at the location of the outer bar, because the intensity signal is smaller than a threshold value.

Another difference is that a small trough remains at the landward side of the inner bar at the fourth point in time (15 July 2006), where almost no trough exists in the original model results. This effect can be seen more clearly from Figure 5.17. In the area near $x=300$ m the persistent foam reduction results in a deeper trough, thus resulting in a more pronounced inner bar. The flattening of the bars that was seen earlier is thus reduced by the persistent foam reduction. Also in this figure, the flattening of the outer bar can be seen clearly.

![15 February 2006 profile at y = 10 (m)](image1)

![7 April 2006 profile at y = 10 (m)](image2)

Figure 5.17 Cross-shore profiles at two points in time (15 February and 7 April 2006) when a clear difference was visible between the modelled bathymetry with and without persistent foam.
Figure 5.18 Results of the Egmond 2004-2006 application at four points in time during the model period. The left panels show the modelled bathymetry as shown earlier in paragraph 5.3.2, the right panels the modelled bathymetry from Beach Wizard with persistent foam reduction through Alexander (2001).
5.4.3 Automatic detection of the intertidal bathymetry

To derive a bathymetry of the intertidal beach from Argus images, the shoreline is mapped on time exposure (timex) images. The detected shoreline is combined with the water level at the time of image collection. By mapping shorelines throughout the tidal cycle a set of altimeters is obtained from which a bathymetry of the intertidal beach can be interpolated.

Currently, the shorelines are mapped semi-manually using the Intertidal Beach Mapper (IBM) tool (see Figure 5.19). As this is a very time consuming procedure, this way of data processing is not very suitable to obtain day to day bathymetric data of the intertidal beach. Therefore the process was automated. The automatic tool is called Auto Shoreline Mapper (ASM). The first version of this tool was not easily usable as the code was in transparent and chaotic and the performance was not sufficient. The current version of the ASM is better structured and promises better results.

The main differences between the IBM and the ASM are that the ASM needs to determine automatically where to search for the shoreline (region of interest – ROI) and which of the detected shoreline points are acceptable. In the IBM routine these two steps were controlled by the user (subscript of Figure 5.19).

![Figure 5.19](image)

**Figure 5.19** Interface of the Intertidal Beach Mapper tool. The user can define the area (region of interest – ROI, the area enclosed by the red line) in which the tool searches for the waterline (blue). The user can manually select the wrong shoreline points and delete these.

Below the steps that the ASM takes to find the shoreline are explained shortly. The overview of the steps in Figure 5.20 is given to support explanation of the improvements made to the ASM.
As a first step the ASM determines the bathymetry of the day before by interpolating waterlines to a user-defined grid using loess interpolation. Next the waterlevel at the time of image collection is calculated. The outcomes of these two steps are combined to define the region of interest. For this, first the expected location of the shoreline is defined by combining the interpolated bathymetry and the calculated waterlevel. This yields a contourline on the bathymetry at the elevation of the waterlevel, this is the expected shoreline. An example of the expected shoreline can be seen in Figure 5.22, where the blue line is the expected shoreline. The region of interest is defined as the area around the expected shoreline. How far the region of interest stretches seaward and landward of the expected shoreline is user-defined.

Several detection methods to determine the shoreline have been developed. The method especially developed for the Dutch beach uses pixel color in the HSV color space to find those pixels that can be identified as the shoreline. The color criterion is not predefined but is based on the pixel colours within the region of interest and is thus calculated anew for every image. This method of defining the color criterion is used in both the IBM and the current ASM version and was not questioned in this research. Next the detected shoreline points are compared to the bathymetry that was defined in the first step. A criterion to accept/reject shoreline points is user-defined. The points that are accepted are stored in the database.

![Diagram](image)

**Figure 5.20** Steps taken by the ASM to derive shoreline points.

Both the steps of setting the region of interest and accepting/rejecting the detected points are highly influenced by the interpolated bathymetry. The quality of this bathymetry is determining for the outcome of the other steps.

The below examples show the influence the bathymetry has on the outcome and the problems that were encountered in the steps that used the bathymetry.

**Influence of the bathymetry on defining the region of interest**

If the bathymetry is based on too few past shoreline points, not-a-number values occur within the interpolated bathymetry. When little smoothing is applied in the interpolation, not-a-number values are also present in the bathymetry. In this case, there may not be an
expected shoreline location in every alongshore location (see Figure 5.21). The blue lines in the below image are the expected shoreline locations. These locations are transposed seaward and landward (purple and lower green line) to form the region of interest. It is already clear that this expected waterline does not result in a sound region of interest, as the region of interest does not cover the entire alongshore direction.

Figure 5.21  Bad definition of the region of interest on a rectified and merged timex image. The yellow line is the old region of interest that is too big; the blue line is the expected location of the waterline; the purple line is the landward extension of the blue line; the green line is the eventual region of interest, of which the lower line is the seaward extension of the blue line and the upper line is a cut off value to exclude buildings close to the dunes. The red line is an intermediate step in defining the green line.

To overcome the problem of a ‘short’ region of interest, the region if interest is extrapolated to the edge of the image. A drawback of this solution is that the extrapolated region of interest does not follow the curves of the beach. Especially on non-straight coasts this leads to problems. Therefore this solution is combined with higher smoothing scales and including shoreline points of more than one day back. These two additional measures reduce the number of not-a-number values.

Another problem encountered when defining the region of interest was the double or triple expected location of the shoreline at a certain alongshore locations. This problem arises in images with emerging sandbars. As all expected shoreline locations are transposed landward and seaward this leads to zigzagging of the region of interest. This can be clearly seen in Figure 5.22. Zigzagging of the region of interest might result in sandbars or parts of the shoreline being excluded from the region of interest. In that case they are not detected and thus bathymetric information at that timestep is incomplete. If several succeeding timesteps result in incomplete bathymetric data, the number of shoreline points used for the interpolation of the bathymetry in the first step reduces in time. This severely reduces the quality of the bathymetry and may result in an expected shoreline location that does not recognize the sandbars at all.
Figure 5.22 Zigzagging region of interest (red) blocks part of the shoreline; this part of the shoreline will not be detected. The blue line is the expected shoreline location. The red line is extended towards the end of the image at the left. At the right, the region of interest is cut off to exclude the black pixels. The green line is an intermediate region of interest in which the black pixels were not yet eliminated.

To overcome the problem of the zigzagging region of interest, only the outer points of the zigzagging part are used to define the region of interest. This leads to inclusion of both the sandbank as well as the entire shoreline (see Figure 5.23), which makes detection possible.

Figure 5.23 Region of interest including the entire shoreline, both the continuous shoreline and the emerging sandbank.

**Influence of the bathymetry on accepting/rejecting detected shoreline points**

The second step that is influenced greatly by the bathymetry is the acceptance/rejection of the detected shoreline points. The location and elevation of the detected points are compared to the bathymetry. Currently the points are accepted if the elevation difference between the detected point and the bathymetry is smaller than a certain user-defined value. Problems occur when the detected point is compared to a not-a-number value in the bathymetry. As no comparison can be made in that case, the detected point is rejected, although it may have perfectly detected the shoreline. This problem of rejection against not-a-number value is clarified by Figure 5.24.
Figure 5.24  Detected shoreline points. Many points are rejected because the bathymetry against which the points are checked contains not-a-number values at the location of the points.

As mentioned before, the not-a-number values in the bathymetry result from lack of data points and small smoothing scales. Increasing the smoothing scales would result in less not-a-number points, but also affects the correctness of the interpolated bathymetry. Too much smoothing is therefore not advisable. Another option is to include more shoreline points (of more days back in time) to interpolate the bathymetry from. A combination of both solves most problems with not-a-number values, but gives a troubled view of the actual bathymetry.

