Three-line modelling of the Terschelling supply

October 1996

M.D. Groenewoud

lower zone middle zone upper zone
ABSTRACT

In the framework of the NOURTEC project experimental nourishments have been executed. The NOURTEC project is an EU-research project in the scope of the program for Marine Science and Technology (Mast II). NOURTEC stands for Innovative Nourishment Techniques Evaluation. Full-scale experiments have been carried out in three different countries (Denmark, Germany and the Netherlands). Different nourishment techniques have been applied (i.e. shoreface nourishments and beach nourishments).

In the period May to November 1993 a shoreface nourishment was carried out at the coast of Terschelling (the Netherlands). An extensive monitoring program has accompanied this exercise.

This study is about the simulation of the evolution of the nourishment with a three-line model. The basic idea of line modelling is that the magnitude of cross-shore transport is proportional to the deviation from the equilibrium shape of the cross-shore profile. For the modelling the cross-shore profile is schematised in zones. Each zone is characterised by a line which represents the sediment volume of the zone. Also longshore dispersion is taken into account. Coastal constants which quantify the magnitude of transport in cross and longshore direction have been determined. For that purpose use was made of the available wave and bathymetric data.

A study was made of the behaviour of the coast prior to the nourishment. The autonomous behaviour was taken into account for determining the shoreface nourishment behaviour.

A comparison between measured development and calculations with the three line-model shows that there are similarities but also considerable differences. One of the difficulties is how to distinguish between autonomous profile development and profile development caused by the nourishment.

The behaviour of the nourishment is partly understood by the model runs. The calculated development of the upper zone is very similar to the measured development. The results for the middle zone are less good. The three-line model will in principle predict symmetrical profile development in longshore direction in case of an alongshore symmetrical supply. From observations it is clear that the nourishment is moving eastward. This can not be modelled with the present three-line model. The differences between measured and calculated development in the lower zone are also considerable.

The research has yielded an increased insight in the complex behaviour of the shoreface nourishment along the coast of Terschelling.
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS

ABSTRACT

TABLE OF CONTENTS

LIST OF SYMBOLS

1. Introduction .................................................. 1

2. Description of the Terschelling case .................. 3

3. Three-line modelling ......................................... 7
   3.1 Introduction .............................................. 7
   3.2 Principles of three-line modelling ................. 7
   3.3 Numerical solution ..................................... 14
   3.4 Schematization of the Terschelling case ........ 16
      3.4.1 Introduction ...................................... 16
      3.4.2 Methods of calculation of zone volumes .... 16
      3.4.3 Choice of the position of the zones ....... 19

4. Bathymetric data .............................................. 21
   4.1 Introduction ............................................ 21
   4.2 Use of the measurements ............................. 21
   4.3 NOURTEC measurements ............................... 23
      4.3.1 Introduction ..................................... 23
      4.3.2 Development y-values in the different boxes . 23
      4.3.3 General evaluation .............................. 30
   4.4 JARKUS measurements .................................. 31
      4.4.1 Introduction ..................................... 31
      4.4.2 Development y-values in the different boxes . 31
      4.4.3 Effect of periodicity of the bar system on analysis 38
      4.4.4 Profile development landward of NAP +3 m border 41
   4.5 General evaluation .................................... 45

5. Longshore coastal constants ................................ 47
   5.1 Introduction ............................................ 47
   5.2 Principles of transport computation ............... 47
      5.2.1 Assumptions ....................................... 47
      5.2.2 CERC transport formula ........................ 48
      5.2.3 Refraction ........................................ 48
      5.2.4 Distribution of sand transport capacity over the depth 50
      5.2.5 Computation of breaker depth and wave height 50
   5.3 Application for the Terschelling case ............. 51
6. Cross-shore coastal constants 55
   6.1 Introduction 55
   6.2 Cross-shore constants 55
   6.3 Correction measured development for autonomous behaviour 56
      6.3.1 Correction upper zone development 56
      6.3.2 Correction middle and lower zone development 57
   6.4 Determination of the cross-shore constants 60

7. Results 67
   7.1 Introduction 67
   7.2 Nourishment behaviour 67
   7.3 Comparison measurements and three-line model calculations 69
      7.3.1 Introduction 69
      7.3.2 Comparison measured versus calculated situation after two years 69
      7.3.3 Comparison measured versus calculated development 72
   7.4 Conclusions 76

REFERENCES

APPENDIX A  Flow diagram and listing 3LINES computer program
APPENDIX B  Flow diagram and listing CERC computer program
LIST OF SYMBOLS

c  wave celerity (m/s)
d_1  depth of separation plane between upper and middle zone (m)
d_2  depth of separation plane between middle and lower zone (m)
d_3  depth of lower border of lower zone (m)
D_{50}  characteristic particle size (50% by weight is finer) (mm)
E  wave energy per square m of surface (J/m^2)
g  acceleration of gravity (m/s^2)
h_1  height of upper zone (m)
h_2  height of middle zone (m)
h_3  height of lower zone (m)
h_b  breaker depth (m)
H_{sig}  significant wave height (m)
H_{rms}  root-mean-square wave height (m)
i  counter of steps in x-direction (-)
j  number of zone (-)
k  wave number (m^-1)
L  wave length (m)
L_1  characterising mean line of the upper zone (m)
L_2  characterising mean line of the middle zone (m)
L_3  characterising mean line of the lower zone (m)
n  counter of time steps (-)
n_b  ratio group velocity/phase velocity at the breaker line (-)
S_1  longshore transport in the upper zone (m^3/year)
S_2  longshore transport in the middle zone (m^3/year)
S_3  longshore transport in the lower zone (m^3/year)
S_{y1}  cross-shore transport from upper to middle zone (m^3/m/year)
S_{y2}  cross-shore transport from middle to lower zone (m^3/m/year)
s_1  longshore coastal constant upper zone (m^3/year/rad)
s_2  longshore coastal constant middle zone (m^3/year/rad)
s_3  longshore coastal constant lower zone (m^3/year/rad)
s_{y1}  cross-shore coastal constant quantifying transport upper to middle zone (m/year)
s_{y2}  cross-shore coastal constant quantifying transport middle to lower zone (m/year)
\Delta t  time step (year)
T  wave period (s)
T_0  time scale of diffusivity (year)
\Delta x  stepsize in x-direction (m)
x  coordinate along the coast (m)
y_1  distance to initial equilibrium position of line 1 (upper zone) (m)
y_2  distance to initial equilibrium position of line 2 (middle zone) (m)
y_3  distance to initial equilibrium position of line 3 (lower zone) (m)
y(z)  distance of profile to a reference line (m)
z  vertical position (m)
\phi_0  angle of wave approach at deep water (degrees)
\phi_b  angle of wave approach at breaker line (degrees)
\rho  density of water (kg/m^3)
CHAPTER 1  INTRODUCTION

Experimental nourishments have been executed in the framework of the NOURTEC project. NOURTEC stands for Innovative Nourishment Techniques Evaluation. The NOURTEC project is an EU-research project in the scope of the program for Marine Science and Technology (Mast II). These nourishments have been executed in three countries.

The projects and dates of execution are:

- Terschelling (the Netherlands)    May 1993- November 1993
- Torsminde Tange (Denmark):        March 1993- June 1993
- Norderney (Germany)               May 1992- June 1992

Extensive monitoring and modelling programmes have been executed. Results are presented in various NOURTEC reports.

This study is about the application and calibration of a three-line model for the Terschelling case. At the island of Terschelling a shoreface nourishment has been executed with a total volume of 2.1 million m$^3$. Chapter 2 gives a description of the project area of Terschelling.

With the three-line model the behaviour of the nourishment is simulated. The basic idea of line modelling is that the magnitude of cross-shore transport is proportional to the deviation from the equilibrium shape of the cross-shore profile. Also dispersion in longshore direction is taken into account. Chapter 3 describes the theory behind the three-line model.

Chapter 4 discusses the available bathymetric data of Terschelling and its interpretation. The trends in profile development before and after the nourishment have been investigated.

An important goal of this study is the determination of coastal constants used in the model which quantify the magnitude of transport in longshore and cross-shore direction. Chapter 5 and Chapter 6 discuss the derivation of respectively the longshore and the cross-shore coastal constants.