In the current version of the ASM two separate bathymetries are interpolated. The first bathymetry is supposed to be smoothed more, and based on more shoreline points than the second one. When checking the detected shoreline points, all points are first compared with the first bathymetry. Those points that were rejected on the basis of not-a-number values are then checked against the second bathymetry. This leads to a much higher number of accepted shoreline points (see Figure 5.25). The second bathymetry could also be used to define the region of interest, but this is up to the user.

Figure 5.25  Detected shoreline points checked against two bathymetries. Less points are rejected against Nan values.

The criterion that is used to accept or reject a shoreline point is currently the same for both the first and second check. Furthermore, it is a fixed value that does not take into account the probability of the detected point as being a true shoreline point or the correctness/error of the bathymetry against which it is checked.
In comparison with IBM, one could say that in the ASM tool the interpolated bathymetry has taken over the human control both in setting the region of interest and accepting the detected shoreline points.

Results so far show that the ASM is capable of determining the correct region of interest, and that the twofold check of the shoreline points increases the number of accepted correct shoreline points. The method promises to obtain shoreline points easily from timex images, thus decreasing the effort to obtain intertidal bathymetries from video.

**Accuracy**

The bathymetries derived from ASM detected shoreline points were compared to DGPS measurements by interpolating the accepted shoreline points to the grid of the DGPS measurements. For this interpolation also the loess interpolater was used. It turned out that the interpolation scales affect the outcome and that the best result is not always achieved with the same scaling. The difference in error between different scaling lengths is rather small, in the order of 1 to 2 cm.

Comparison of the outcome of the ASM with DGPS measured data gave the following best results:

- for March 20th the rms error is 0.20 m (using loess scaling of \( L_x = 10 \) m and \( L_y = 50 \) m)
- for May 7th the rms error is 0.36 m (using loess scaling of \( L_x = 25 \) m and \( L_y = 100 \) m)
- for May 12th the rms error is 0.25 m (using loess scaling of \( L_x = 10 \) m and \( L_y = 25 \) m)

The reason that for May 7th the best results are achieved with larger scaling lengths is because the DGPS data of that day was sampled on a larger grid (20 by 20 m instead of 10 by 10 m).

For March 20th the shoreline was also manually picked using IBM. Using the same scaling lengths as for the results of the ASM (\( L_x = 10 \) and \( L_y = 50 \)), the error was 0.19 m. This shows that, using the ASM, similar results can be achieved.

**5.4.4 Model Improvement in the nearshore zone**

In the above, we have shown that the updated bathymetry converges toward the true bathymetry even when an out-dated initial bathymetry is used to begin the assimilation. It appears, however, that there can be lasting impacts of an inaccurate initial bathymetry near the shoreline. This is a result of our neglecting to consider the spatial covariance of the updated bathymetry and error. In comparison to the measured bathymetry the results show that there are two forms of systematic estimation errors. The first is an erroneous building of a nearshore terrace in the bathymetric estimate (at Duck). The second is the erroneous deepening near the shoreline ("digging"). Both effects are due to the same problem, namely that the bathymetric adjustment in the subtidal area is governed by the spatial distribution of wave dissipation. Over a trajectory from offshore to onshore, the wave dissipation has a history, which is not entirely accounted for by adjusting the bathymetry due to local differences. For example, if in the true bathymetry a large bar exists, which is not present (yet) in the computational bathymetry, the model will correctly react by raising the bar in that area. However, due to the dissipation over the bar in reality, there will be less
dissipation left in the nearshore area. There, the model will react by increasing the local depth, which is possibly incorrect, see Figure 5.26.

![Diagram of dissipation and bathymetry](image)

**Figure 5.26** Schematic of a barred bathymetry (bottom solid line) and associated dissipation (top solid line), and the modelled bathymetry (bottom dashed line) and the modelled dissipation (top dashed line). The arrows indicate the direction of the adjustment of the modelled bathymetry.

The solution to this problem is to not use dissipation in the extreme shallow depth where this problem is the largest, but to use another source such as the celerity of the broken waves. The video time stack data necessary to do this has been collected since 14 June 2006 which is at the end of the modelling period. We will test the improvement in the bathymetry estimate by using (bore) speed information by rerunning the simulation from 14 June 2006 onwards and comparing to the simulation without this added information.

The a priori expected gain in model reliability is to reduce the local error in the inner surf zone from O(1 m) with extreme values of 2 meters to a local mean error of less than 50 cm. The improvement in the estimate of the Momentary Coast Line (MOL) volume is then 100m*0.5m=50 m³/m. This would be 10% of the long-term variation of about +/- 500 m³.

### Formulation

The formulation is as follows: if we denote the celerity as $c$ we need to calculate

$$\frac{dc}{dh} = \frac{d}{dh} \left( \frac{g}{k} \tanh(kd) \right)$$

(5.10)

using the linear dispersion relation in which $k$ is the wave number at the peak frequency, $h$ is the mean depth (still+setup) and $d=h+\alpha H_{mr}$, the total depth inclusive (some fraction $\alpha$ of the) wave height. Taking the derivatives with respect to $h$, for a given $H_{mr}$, we get
\[
\frac{dc}{dh} = \frac{g}{\sqrt{k \tanh(kd)}} \left( \frac{k}{\cosh^2(kd)} - \tanh kd \frac{dk}{dh} \right) \tag{5.11}
\]

This is equal to the kinematic derivative

\[
\frac{dc}{dh} = d\left(\frac{\omega}{k}\right) = \frac{d\omega}{dh} k - \frac{dk}{dh} \frac{\omega}{k^2} \tag{5.12}
\]

Equating, and invoking conservation of waves \( \frac{d\omega}{dh} = 0 \), and after some manipulation we find

\[
\frac{dk}{dh} = \frac{-2k^2}{\sinh 2kd + 2kd} \tag{5.13}
\]

and

\[
\frac{dc}{dh} = -\frac{\omega}{k^2} \frac{dk}{dh} = \frac{4\pi f_p}{\sinh 2kd + 2kd} \tag{5.14}
\]

where \( f_p \) is the peak frequency

This formulation is applicable in finite depth (not deep water since the celerity has no relation to depth there). In shallow water where the bores occur this formulation becomes

\[
\frac{dc}{dh} = \frac{\pi f_p}{kd} = \frac{f_p}{k (h + \alpha H_{rms})} = \frac{1}{2} \sqrt{\frac{g}{(h + \alpha H_{rms})}} \tag{5.15}
\]

and

\[
c = \sqrt{\frac{g}{k} \tanh(kd)} = \sqrt{gd} = \sqrt{g \left( h + \alpha H_{rms} \right)} = \sqrt{g \left( h + \alpha H_{rms} \right)}
\]

\[
= \sqrt{gh(1 + \alpha H_{rms}/h)} \approx \sqrt{gh(1 + 0.4\alpha)} = 1.2\sqrt{gh}
\tag{5.16}
\]

if \( \alpha = 1 \), and is close to the bore speed (Svendsen, 2003, pp. 248), which is just larger than the conventional shallow water speed, see Figure 5.27.
Figure 5.27  Measured bore speeds (Svendsen, 2003).

Theory on celerity estimation of time stacks

From “Development of wave number estimation methods applied to coastal motion imagery” by Nathaniel G. Plant, K. Todd Holland, Merrick C. Haller, submitted to IEEE Transactions on Geoscience and Remote Sensing:

“We assume that geo-referenced image sequences exhibiting intensity modulations attributable to surface gravity waves are available and that their sampling rate is sufficient to resolve the incident wave spectrum—or at least that part of the spectrum that exhibits sensitivity to the bathymetry. The imagery can be expressed as $I(x_i,y_i,t)$, where $x_i,y_i$ is the spatial coordinate of the ith image pixel, and t are discrete sampling times. At frequencies of interest, we wish to characterize the spatial variation of the wave field, including changes in wavelength and direction. This information can then be used to estimate water depth via a valid wave dispersion relationship. The objective is to describe an efficient and accurate method of calculating estimates of $c$ (or, equivalently, $k$).”