The three-line model calculations have been compared with the bathymetric data of Terschelling. The results of this comparison are discussed in Chapter 7.
CHAPTER 2 DESCRIPTION OF THE TERSCHELLING CASE

The Dutch Wadden island of Terschelling is a barrier island located at the north of the Netherlands (see Fig. 2.1). The island is WSW-ENE oriented. The study site is located north of the island between RSP 10 km and RSP 22 km (see Fig. 2.1). RSP refers to the Dutch beach pole system. The northern coast is exposed to the North Sea and consists of dunes and beaches. The nearshore zone is characterised by 2 or 3 parallel breaker bars. To the northwest of the island a large field of sandwaves is present. The sandwaves have an amplitude up to 1.5 m and decrease in size in eastward direction (around RSP 15 km). The wave length of the sandwaves is approximately 1 km.

The tides in this study area are semi-diurnal and their tidal range is between 1.6 m (neap) and 2.1 m (spring). The eastward directed flood tidal currents are generally stronger than the ebb tidal currents.

The average significant wave height is in the order of 1.5 m and has a period of approximately 8 s (Hoekstra et al., 1994).

The median grain sizes vary from 0.22 mm to 0.26 mm at the intertidal beach, decreasing to 0.15-0.16 mm at the lower shoreface. A strong correlation exists between morphology and grain size. Sediment on the crest of a bar is generally coarser than in the trough of a bar (Guillén, 1995).

Fig. 2.1 Map of the Netherlands and Terschelling with the study area. The nourishment is located between RSP 13.6 km and RSP 18.2 km.
The Dutch government instituted in 1990 a coastal defence policy for dynamic conservation of the Dutch coastline (Rijkswaterstaat, 1990). This policy is based on the concept of a standard reference coastline beyond which no erosion is acceptable. The shoreline of Terschelling shows an erosive trend of about 1-5 m/yr during the period 1982-1991 (Noordstra, 1992). The shoreline erosion corresponds to a loss of approximately 110,000 m³/year in the project area (RSP 13.6 - RSP 18.3) (NOURTEC, 1994).

The erosion of the coastline of Terschelling forced the Dutch coastal authority (Rijkswaterstaat) to take measures. It was decided to perform a shoreface nourishment as a full-scale trial of this form of coast protection method.

In the period of May to November 1993 an amount of 2.1*10⁶ m³ of sand was placed between the outer two breaker bars of the three-bar system. The placement of the nourishment in a typical cross-shore profile is shown in Fig. 2.2. The surface of the nourishment is approximately at NAP -5 m. The grain size of the nourishment is slightly coarser (D₅₀ = 0.20 mm) than the native sand at the nourishment location (D₅₀ = 0.18 mm). The length of the nourishment is approximately 4.6 km; the nourishment stretches from RSP 13.6 km to RSP 18.2 km (see Fig. 2.1).

The area has been levelled twice in detail before the nourishment was executed (dates: February 11-15, 1993 and May 19, 1993). After the nourishment the monitoring has continued. (Since 1965 yearly measurements are available of cross-shore profiles at 200 m mutual distance along the entire Terschelling coast).

![Cross-shore profiles before and after execution of the nourishment at RSP 17 km.](image-url)
Various types of measurements have been carried out like bathymetric measurements, wave height measurements, sediment samplings etc. The results and interpretation of these measurements can be read in the various NOURTEC reports. This study will also make use of the performed measurements in applying the three-line model to the Terschelling case.

The available bathymetric data will be discussed in more detail in Chapter 4.
CHAPTER 3 THREE-LINE MODELLING

3.1 Introduction

In this chapter the theory behind n-line modelling will be explained. This will be done for a three-line model. The theory of a three-line model can be extended to a multiple-line model. The principles of three-line modelling will be discussed in Section 3.2. A numerical solution of the set of equations derived in Section 3.2 will be presented in Section 3.3. A computer model called 3LINES is based on that numerical scheme (see Appendix A). Section 3.4 discusses the application of the model for the Terschelling case.

3.2 Principles of three-line modelling

In the three-line model the cross-shore profile is schematised in three zones with horizontal separation planes (Fig. 3.1). It is assumed that in each zone the mutual distances of the boundary depths remain constant and thus that the profile of a zone only moves horizontally. It is thus sufficient to compute only an average line in each zone because it characterises the actual profile in this zone.

The cross-shore sediment transport rate between the zones is assumed to be proportional to the difference between the equilibrium distances and the actual distances between the characterising lines.

In literature like Smit (1987) or Bakker (1969) these characterising lines each have a distance to a reference line which can be defined as:

\[ L_i = \frac{1}{h_i} \int_{-d_i}^{0} y(z) dz \] (3.1)

\[ L_2 = \frac{1}{h_2} \int_{-d_2}^{-d_1} y(z) dz \] (3.2)

\[ L_3 = \frac{1}{h_3} \int_{-d_3}^{-d_2} y(z) dz \] (3.3)
The parameters in Eqs. 3.1, 3.2 and 3.3 (see also Fig. 3.1) mean:

\[ d_1 = \text{depth of separation plane between zone 1 and 2} \]
\[ d_2 = \text{depth of separation plane between zone 2 and 3} \]
\[ d_3 = \text{depth of lower limit of zone 3} \]
\[ h_1 = \text{height of zone 1} \]
\[ h_2 = \text{height of zone 2} \]
\[ h_3 = \text{height of zone 3} \]
\[ L_1 = \text{characterising mean line of upper zone} \]
\[ L_2 = \text{characterising mean line of middle zone} \]
\[ L_3 = \text{characterising mean line of lower zone} \]
\[ y(z) = \text{distance of point of profile to a reference line} \]
\[ z = \text{height above the } y\text{-axis} \]

The same principle but with another schematization is used in this study. To simplify the equations, other reference axes have been used to avoid the use of the equilibrium distances (Smit, 1987). Instead of the distances \( L_1, L_2 \) and \( L_3 \) of the lines to a reference axis, use has been made of the distances \( y_1, y_2 \) and \( y_3 \) to the lines of the equilibrium profile. The differences \( (L_1-L_2) \) and \( (L_2-L_3) \) to the equilibrium distances between the lines now have been replaced respectively by the differences \( (y_2-y_1) \) and \( (y_3-y_2) \) (see Fig. 3.2).
Fig. 3.2  
**Cross-section and plan view of the three-line schematization.**

The parameters of Fig. 3.2 mean:

- \( S_1 \) = longshore transport in the upper zone
- \( S_2 \) = longshore transport in the middle zone
- \( S_3 \) = longshore transport in the lower zone
- \( S_{xy} \) = cross-shore transport from the upper to the middle zone
- \( S_{yz} \) = cross-shore transport from the middle to the lower zone
- \( y_1 \) = distance to the initial equilibrium position of the upper zone
- \( y_2 \) = distance to the initial equilibrium position of the middle zone
- \( y_3 \) = distance to the initial equilibrium position of the lower zone

In theory an initial position (before any nourishment takes place) is assumed where the lines \( L_1, L_2, L_3 \) are straight, parallel to the y-axis and where the zones are in equilibrium position (Fig. 3.3.a).

A disturbance of the equilibrium profile (Fig 3.3.b), for instance by a shoreface nourishment, will cause an equilibrium profile re-establishing transport (Fig 3.3.c). Distances \( y_1, y_2 \) and \( y_3 \) are the deviations of the lines of the three zones compared to their initial position. Finally the profile will have a (shifted) equilibrium shape where \( y_1 = y_2 = y_3 \) (Fig 3.3.d). When \( y_1 = y_2 = y_3 \) the differences \( (y_2 - y_1) \) and \( (y_3 - y_2) \) are both zero and no resulting cross-shore transport is assumed to occur anymore.
In order to derive the equations for the development of the three lines first the effect of cross-shore transport and later on the influence of longshore transport will be taken into account.

**Cross-shore transport**

If the transport rates $S_{y_1}$ and $S_{y_2}$ (see Fig. 3.2) are assumed to be proportional to the differences $(y_1 - y_2)$ for $S_{y_1}$ and $(y_2 - y_3)$ for $S_{y_2}$, then the following equations can be written:

$$S_{y_1} = s_{y_1} (y_1 - y_2) \quad (3.4)$$

$$S_{y_2} = s_{y_2} (y_2 - y_3) \quad (3.5)$$

with:

- $S_{y_1}$ = cross-shore transport from the upper to the middle zone [$m^3/m/year$] (positive in seaward direction)
- $S_{y_2}$ = cross-shore transport from the middle to the lower zone [$m^3/m/year$] (positive in seaward direction)
- $s_{y_1}$ = cross-shore coastal constant [m/year]
- $s_{y_2}$ = cross-shore coastal constant [m/year]
Ignoring the effect of longshore transport for the time being, continuity gives:

\[ y_1 h_1 + y_2 h_2 + y_3 h_3 = \text{constant} \]  
(3.6)

with:

\[ S_{y1} = -h_1 \frac{dy_1}{dt} \]  
(3.7)

\[ S_{y2} = +h_2 \frac{dy_2}{dt} \]  
(3.8)