Essentially, this can be done in two ways: in the time domain and the frequency domain. The first method is to measure a time-delay (or highest value of the correlation) between signals measured at two points of which the coordinates are known. Dividing the distance between the two points by the delay gives the (projection of) the phase speed of the wave. This is essentially the method by Bos (2006). Another way is to transform to the frequency domain (as done by Plant et al.) and consider the phase delay instead of the time delay. “An
apparent advantage of the spectral formulation is that the problem of filtering the time series within particular frequency bands is accomplished via Fourier transform and the nonlinear problem of identifying time-delays in the observations is avoided. A disadvantage is that a phase ambiguity” and aliasing between measured point can occur. We have used the second method, using processing code shared by N. Plant and refer to their paper for details. The end result of their method are spatial fields of absolute wave numbers, which can be read into the Beach Wizard module.

Layout of time-stack grid

For the Egmond Beach, in the field of view of the cameras a number of pixels are selected where so-called time stacks are collected. The collection design of the timestack arrays is shown in Figure 5.28. The design consists of 21 cross-shore arrays with an alongshore distance of 100 m. The cross-shore resolution of the arrays varies over the arrays, becoming coarser seaward. The intensity in the grid pixels is collected hourly with a frequency of 2 Hz. for a duration of 17 minutes.

Figure 5.28  Design of the timestack arrays collected in Egmond from the Jan van Speijk lighthouse Argus station on 14 June 2006 – 31 December 2006.
6 Morphodynamic modelling of a shoreface nourishment

6.1 Introduction

Within the VOP Project Kustlijnzorg 2007, RIKZ of Rijkswaterstaat and WL | Delft Hydraulics are collaborating on the development/improvement, validation and application of morphodynamic models.

Last years, much effort has been assess to the improvement of DELFT3D – Online model, based on the engineering sand transport formulations of TRANSPOR2004 model (Van Rijn, 2007–a and –b, Van Rijn et al., 2007). In particular, the attention was focussed on the development of a general bed load transport equation that can be used for both steady and oscillatory flows, using the concept of instantaneous bed shear stress. This equation includes both wave-related and current-related components, with a numerical intra-wave approach (method of Isobe-Horikawa, 1982, modified by Grasmeijer, 2002). Besides, the suspended transport is computed as the sum of the current-related transport of sediment by the mean current, including the effect of wave stirring on the sediment load, and of the wave-related transport, resulting of the asymmetric oscillatory wave motion near the bed in shoaling waves (based on the method of Isobe-Horikawa, 1982, modified by Grasmeijer, 2002).

Moreover, academic research has been performed during the last years, regarding the processes that determine the cross-shore profile development and cyclic bar behaviour (Wijnberg and Terwindt, 1995). Research efforts in 2DV profile modelling, reported in the literature, suggest promising ways of improving the predictive capability of process-based models, using wave energy decay concepts. Last years, the DELFT3D – Online model has been updated so that it now includes the surface roller model of Nairn (1990) (Reniers et al., 2004) and two breaker delay concepts (Roelvink et al., 1995, and Reniers et al., 2004).

These recent improvements of the DELFT3D – Online model formed the impetus for an application to study morphodynamics of a shoreface nourishment at Egmond-aan-Zee under the action of wave climates and tides.

The Egmond region was selected because this area has been the focus of many field experiments (COAST 3D project, Soulsby, 2001) and model validation studies in recent years (see e.g. Elias et al., 2000; Van Duin et al., 2004; Klein et al., 2001; Sun 2004). Moreover, the VOP project focuses on the application of the DELFT3D model on this area to support design of future human interventions.

The present study is based on a combination of profile and area modelling approaches. The profile mode has been used to calibrate the model, based on a sensitivity analysis of the main settings and of different representations of waves and tides. Results have been systematically compared to observed bathymetric data. The area mode has been used to validate the model, before its application to support design of future shoreface nourishment in 2008.
6.2 Model set-up

This paragraph aims at describing the constructed computational grids and the hydrodynamic boundary conditions, including a description of the adopted wave climate and morphological tide.

6.2.1 Study area

At Egmond-aan-Zee, the mean tidal range varies between 1.2 m in the neap cycle to 2.1 in the spring cycle. The tidal peak current are about 0.5 m/s in the offshore zone, with the flood current to the North slightly larger than the ebb current directed to the South.

The mean monthly offshore wave height has a seasonal character, and varies from about 1 m in the summer months (May to August) to about 1.5 to 1.7 m in the autumn and winter (October to January). The mean wave height can reach 5 m at 15 m depth, during major storms.

The beach width is about 100 m to 125 m with a slope between 1:30 and 1:50. Two main longshore breaker bars run parallel to the shoreline most of the time. The inner bar is located 200 m from the shoreline at 2 m below the mean sea water level (MSWL), whilst the crest of the outer bar is located at about 500 m from the shore at 4 m below the MSWL. The inner bar is separated from the outer one by a wide trough. The area is characterised by medium well-sorted sands (0.25 to 0.5 mm), although in the trough between the inner and outer bars, the sand is coarser (> 0.5 mm) and has a moderate sorting. The cross-shore slope amounts to 1:100, and the median grain size is about 0.2 mm (Elias et al., 2000; Van Rijn et al., 2003).

6.2.2 Computational grids

Profile and area models have been distinguished, and grids have been constructed based on the bathymetry surveys carried out at Egmond. The profile grid was constructed to cover the active zone in the cross-shore direction and has its seaward boundary at the 12 m depth contour. The landward boundary includes the beach dune at a height of about 3.5 m. To ensure that enough sand is available in the upper beach, the grid was extended in the landward direction. The area grid was constructed to cover the area where the shoreface nourishment was done.

Profile modelling

With the implementation of gradient boundary conditions (a so-called Neumann boundary condition) in DELFT3D, a combination of tide, wind and wave driven currents does not induce any visible boundary effects along the lateral boundaries. Therefore, DELFT3D can be reliably run as a profile model by only considering one longshore grid cell. Adopting constant gradient conditions in the longshore direction, the longshore transport gradient is null, enabling to consider only cross-shore transport processes along the profile.

The profile grid was constructed using 57 grid cells (Figure 6.1). The resolution increases from 60 m at the seaward boundary to 20 m in the surf zone. 12 layers have been selected in
the vertical direction. The \( \sigma \)-layers distribution has highest resolutions at the bed and near the water surface, decreasing towards the middle of the water column, and ranging as \([2\%, 3.2\%, 5\%, 7.9\%, 12.4\%, 19.6\%, 19.6, 12.4\%, 7.9\%, 5\%, 3.2\% \text{ and } 1.8\%]\).

For the simulations, 2 different profiles have been used based on the bathymetries surveyed along the segments B.P. 37.00 and B.P. 39.00.

![Computational grid for the profile model with bathymetry of 04 Nov. 2004](image)

Figure 6.1  Computational grid for the profile model with bathymetry of 04 Nov. 2004

### 6.2.3 Boundary conditions

The tidal information is used for the hydrodynamic computation. For the profile modelling, this information consists on either (i) a real-time series of water levels (including surges), (ii) an astronomic tide, or (ii) a harmonic tide.

When adopting a harmonic representation, a complete tidal cycle (e.g. neap-spring tide) should be ideally simulated, but leading to an unacceptable high computational effort. Then, a representative tide, so-called morphological tide, resulting in a reliable description of the net sediment transports, has been defined. Moreover, the conditions at the northern and southern boundaries correspond to Neumann boundaries. Instead of a fixed water level or velocity, the Neumann boundary condition is the longshore water level gradient. The main characteristic of this condition is that the boundary is transparent for out-going waves, such as short wave disturbances. In many cases, such as for the present study, the longshore gradient of the water level does not vary much in the cross-shore direction, even when considering the area model. A uniform boundary condition can then be assigned at each lateral boundary. The harmonic components at the boundaries of the profile model are listed in Table 6.1.
Table 6.1  Harmonic components at the boundaries of the profile model for the year 2004.

<table>
<thead>
<tr>
<th>Angular Velocity (°/hour)</th>
<th>Southern Boundary</th>
<th>Northern Boundary</th>
<th>Sea Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amplitude (10^3 cm)</td>
<td>Phase (°)</td>
<td>Amplitude (10^3 cm)</td>
</tr>
<tr>
<td>28.99</td>
<td>1.0353</td>
<td>71.39</td>
<td>1.0353</td>
</tr>
<tr>
<td>57.99</td>
<td>1.7121</td>
<td>313.05</td>
<td>1.7121</td>
</tr>
<tr>
<td>86.98</td>
<td>1.5921</td>
<td>251.22</td>
<td>1.5921</td>
</tr>
<tr>
<td>115.97</td>
<td>1.1258</td>
<td>135.98</td>
<td>1.1258</td>
</tr>
<tr>
<td>144.96</td>
<td>2.6285</td>
<td>31.37</td>
<td>2.6285</td>
</tr>
<tr>
<td>173.96</td>
<td>1.153</td>
<td>284.17</td>
<td>1.153</td>
</tr>
</tbody>
</table>

6.2.4  Wave schematization

The wave climate consists of a selection of wave conditions in order to limit the computational effort. A sensitivity analysis has been performed to define the optimal number of wave conditions and the way the selection should be obtained. The reduction was indeed achieved by either (i) ensuring identical gross northward and southward transports, or (ii) ensuring identical offshore and onshore transports, by means of scaling the selected wave conditions.

Adopting the first method (i), Walstra et al. (2004) showed that such a simple reduction technique gives a very good agreement for the cross-shore distributions of the longshore sediment transports in both the northerly and the southerly directions. In this previous study, the net transports at Egmond were computed of about 110 000 m^3/year towards the North, which are in accordance with values in literature (e.g. Van Rijn, 1997). The gross transports are about 1.2 Mm^3/year towards the North and 1.1 Mm^3/year towards the South. On this way, a weight is obtained indicating the total duration of each wave condition.

Table 6.2  Reduced morphological 5 conditions wave climate applied for the period November 2004, ensuring identical offshore and onshore transports.

<table>
<thead>
<tr>
<th>Condition</th>
<th>H_s (m)</th>
<th>T_p (s)</th>
<th>Direction (°N)</th>
<th>Morphological Factor (MorFac)</th>
<th>acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.94</td>
<td>7.56</td>
<td>321.96</td>
<td></td>
<td>10.021</td>
</tr>
<tr>
<td>2</td>
<td>2.05</td>
<td>7.00</td>
<td>305.76</td>
<td></td>
<td>11.850</td>
</tr>
<tr>
<td>3</td>
<td>3.94</td>
<td>9.47</td>
<td>323.60</td>
<td></td>
<td>4.957</td>
</tr>
<tr>
<td>4</td>
<td>5.43</td>
<td>9.71</td>
<td>322.00</td>
<td></td>
<td>0.081</td>
</tr>
<tr>
<td>5</td>
<td>6.37</td>
<td>6.37</td>
<td>316.75</td>
<td></td>
<td>0.163</td>
</tr>
</tbody>
</table>

6.2.5  Morphological set-up

To reduce the computational time, a so-called morphological acceleration factor is used. This morphological acceleration factor, MorFac, is a device used to assist in dealing with the difference in time-scales between hydrodynamic and morphological developments. It works very simply by multiplying the changes in bed sediments by a constant factor, thereby...
effectively extending the morphological time step. This technique is very similar to the "elongated tide" technique proposed by Latteux (1995) and implies that long morphological simulations can be achieved using hydrodynamic simulations of only a fraction of the required duration. Obviously, there are limits to the morphological acceleration factor that can be applied, depending on the characteristics of the location under consideration.

The morphodynamic model simulations are performed by applying the selected wave conditions consecutively. The order of execution is randomly defined. For each wave condition the flow model runs 2 hours before the bed-updating is activated to ensure realistic flow and transport predictions. Each wave condition is scaled to a representative morphological tide with duration of 12.5 hours. After completion of a wave condition, the resulting bathymetry is used as the starting bathymetry for the next wave condition. This set-up allows us to select different MorFac-values for the individual wave conditions. An example of these values are listed in Table 6.2. It can be seen that the MorFac-values are high for the average wave conditions and low for the storm wave conditions. This is an advantage of the followed approach: the long duration of the average wave conditions with small bottom changes allows higher MorFac-values. For high wave conditions, it is the opposite: short duration, but relative large bottom changes, which requires relatively low MorFac-values.

6.2.6 Parameter settings

The updated expressions of TRANSPOR2004 (Van Rijn, 2007,a,b) are used to calculate the sediment transports, including the bed load transport \( q_b \) and the suspended load transport \( q_s \). The bed load vector due to both current and wave effects (including wave asymmetry) represents the current-related contribution \( q_{b,c} \) in the current direction) and a wave-related contribution \( q_{b,w} \) in the wave direction, following or opposing, depending on conditions). The suspended load transport represents the current-related contribution due to advective processes \( q_{s,c} \) in the current direction) and the wave-related contribution, mainly due to wave asymmetry effects \( q_{s,w} \) in the wave direction).

Scaling all contributions to the sediment transport (i.e. the suspended current transport, bed load transport due to currents and waves and suspended transport due to the oscillatory wave motion) has been the topic of previous studies (e.g. Brière and Walstra, 2006). Default settings for \( f_{sus}, f_{bed}, f_{bedw}, \) and \( f_{susw} \) are summarized in Table 6.3.

The sediment type is sand with a default medium diameter of 0.2 mm (\( d_{10} = 0.15 \) mm and \( d_{90} = 0.3 \) mm). A grain size sensitivity analysis has been performed using a 2-fractions distribution with diameters \( d_{50} [\text{mm}] \) varying in the range of \{0.2, 0.25\} \{0.2, \ 0.3\} \{0.2, \ 0.4\} \{0.15, 0.2\} \{0.15, 0.25\} \{0.15, 0.3\}.

The wave energy balance and the roller energy balance which are solved in the FLOW model used the default \( \gamma \)-expression (wave height to water depth ratio) of Ruessink et al. (2003). Besides, the \( \gamma \)-expression of Battjes and Stive (1985) was also adopted, as well as constant values varying in the range of \{0.5, 0.7\}.

The presence of a surface roller significantly influences the vertical velocity profile of the undertow leading to a shoreward shift of the maximum cross-shore current velocities. In a morphological point of view, including a roller model causes a delayed response on the
profile development, due to the phase shift between the transport gradients and the morphology. The effect results in more realistic cross-shore profile behaviour. The slope of the wave front ($\beta_n$) is an important parameter involved in the roller energy balance equation and its influence has been analysed using values of 0.03 and 0.05.

The time step for the FLOW simulations was selected by having a courant number of approximately 10 (the courant number is a numerical stability criterion). Furthermore, test simulations indicated that stable solutions were obtained if a time step of 12 seconds was used.