Substitution of \( S_{y1} \) and \( S_{y2} \) yields:

\[ \frac{dy_1}{dt} \bigg|_{\text{cross}} = -\frac{s_{y1}}{h_1} (y_1 - y_2) \]  
(3.9)

\[ \frac{dy_2}{dt} \bigg|_{\text{cross}} = -\frac{s_{y2}}{h_2} (y_2 - y_3) + \frac{s_{y1}}{h_2} (y_1 - y_2) \]  
(3.10)

\[ \frac{dy_3}{dt} \bigg|_{\text{cross}} = \frac{s_{y2}}{h_3} (y_2 - y_3) \]  
(3.11)

The use of Eqs. 3.9, 3.10 and 3.11 relies on proper estimates of the coastal constants \( s_{y1} \) and \( s_{y2} \) (see Chapter 6 for a discussion on estimates of these constants).

**Longshore transport**

For a description of the basic ideas of effects of gradients in longshore transport on coastal dynamics reference is made to, for instance, Bakker (1969). The ideas originate from Bossen and were first published by Pelnard Considère (1954), who gave experimental support to them by experiments. Because the matter is of crucial importance for understanding the present report, the outline will be given below.

As the principle holds for as well \( S_1, S_2 \) and \( S_3 \), in this summary the longshore transport will be characterised by the symbol \( S_x \) and the subscripts of \( h_1, h_2, \) and \( h_3 \) will be omitted.

For the effect of a gradient in longshore transport Bakker uses the following equation of continuity:

\[ \frac{\partial S_x}{\partial x} + h \frac{\partial y}{\partial t} = 0 \]  
(3.12)

with \( h \) as the thickness of the layer over which erosion or accretion takes place. The gradient of sediment transport \( (\partial S_x/\partial x) \), determining the changes of the coastline, is mainly due to changes in wave height or in angle of wave approach \( \varphi \) (Fig. 3.4) along
Fig. 3.4  Definition of angle of wave approach.

the coast. The coast is curved; the cross-shore profiles are assumed to be equilibrium profiles.

The wave climate is assumed to be constant along the coast. The change of angle of wave approach therefore determines the gradient in longshore transport. With small changes of the angle, the longshore transport is assumed to depend linearly on the angle of wave approach.

\[
\frac{\partial S_x}{\partial \varphi} = s_x \tag{3.13}
\]

with:

\( s_x \) = longshore coastal constant

The chain rule gives:

\[
\frac{\partial S_x}{\partial x} = \frac{\partial S_x}{\partial \varphi} \frac{\partial \varphi}{\partial x} \tag{3.14}
\]

Substitution of Eq. 3.14 in Eq. 3.12 yields:

\[
\frac{\partial S_x}{\partial \varphi} \frac{\partial \varphi}{\partial x} + h \frac{\partial y}{\partial t} = 0 \tag{3.15}
\]

For the gradient \( \frac{\partial S_x}{\partial \varphi} \) the constant \( s_x \) can be substituted. Assuming small angles:

\[
s_x \frac{\partial}{\partial x} (\varphi) = s_x \frac{\partial}{\partial x} (-\frac{\partial y}{\partial x}) = -s_x \frac{\partial^2 y}{\partial x^2} \tag{3.16}
\]

The resulting equation then becomes:

\[-s_x \frac{\partial^2 y}{\partial x^2} + h \frac{\partial y}{\partial t} = 0 \tag{3.17}\]
The change of the position of the coastline \((\partial y/\partial t)\) thus appears to be proportional to the curvature of the coastline. This also applies if the profile is divided into several zones. The equations for the zones then become:

\[
\frac{dy_1}{dt}_{\text{long}} = \frac{s_1}{h_1} \frac{\partial^2 y_1}{\partial x^2} \tag{3.18}
\]

\[
\frac{dy_2}{dt}_{\text{long}} = \frac{s_2}{h_2} \frac{\partial^2 y_2}{\partial x^2} \tag{3.19}
\]

\[
\frac{dy_3}{dt}_{\text{long}} = \frac{s_3}{h_3} \frac{\partial^2 y_3}{\partial x^2} \tag{3.20}
\]

with:

\[
s_1, s_2 \text{ and } s_3 = \text{longshore coastal constants}
\]

The following remarks on this derivation should be made:

- The assumption of unidirectional waves is not essential (in some way). If one assumes that the longshore transport depends on \((-\partial y/\partial x)\), the same result is obtained.
- In anticipation on Chapter 5, it is pointed out, that refraction of the waves on the deeper part (not taken into account in the considerations above) is neglected.