Table 6.3 Summary of the main model parameters applied in the Delft3D area model and profile model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAVE</td>
<td>(energy balance equations)</td>
<td></td>
</tr>
<tr>
<td>F-lam</td>
<td>Breaker delay model</td>
<td>Roelvink et al. (1995)</td>
</tr>
<tr>
<td>GamDis</td>
<td>$\gamma$-expression (wave height to water depth ratio)</td>
<td>Russink et al. (2003)</td>
</tr>
<tr>
<td>Betaro</td>
<td>Slope of wave front on which roller force acts</td>
<td>0.03 and 0.05</td>
</tr>
<tr>
<td>FLOW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dt</td>
<td>Time step</td>
<td>12 (s)</td>
</tr>
<tr>
<td>Dryflc</td>
<td>Minimum depth for drying and flooding</td>
<td>0.2 (m)</td>
</tr>
<tr>
<td>Vicouv</td>
<td>Horizontal eddy viscosity (background value, is</td>
<td>0.1 (m$^2$/s)</td>
</tr>
<tr>
<td></td>
<td>determined by local production of turbulence due</td>
<td></td>
</tr>
<tr>
<td></td>
<td>to breaking waves)</td>
<td></td>
</tr>
<tr>
<td>Dicouv</td>
<td>Horizontal eddy diffusivity</td>
<td>0.1 (m$^2$/s)</td>
</tr>
<tr>
<td>Vicoww</td>
<td>Vertical eddy viscosity (background value, is</td>
<td>1.0E-6 (m$^2$/s)</td>
</tr>
<tr>
<td></td>
<td>determined by local production of turbulence due</td>
<td></td>
</tr>
<tr>
<td></td>
<td>to breaking waves)</td>
<td></td>
</tr>
<tr>
<td>Dicoww</td>
<td>Vertical eddy diffusivity (background value, is</td>
<td>1.0E-6 (m$^2$/s)</td>
</tr>
<tr>
<td></td>
<td>determined by local production of turbulence due</td>
<td></td>
</tr>
<tr>
<td></td>
<td>to breaking waves)</td>
<td></td>
</tr>
<tr>
<td>Rhow</td>
<td>Density of water</td>
<td>1023 (kg/m$^3$)</td>
</tr>
<tr>
<td>Thick</td>
<td>Vertical distribution of numerical grid (%) (g-</td>
<td>2, 5, 8, 10, 15, 20, 15, 10, 8, 5, 2.</td>
</tr>
<tr>
<td></td>
<td>layers, from surface to bottom)</td>
<td></td>
</tr>
<tr>
<td>Transport and Bed Updating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D50</td>
<td>50% sediment diameter</td>
<td>150, 200, 250, 300 and 400 (µm)</td>
</tr>
<tr>
<td>FwFac</td>
<td>Factor on streaming effects in wave boundary layer</td>
<td>0.0</td>
</tr>
<tr>
<td>Alfabn</td>
<td>Transverse bed gradient factor.</td>
<td>1.5 and 50.0</td>
</tr>
<tr>
<td>Alfabs</td>
<td>Longitudinal bed gradient factor</td>
<td>1.0 and 30.0</td>
</tr>
<tr>
<td>FSUS</td>
<td>Suspended transport factor</td>
<td>1.0</td>
</tr>
<tr>
<td>FBED</td>
<td>Bed load transport factor</td>
<td>1.0</td>
</tr>
<tr>
<td>FBEDW</td>
<td>Wave-related bed load transport factor</td>
<td>1.0</td>
</tr>
<tr>
<td>FSUSW</td>
<td>Wave-related suspended transport factor</td>
<td>0.3</td>
</tr>
</tbody>
</table>
6.3 Profile modelling

The profile model was used to calibrate the model by performing a sensitivity analysis of the main parameters responsible for bar dynamics using the DELFT3D model (Brière and Walstra, 2006).

First, the effect of the description of the tide (z-level time-series, astronomic tide, harmonic tide) on the development of the bed during the period 04/11/04 – 30/11/04 is investigated. Next, the influence of the wave climate schematisation is studied. Finally, the influence of parameters such as the $\gamma$-expression, the slope of the wave front $\beta_m$, the bed gradient factors for bed load transport Alfabn and Alfabs, and a 2-fractions distribution, are analysed.

For each simulation, only one parameter was varied while all other parameters were kept constant according to the settings listed in Table 6.3 or described in paragraph 6.2.6. In the following paragraphs, the profiles obtained after approximately one month of simulation are compared with observation data.

Since the model has been calibrated, it has been applied to the following periods 30/11/04 – 24/04/05, 24/04/05 – 28/07/05, 28/07/05 – 08/12/05, and 08/12/05 – 07/05/06, and the profiles obtained after each period of simulation are compared with observation data.

6.3.1 Tidal representation

In this paragraph, we refer to the period 04/11/04 – 30/11/04. The initial bathymetry (Figure 6.1) reflects a cross-shore profile on which the shoreface nourishment has been carried out from July to November 2004. The nourishment took place approximately on a 4 kms long and 400 m wide area, for a 2 000 000 m$^3$ total amount of sand deposit, that modified the cross-shore bottom profile approximately from $x = 250$ m to $x = 550$ m in the . More details on hydrodynamics and morphological characteristics of Egmond have been presented in paragraph 6.2.1.

Hindcasting simulations have been performed with the DELFT3D model to investigate the morphological development of the cross-shore Egmond profile under the action of waves and tides. The influence of different tidal description has been first studied, adopting either (i) a water level time series including surges, (ii) a astronomic tide, or (iii) a harmonic tide. For these simulations, a full wave climate (time series of $\{Hs, Tp, Dirp\}$) is adopted, and the default settings described in paragraph 6.2.6 are chosen.

The morphological development obtained after approximately one month is plotted for each representation of the tide in the Figure 6.2. During this period, two severe storms have occurred (Figure 6.3), resulting in a offshore migration of the outer bar, as shown by the observation data. Whatever the representation of the tide, this specific behaviour of the outer bar is well represented by the model, whereas, despite the relatively short duration of the simulation, the model predicts a significant off-shore movement of the nourished bar. Model results show as well that the height of the nourished bar increases significantly, which is unrealistic. The inter-tidal beach area experiences erosion during all tidal conditions, which is attributed to the fact that both the hydrodynamics and transports are unreliable in this area. The proportion of the different contributions of sediment transport is not well
evaluated. Consequently, sediment transport in the offshore direction is overestimated. However, this development in the inter-tidal beach area does not adversely affect the predictions in the middle and outer surf zone as the morphodynamic simulation only covers one month.

Figure 6.2  Profile development for the period 04/11/04 – 30/11/04 induced by different representations of the tide

Figure 6.3  Wave climate for the period 04/11/04 – 30/11/04: significant wave height and peak direction.
The results obtained using different descriptions for the tidal forcing are in good agreement between each others. A harmonic representation of the forcing defined for the considered year, can be therefore used instead of the water level time-series of the specified period.

### 6.3.2 Wave schematisation

As seen in paragraph 6.2.5, a so-called morphological acceleration factor can be used to reduce the computational time. In that case, the morphological simulation for the period 04/11/04 – 30/11/04 can be achieved using hydrodynamic simulations of only one fraction of the required duration. The tidal forcing used is therefore based on a harmonic representation of the tide, referred as the morphological tide with duration of 12.5 hours.

The morphodynamic model simulations are performed by applying a selection of wave conditions consecutively. A sensitivity analysis has been performed to define the optimal number of wave conditions and the way the selection should be obtained.

The reduction was achieved by (i) ensuring identical gross northward and southward transports, and by (ii) ensuring identical offshore and onshore transports, by means of scaling the selected wave conditions. The number of selected conditions is 5 or 10, which are executed in a randomly order. The morphological development of the studied profile for the period 04/11/04 – 30/11/04 is plotted in Figure 6.4.

![Figure 6.4](image)

**Figure 6.4** Profile development for the period 04/11/04 – 30/11/04 induced by different schematisations of the wave climate

During the period 04/11/04 – 30/11/04, two severe storms have occurred (Figure 6.3), resulting in a selection of high energy wave conditions. The highest conditions correspond nevertheless to short-term events, and their associated weight is therefore low, as shown in
Table 6.2 for example. Result obtained using such a schematisation of the wave climate is in good agreement with the one obtained when adopting the real time-series of waves. Moreover, only slight differences can be noticed, according to the number of wave conditions chosen or the way to achieve the reduction.

6.3.3 Sensitivity analysis of main parameters

When considering the waves, a few parameters can influence the morphological development of the studied profile, as shown by Brière and Walstra (2006). In particular, the wave energy balance and the roller energy balance used the $\gamma$-expression (wave height to water depth ratio) which can be specified according to Ruessink et al. (2003), to Battjes and Stive (1985), as well as to constant values (here in the range of [0.5, 0.7]). Moreover, to include a roller model causes a delayed response on the profile development, resulting in more realistic cross-shore profile behaviour (Brière and Walstra, 2006). The influence of the slope of the wave front has been therefore evaluated by specifying values for $\beta_m$ of 0.03 and 0.05.

The morphological developments obtained after approximately one month and plotted in Figure 6.2 and Figure 6.4, display unrealistic behaviours of the nourished bar, with an significant off-shore movement and a large increase of the height of the nourished bar. Consequently, it appears that sediment transport in the offshore direction is overestimated. Therefore, sensitivity analysis of the bed slope effect and of the dependence on the grain size distribution, for which these parameters can potentially affect the profile development, have been performed. The bed slope effect has been studied setting the transverse and longitudinal bed gradient factors, Alfab and Alfas, respectively to 1.5 or 50 and to 1 or 30. The grain size sensitivity analysis has been performed using a 2-fractions distribution with diameters $d_{50}$ [mm] varying in the range of {0.2, 0.25} {0.2, 0.3} {0.2, 0.4} {0.15, 0.2} {0.15, 0.25} {0.15, 0.3}. The effect of the water level has been also studied, by including the set-up calculated by comparing the real water level to the predicted one.

Results are summarised as follows:

- The wave height over water depth ratio ($\gamma$) is an important parameter for the wave height prediction in the surf zone, as it imposes an upper limit on the wave height (fraction of the local water depth). A study by Ruessink et al. (2003) showed that a significant improvement of the wave height prediction in the surf zone could be achieved with a cross-shore varying $\gamma$. The formulation of Ruessink et al. is compared (Figure 6.5) against a number of constant (in space and time) $\gamma$-values and against the formulation of Battjes and Stive (1985). The large differences in the profile development, obtained using a constant gamma-value or using the variable expression of Ruessink et al. (2003) are associated to differences in hydrodynamics. The near-bed current and longshore current velocities increase slightly using the variable $\gamma$-expression compared to using a constant-value, due to highest significant wave height gradients above the bar crest. It results in a less pronounced bar which also migrates further offshore, due to the highest significant wave height gradients above the bar crest. For a low $\gamma$-value ($\gamma = 0.5$), wave breaking occurs before the outer bar and has not consequently a large effect on the profile development, whereas a larger $\gamma$-value ($\gamma = 0.7$) leads to the flattening of the outer bar, as the wave breaking occur more directly on
the bar crest. Although Ruessink et al. have shown, from Egmond in situ data sets, that using a variable $\gamma$-expression leads to a significantly improved wave height prediction across the breaker bars, this expression seems to induce too large offshore-directed transports, resulting in an unrealistic final profile. Therefore, a constant $\gamma$-value of 0.7 is used for the next simulations.

![Profile Development between 04/11/04 and 30/11/04](image)

**Figure 6.5** Profile development for the period 04/11/04 – 30/11/04 induced by different $\gamma$-expressions

- Laboratory and field measurements have shown that waves do not break at bar crests but in the trough behind them (Grasmeijer and Ruessink, 2003), with observed maximum undertow velocities located further shoreward than the process-based models can predict when any roller model is included. On the other hand, the presence of a surface roller causes a delayed response on the profile development, due to the phase shift between the transport gradients and the morphology. The slope of the wave front ($\beta_w$) is an important parameter involved in the roller energy balance equation. It determines to a large extent the rate of wave energy transferred to the roller and from the roller to the underlying water. Briere and Walstra (2006) suggested to use a value in the range from 0.05 to 0.1. However, tuning of the roller model via the $\beta_w$-parameter did not influence significantly the profile development for the period 04/11/04 – 30/11/04. In the reference simulations, a constant value of 0.05 has been used.

- When increasing either the transversal or the longitudinal bed slope factor, the profile development is significantly influenced. In particular, a damping effect is noticed over the outer bar, with the underestimation of its migration and the flattening of its height. Although bed slope effects result in minimizing the offshore migration of the nourished bar, the general development of the profile appears unrealistic. Consequently, it is
recommended to set the transversal and longitudinal bed gradient factors, Alfabs and Alfabn, to their default values, respectively 1.5 and 1.

- Particle movement will occur when the instantaneous fluid force on a particle is larger than the instantaneous resisting force related to the particle weight and the friction coefficient. The grain size is obviously an important parameter involved in the initiation of motion. Moreover, the grain size controls the degree of sediment transports as this parameter appears in all transport formulations. In DELFT3D, the sediment characteristics can be modified by specifying different grain sizes (user-prescribed parameters $d10$, $d50$ and $d90$) in different locations. As seen previously, significant offshore migration is noticed for uniform particles (diameter $d50$ equal to 0.2 mm). On the other hand, increasing the diameter $d50$ to 0.4 mm in the area of the nourished bar (Figure 6.6) leads to more realistic behaviour with final shape similar to the observed one (Figure 6.7).

![2 sediment fractions](image)

Figure 6.6 Profile at 04/11/04 with 2 sediment fractions: general diameter $d50$ equal to 0.2 mm except on the nourished bar where $d50$ equals to 0.4 mm.

- The profile development is not influenced: when increasing the maximum value allowed for the ratio significant wave height / water depth, neither when including a water level set-up (Figure 6.8). This elevation of the water level has been obtained by comparing the predicted water levels to the observed ones. A mean value has been computed for each wave class and has been used to compute the transports induced by this class. The schematisation has been then performed and, finally, the profile development has been obtained, adopting a water level set-up corresponding to the selected wave class.

- A comparison has been performed between the results obtained with different DELFT3D versions (Figure 6.9), showing that the current research version, on which improvements have been attended, give better qualitative results than standard versions 3.52 or 3.54.
Figure 6.7  Profile development for the period 04/11/04 – 30/11/04 induced by different settings

Figure 6.8  Profile development for the period 04/11/04 – 30/11/04 induced by wave different settings
6.3.4 Validation

Using the selected settings discussed in the previous sections, the model has been applied to the following periods 30/11/04 – 24/04/05, 24/04/05 – 28/07/05, 28/07/05 – 08/12/05, and 08/12/05 – 07/05/06. For each simulation, the initial profile is chosen based on the observations and the final one is compared to the observed one. Wave climates and the final profiles are plotted respectively in Figure 6.10 and in Figure 6.11 to Figure 6.14.