Combination of both physical processes with linear addition gives:

\[
\frac{dy_1}{dt} = \frac{s_1}{h_1} \frac{\partial^2 y_1}{\partial x^2} - \frac{s_{y1}}{h_1} (y_1 - y_2) \tag{3.21}
\]

\[
\frac{dy_2}{dt} = \frac{s_2}{h_2} \frac{\partial^2 y_2}{\partial x^2} + \frac{s_{y1}}{h_2} (y_1 - y_2) - \frac{s_{y2}}{h_2} (y_2 - y_3) \tag{3.22}
\]

\[
\frac{dy_3}{dt} = \frac{s_3}{h_3} \frac{\partial^2 y_3}{\partial x^2} + \frac{s_{y2}}{h_3} (y_2 - y_3) \tag{3.23}
\]

In these equations the longshore transport is determined by the constants \(s_1, s_2 \text{ and } s_3\) and the direction of the coast. The cross-shore transport is determined by the constants \(s_{y1} \text{ and } s_{y2}\) and the deviation from the equilibrium position. These three equations determine the development of \(y_1, y_2 \text{ and } y_3\) in time and position along the coast.
3.3 Numerical solution

In order to make a computer program based on this theory a numerical solution had to be found. The derivation of this numerical scheme is explained in this section. The numerical method used is: 'Euler explicit', a Time Forward, Central Space method. A system of three coupled partial equations is to be solved:

$$\frac{\partial Y_i}{\partial t} = A \frac{\partial^2 Y_i}{\partial x^2} + B Y_i$$

(3.24)

with:

$$Y_i = \begin{pmatrix} y_{i,1} \\ y_{i,2} \\ y_{i,3} \end{pmatrix}$$

(3.25)

with:

- $i = \text{number of steps } \Delta x \text{ along the coast (see Fig. 3.5)}$
- $1,2,3 = \text{number of zone}$

and

$$A = \begin{pmatrix} \frac{s_1}{h_1} & 0 & 0 \\ 0 & \frac{s_2}{h_2} & 0 \\ 0 & 0 & \frac{s_3}{h_3} \end{pmatrix}$$

(3.26)

and

$$B = \begin{pmatrix} -\frac{s_{y1}}{h_1} & \frac{s_{y1}}{h_1} & 0 \\ \frac{s_{y1}}{h_2} & -\left(\frac{s_{y1} + s_{y2}}{h_2}\right) & \frac{s_{y2}}{h_2} \\ 0 & \frac{s_{y2}}{h_3} & -\frac{s_{y2}}{h_3} \end{pmatrix}$$

(3.27)

Matrix A contains the longshore constants and matrix B contains the cross-shore constants.
Fig. 3.5  Definition of counter i and step size Δx.

The differentials can be approximated by:

\[
\frac{\partial y_i}{\partial t} = \frac{y_i^{n+1} - y_i^n}{\Delta t}.
\]  \hspace{1cm} (3.28)

\[
\frac{\partial^2 y_i}{\partial x^2} = \frac{y_i^{n+1} - 2y_i^n + y_i^{n-1}}{\Delta x^2}.
\]  \hspace{1cm} (3.29)

Substitution of Eq. 3.28 and Eq. 3.29 in Eq. 3.24 gives:

\[
\frac{y_i^{n+1} - y_i^n}{\Delta t} = A^* \left( \frac{y_i^{n+1} - 2y_i^n + y_i^{n-1}}{\Delta x^2} \right) + B^* Y_i^n
\]  \hspace{1cm} (3.30)

with:

\[
Y_i^n = \begin{pmatrix} y_{i,1} \\ y_{i,2} \\ y_{i,3} \end{pmatrix}
\]  \hspace{1cm} (3.31)