- The period 30/11/04 – 24/04/05 is characterised by a wave climate with high-energy conditions, explaining why the predicted profile is quite different from the initial one. A unrealistic offshore migration of the nourished bar has occurred, whereas the outer bar has been damped. It differs from the observation, which displays the stabilisation of the nourished bar and the onshore migration of the outer bar.
- The overestimation of the offshore migration of the nourished bar can be generalised to all periods, especially when adopting only one sand fraction and when the wave climates relate to winter periods (high-energy conditions).
- On the other hand, the outer bar is migrating onshore at a more or less high rate during all simulations, which is in agreement with the observations. Nevertheless, the predicted profiles are more flattening than the observed one.
- A key point inherent to the simulations is the overestimation of the dynamics (migration, height) of the nourished bar, whereas observations display a stable shape and height over the 2 years simulated. This phenomena is probably related to hydrodynamics and to 3D effects, which require therefore to investigate the beach development using a 3D model.
Figure 6.10  Wave climate (significant wave height) for the period 30/11/04 – 07/05/06

Figure 6.11  Profile development for the period 30/11/04 – 05/04/05 obtained adopting 1 and 2 sand fractions and using a morphological tide and a time series
Figure 6.12  Profile development for the period 05/04/05 – 28/07/05 obtained adopting 1 and 2 sand fractions and using a morphological tide and a time series.

Figure 6.13  Profile development for the period 28/07/05 – 08/12/05 obtained adopting 1 and 2 sand fractions.
6.4 Area modelling

The grid of the area model is shown in Figure 6.15. The grid covers an area of 6500 m by 1300 m, with a constant horizontal grid spacing of 40 m in longshore direction and 20 m in cross shore direction. The vertical σ-layers distribution has the highest resolutions at the bed and near the water surface, and is taken identical to that of the profile model. Modelling efforts with the area model have been limited to the period of 04/11/04 to 30/11/04.

The dataset of 04/11/04 only covers a relatively small area around the nourishment and the inner bar (see Figure 6.16). The initial model bathymetry has been constructed by using this dataset and completing it with the observed dataset from 30/11/04.

The bathymetric evolution of November 2004 at Egmond was dominated by longshore transport processes. The two north-westerly storms caused a southward migration of the entire complex of bars and troughs of approximately 500 metres. Furthermore, both the inner and outer bar migrated seaward.

Tidal boundary conditions and wave conditions are taken identical to those of the profile model. Other input parameters, such as the roller model and the morphological settings, are also derived from the optimum settings of the calibrated profile model.

Figure 6.18 shows the bathymetric evolution of the area model after the three wave conditions. These results show a promising resemblance with the observed bathymetric changes in November 2004. The behaviour of the inner bar in particular appears to be well predicted by the area model which shows the correct onshore and offshore migration of the bar in the right locations. The bars are however flattened out too much by the model. This effect may be reduced by applying the Ruessink et al. breaker formulation. The formation of rip-like instabilities along the shoreline is not realistic either and appears to be due to, among other things, an underestimation of the longshore current close to the shore.

A further analysis of the model results reveals that the performance of the model improves significantly if only the first wave condition (storm) is considered. The instabilities mostly develop during the calmer second and third wave condition. Figure 6.17 shows the bathymetric evolution after only the first condition. The bed level changes at deeper water (outer bar) are not very different from the full set of conditions, indicating that the calmer
conditions do not cause large bathymetric changes in deep water. Closer to the shore however, the results after just one condition look more realistic. This is mostly caused by the fact that the instabilities at shallow water become more prominent in the second and third condition.

Figure 6.15  Computation grid area model
Figure 6.16 Initial bathymetry: 4 November 2004 (left panel) and observed final bathymetry: 30 November 2004 (middle panel) and erosion/sedimentation (right panel).

Figure 6.17 Initial bathymetry: 4 November 2004 (left panel) and simulated final bathymetry using schematised wave climate: 30 November 2004 (middle panel) and erosion/sedimentation (right panel).
Figure 6.18  Initial bathymetry: 4 November 2004 (left panel) and simulated final bathymetry only using the storm wave condition (middle panel) and erosion/sedimentation (right panel).

The simulations with the 3D model have revealed two problems that prevented us from running the model over a period of longer than one month.

Firstly, the formation of the crescent-like shapes along the beach line grows out of control, in particular during the calmer wave conditions, which prevents long-term simulations. The focus of the area modelling has therefore mostly been on improving the behaviour of the beach line. These efforts have so far been unsuccessful, as the instabilities along the shore appear to be a very persistent feature.

Secondly, the area model has a tendency to flatten out the inner bar. This was also seen, but to a much lesser extent, in the simulations of the profile model.

The following conclusions can be drawn from the calibration of the area model:

- The crescent-like shapes occur both relatively calm conditions and in stormy conditions with waves that come in with a large angle of incidence (approximately 45 degrees) to the shore. In the calmer conditions, however, they grow larger, whereas the higher longshore velocities during the storm conditions smooth out the instabilities to some extent.
- The formation of instabilities does not occur in depth-averaged (2DH) simulations (not shown). This may be partially related to the fact that wave-driven longshore current velocities are somewhat higher in 2DH mode. Another important difference between the depth-averaged and fully 3D model is the way in which bed shear stresses are computed.
in both the hydrodynamic model and the sediment transport routines. As things stand now, this appears to be the main cause for the problems, and should therefore be investigated in more detail.

- An increase in longshore velocities, especially close to the shore, results in a smoother coast line. However, even in the case of unrealistically high longshore velocities (obtained by strongly decreasing the bed roughness) the rip-like features still occur.
- Long waves have an effect on the formation of the instabilities. In one set of simulations, a high frequency component \( (T = 120\, \text{s}, \text{amplitude} = 0.05\, \text{m}) \) was added to the offshore water level boundary conditions. This resulted in a much smoother coast line (in particularly during the storm condition), whereas the inner and outer bar were not strongly affected.
- The strong growth and offshore migration of the outer bar in the profile model does not show up in the area model and should be further looked into. There may also be a relation with the behaviour of the inner bar which is more flattened out in the 3D model than in the profile model.

### 6.5 Conclusions

There is a relatively large variation in cross-shore profiles in the alongshore direction. As a result, the bathymetric evolution of November 2004 at Egmond was dominated by longshore transport processes, which are not taken into account in the Delft3D profile model. This explains to a large extent the differences between the results of the area model and the profile model. However, the growth and offshore migration of the outer bar in the profile model cannot be explained by longshore gradients. Longshore transport gradients could damp the development of comparable bars in the 3D simulation. Further research is required to investigate the differences between the profile and 3D simulations.
Figure 6.19  Cross-shore profiles computed by the area model, the Delft3D profile model and Beach Wizard
6.6 Application

6.6.1 Introduction

To investigate the effects of various nourishment designs in the model, a longshore uniform bathymetry, representative for the Egmond region, was used as the basis for the construction of a number of hypothetical of shoreface nourishment designs. All predictions are compared.
with a reference simulation (Alternative case 0 top, Figure 6.23) and are made for a one-year period.

One of the nourishments (Alternative 2) described in the VOP 2004 report was re-investigated with the latest updates to TR2004 sediment transport relation. In the previous study, a schematised model for Egmond was set up with a longshore uniform bathymetry. As a typical beach profile the longshore averaged bottom profile from the Coast3D campaign was selected (see Figure 6.21 and Figure 6.22).

![Perspective plot of area model domain for Alternative 02: Nourishment height = -5 m, Length= 2000 m (Volume: 400 m$^3$/m)](image)

Figure 6.21  Perspective plot of area model domain for Alternative 02: Nourishment height = -5 m, Length= 2000 m (Volume: 400 m$^3$/m)

![Nourishment design Alternative 02: Nourishment height = -5 m (Volume: 400 m$^3$/m).](image)

Figure 6.22  Nourishment design Alternative 02: Nourishment height = -5 m (Volume: 400 m$^3$/m).