An expression can be derived for each y-value at x = (i*Δx) at the next moment t = (n+1)*Δt. This results for the zones j = 1, 2 and 3 in:

\[
y_{i,j}^{n+1} = \left[ y_{i,j} + \Delta t * \left( B^* Y_{i,j} \right) + a_{ii} * \frac{\Delta t}{\Delta x^2} * \left( y_{i-1,j} - 2y_{i,j} + y_{i+1,j} \right) \right]^{n+1}
\]  \hspace{1cm} (3.32)

with:

\[ a_{ii} = \text{element of matrix A (see Eq. 3.26) } \]
For each equation there is a stability criterion:

\[
\frac{a_y \Delta t}{\Delta x^2} < \frac{1}{2}
\]  

(3.33)

The accuracy is sufficient if:

\[
\frac{a_y \Delta t}{\Delta x^2} < \frac{1}{6}
\]  

(3.34)

This restriction has been used in the three-line computer program 3LINES (a flow diagram and a listing can be found in Appendix A). This program computes the behaviour of the nourishment with the use of the equations mentioned above. The program has been written in Turbo Pascal 7.0 by Bakker and Kersting. Chapter 5 and 6 are about the determination of the constants used in the program.

3.4 Schematization of the Terschelling case

3.4.1 Introduction

For the use of the three-line model a decision has to be made about the positions of the borders of the different zones. The choice of the position of the borders depends on the bathymetry at the nourishment site.

The cross-shore profiles at the nourishment site are characterised by a three-bar system. The method of calculation of the volumes effects the choice of the position of the borders of the zones. This will be explained in the next section. Section 3.4.3 will discuss the choice of the positions of the borders for the Terschelling case.

3.4.2 Methods of calculation of zone volumes

Two methods of volume calculations will be discussed in this section. The first method is a commonly used method of calculation. This method (referred to as method 1) has some disadvantages in case of a bar-system. Therefore a different method of calculation has been used. This method (referred to as method 2) uses a different definition of the volumes of the zones.

Fig. 3.6 shows a (fictitious) cross-shore profile that is comparable to the profiles at Terschelling. The cross-shore profile is schematized in three zones. Volume area A through E represent sediment volumes beneath the profile. Volume area W represents a volume of water. By means of this cross-shore profile the two different methods of calculation will be explained.
Fig. 3.6  Fictitious cross-shore profile.

**Method 1**

One of the possibilities is to calculate exactly the amount of sand between two horizontal borders. Calculation of the volumes of the three zones would result in:

Volume upper zone = A + C
Volume middle zone = B + D
Volume lower zone = E

This method of calculation of the volumes in the three zones has disadvantages. For instance when sediment moves from volume area C (see Fig. 3.6) to the landward trough this results in a decrease of the upper zone volume and an increase of the middle zone volume. This would give the impression that sediment has moved offshore although in reality sediment has moved in onshore direction.

To avoid this false interpretation a different method will be used for the analysis of the volumes of the zones. This method will be discussed next.

**Method 2**

This method uses different definitions of the volumes of the zones. Each zone will be discussed separately.

**Upper zone**

The volume of the upper zone is defined as the volume between its two horizontal borders from an inland reference axis to the *most landward crossing* with the lower border of the upper zone. In Fig. 3.6 this would be volume area A.

Volume upper zone = A
**Middle zone**

The volume of the middle zone is not only defined as the volume of sediment between its upper and lower border (volume area $B + D$); the total profile between the most landward crossing of the profile with the upper border and the most seaward crossing of the profile with the lower border is reckoned to be a part of the middle zone system. Therefore the volume of sediment that exceeds the upper border of this zone between those two limits is also included (volume area $C$). Likewise the volume of water (read: absence of sediment) beneath the lower border of the middle zone and between those limits (volume area $W$), is substracted from the volume of the middle zone.

$$\text{Volume middle zone} = B + D + C - W$$

**Lower zone**

The volume of the lower border is defined as the volume between its two horizontal borders from an inland reference axis to the most seaward crossing with its lower border.

The volume of water of volume area $W$ is added to volume $E$ of the lower zone. This implies that the size of volume area $W$ does not affect the volume of the lower zone. A change in volume of water $W$ does not affect the sum of $E + W$. The volume of water $W$ (read: absence of sediment) is already taken into account in the middle zone.

$$\text{Lower zone} = E + W$$

This method of definition of zone volumes has the advantage that if the sediment transport remains between the described limits of the middle zone, no change in volume of the three zones takes place. If for instance sediment moves from area $C$ to the trough landward, it will not lead to a decrease of the upper zone. The volume of the middle zone remains constant. Likewise if sediment moves from the middle bar to the trough seaward it does not change the volume of the middle zone. The sediment is still part of the same (partial) system.