The nourishment designs are based on three nourishment designs all consisting of a volume of 400 m$^3$ per meter. The seaward slope has been set to 1:10. The following nourishment designs were considered:

- A nourishment against the seaward slope of the outer bar with the same height as the outer bar (-2.7 m, Alternative case 1, Figure 6.23 bottom).
- A nourishment against the seaward slope of the outer bar has been constructed by assuming construction height of -5 m (Alternatives case 2, Figure 6.24 top).
- Alternative case 4 constitutes the design in which the trough between the outer and inner bar is filled up (Figure 6.24 bottom).
These designs have been already applied in Walstra et al. (2004). However, the parameter settings were different. In this study, we use the model set-up previously, but applying the wave climate as defined in Walstra et al. (2004).

The wave climate applied by Van Duin et al. (2004) consists of 12 wave conditions which were reduced to four wave conditions (Table 6.4) to limit the computational effort (Walstra et al., 2004). The reduction is achieved by ensuring identical gross northward and southward transports by means of scaling the selected wave conditions. It was decided to select two storm and two moderate wave conditions from a south-westerly (224 °N) and north-westerly direction (334 °N).

Table 6.4 Wave climate from Walstra et al. (2004)

<table>
<thead>
<tr>
<th>Condition</th>
<th>H_s (m)</th>
<th>T_p (s)</th>
<th>Direction (°N)</th>
<th>Morphological Factor (MorFac)</th>
<th>acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>225H</td>
<td>2.75</td>
<td>8.3</td>
<td>224</td>
<td></td>
<td>11.14</td>
</tr>
<tr>
<td>225A</td>
<td>1.25</td>
<td>6.3</td>
<td>224</td>
<td></td>
<td>127.84</td>
</tr>
<tr>
<td>325H</td>
<td>2.75</td>
<td>9.5</td>
<td>334</td>
<td></td>
<td>8.83</td>
</tr>
<tr>
<td>325A</td>
<td>1.25</td>
<td>7.5</td>
<td>334</td>
<td></td>
<td>91.04</td>
</tr>
</tbody>
</table>

All model settings are identical to those applied previously to ensure a consistent application of the model with insights given by the analysis (comparison area/profile models).

The time step for the FLOW simulations was selected by having a courant number of approximately 10 (the courant number is a numerical stability criterion), and a time step of 6 seconds was used. The wave energy balance and roller energy balance which are solved in the FLOW model used a constant γ-expression (wave height to water depth ratio) of 0.7. Furthermore, the breaker delay parameterisation of Roelvink et al. (1995) was used. The FLOW model uses the k-ε turbulence closure model to include the effects of wave breaking on the turbulence levels.

The updated expressions of TRANSPOR2004 are used to calculate the sediment transports. Furthermore, the bed roughness predictor and the predictor for the diameter of the suspended sediment diameter, which are part of the TRANSPOR2004 formulations, are applied.

### 6.6.2 Profile modelling

The profile development of the reference case (Alternative case 0) displays a flattening of the profile without significant outer bar migration, either seawards or onwards (Figure 6.23). Such flattening is observed for all alternative cases considered (Figure 6.23 and Figure 6.24). In general, the profile development exhibits an onshore migration of the outer bar. Evolution in shallow waters (from 0 to 300 m) remains unrealistic.
Figure 6.23 Profile development after 1 year for a representative profile (alternative case 0) and 1 nourishment design (alternative case 1).

The volume changes in different sub-sections have been computed and are shown in Figure 6.25. The main changes occur in shallow waters, between 0 to 400 m from the Beach Pole. However, volume changes are in the same order when comparing results obtained for Alternative cases 0, 1 and 2. When designing the nourishment in which the trough between the outer and inner bar is filled up, differences with the reference case (alternative case 0) are more significant. In particular, sub-section 200-400 exhibits higher accretion. On the other hand, the volume loss increases in sub-section 400-600, compared to the reference case. The only case displaying a volume increase in both sub-sections 200-400 and 400-600 is the design with a nourishment against the seaward slope of the outer bar, constructed by assuming a height of -5 m (alternative case 2). Moreover, cumulative volume change, in sub-sections 200-400 and 400-600, is maximum when adopting this design (alternative case 2). Such increase is compensated by a volume loss in sub-section 600-800. In deeper waters, the profile developments display similar behaviour for all cases.

Alternative case 2 suggests an on-going development as follows: the nourished sub-section between 600 and 800 m from the Beach Pole seems splitting in two parts, developing the outer bar at approximately 700 m from the beach pole, and feeding the inner bar, which might shift seawards as well, at 300-400 m from the Beach Pole. Such development is typical of a shoreface nourishment, protecting the coast by increasing volumes in the upper part of the beach.
Figure 6.24  Profile development after 1 year for 2 nourishment designs (alternative cases 2 and 4).

Figure 6.25  Volume changes in sub-sections defined from the Beach Pole position. Dark blue, light blue, yellow and red display results for Alternative cases 0, 1, 2 and 4, respectively.
This application suggests that the appropriate design would be considered by nourishing the seaward slope of the outer bar with a height of -5 m (alternative case 2). Moreover, such design is financially the least expensive, compared to alternative cases 1 and 4. Anyway, the results have to be considered with care, as the calibration/validation analysis showed the limits of applying Delft3D as a profile model.

6.6.3 Area modelling

The initial and final bathymetries are shown in for the reference situation (without a nourishment) are shown in Figure 6.26. The initial and final bathymetry of the case with a nourishment can be seen in Figure 6.27. After one year, the nourishment has diffused considerably and the effect on the outer bar is very limited. However, shoreward of the outer bar the nourished alongshore section has experienced considerable sedimentation. After one year the alongshore position of the nourishment has not changed significantly. The outer bar is more or less alongshore uniform after one year. Although there is a northward residual transport, the nourishment is fairly stable in alongshore direction and is mainly diffused.

![Figure 6.26](image-url) Initial bathymetry (left panel), computed final bathymetry (middle panel) and computed erosion/sedimentation (right panel) of schematised model without nourishment
Figure 6.27  Initial bathymetry (left panel), computed final bathymetry (middle panel) and computed erosion/sedimentation (right panel) of schematised model with nourishment (Alternative 2)

Initial and final cross-shore profiles along the central cross-section (middle of the nourished area) for the cases with and without nourishment are shown in Figure 6.28. The nourishment has resulted in the development of an extra bar, the seaward extent of the nourishment has formed a bar and at the position of the original outer bar again a bar is present. This behaviour is in qualitative agreement with the observed development of the shoreface nourishment at Egmond (Van Duin et al., 2004; Spanhoff et al., 2004).

The sedimentation-erosion patterns for the area model are shown in Figure 6.29. These bottom changes have been averaged over the indicated rectangular areas. The left and central plot show the bottom changes for the cases without and with the nourishment. In the right-hand plot the relative bottom changes due to the nourishment are show (these have been obtained by subtracting the values in the left-hand plot from the values in the central plot). The absolute bottom change patterns of Alternative 2 are comparable to those of the reference situation, but the relative bottom changes clearly reveal the sediment trapped behind the nourishment. This effect benefits the complete upper part of the profile that is protected by the nourishment. Beyond the distal ends some limited erosion occurs. The sedimentation in areas seaward of the nourishment indicates that some of the nourished sand has moved offshore. In the model domain, the overall effect of the nourishment seems positive: the protected beach area clearly benefits, whereas the up- and downdrift erosion is limited.
Figure 6.28 Initial and final computed beach profiles with and without nourishment

Figure 6.29 Absolute sedimentation-erosion for the case without a nourishment (left plot) and with a nourishment (central plot) and sedimentation-erosion relative to the reference situation (right) for Alternative 02.
7 References


Van Dongeren et al., 2007. Beach Wizard: nearshore bathymetry estimation through assimilation of model computations and remote observations. submitted to Coastal Engineering