The coastal profile is divided in a beach zone (upper zone), a zone characterised by bars (middle zone) and a zone seaward of those bars (lower zone).

**Positions of the horizontal borders**

For this method the choice of the levels of the borders between the different zones is very important. This will be explained by the following example.

Fig. 3.7 shows a part of the profile of Fig. 3.6, viz. the middle and the lower zone. Fig. 3.7a shows the situation where the outer bar exceeds the level of the border between the middle and the lower zone. The volume area of the middle zone is: $B + D - W$. The volume area of the lower zone is: $E + W$.

If the top of the outer bar does not reach the level of the border between middle and lower zone a larger part of the profile would be added to the lower zone. Fig. 3.7b shows this schematically. Due to the definition of the zones the calculated volumes
will be totally different. The volume of the lower zone suddenly becomes much less because of the absence of volume area W. The value of the middle zone will increase strongly because the volume of water W is no longer substracted from the total volume of the middle zone.

It is therefore necessary that either the top of the outer bar is always above this horizontal border or always below this horizontal border. Otherwise it is not useful to use this method.

A similar problem can occur for the middle and the upper zone. However the most landward bar is in general much smaller than the two seaward bars and therefore the effect of the position of the border between middle and upper zone will also be smaller.

3.4.3 Choice of the position of the zones

The available profiles have been studied and it was decided to take NAP -3 m and NAP -6 m as the borders between the zones. As an example of this schematization the zones are plotted with two cross-shore-profiles (RSP 17: before and after execution of the nourishment, Fig 3.8).

The upper zone ranges from NAP +3 m to NAP -3 m, the middle zone ranges from NAP -3 m to NAP -6 m and the lower zone ranges from NAP -6 m to NAP -9 m.

The shoreface nourishment was placed in the outer trough between NAP -5 m and NAP -7 m. Due to the used definition of the zones the shoreface nourishment is entirely located in the middle zone. In fact this was one of the main arguments for the present selection of the zones.

The top of the outer bar almost always exceeds the NAP -6 m level. There were very few cases where the top a of the outer bar did not reach the level of NAP -6 m. These cases c.q. measurements were not taken into account for examining of the measured profile behaviour (see Chapter 4). In this way the middle zone always reaches until a point seaward of the top of the outer bar.

With this schematization the small inner bar is in most cases part of the upper zone.
Fig. 3.8  Position of the borders between the zones for the Terschelling case.

The division into three zones happens to be the same division as Kersting used in his forecast study of the Terschelling supply (Kersting, 1995a). His results can therefore directly be compared with the results of this study.
CHAPTER 4 BATHYMETRIC DATA

4.1 Introduction

In order to get insight in the behaviour of the nourishment bathymetric measurements have been carried out. The bathymetric measurements of the nearshore zone are carried out by vessels of Rijkswaterstaat. Depths along predetermined survey lanes are measured using digital acoustic depth sounders. The sampling density of the equipment can be as high as seven points per lineal meter. The survey area is located between RSP 10 km and RSP 22 km. The measuring lanes extend approximately 2000 m offshore and are perpendicular to the coast. The spacing of the lanes is 200 m with a smaller spacing of 25 to 100 m in the nourishment area. The beach elevation is measured using an electronic measuring device. Landward the surveys extend at least to the dune foot. These measurements are referred to as the NOURTEC measurements.

Similar measurements have already been executed since 1965: the so-called JARKUS measurements. These yearly coastal profile measurements are performed along the entire Dutch coast. The spacing of the lanes is 200 m at Terschelling. The measurements mostly extended less far offshore than the NOURTEC measurements. The JARKUS measurements of Terschelling will be used to study the behaviour prior to the nourishment.

Section 4.2 explains how both the NOURTEC and the JARKUS have been analysed to calibrate the three-line model. In Section 4.3 the results of the analysis of the NOURTEC measurements will be discussed. Section 4.4 will discuss the results of the analysis of the JARKUS measurements. Section 4.5 presents a general evaluation of the analysis of the bathymetric data.

4.2 Use of the measurements

The measurements were used to calculate the development of the y-values in time. For that purpose the coast around the nourishment was divided in 8 stretches of 1.2 km length. Each stretch of 1.2 km length is represented by a letter (A, B, C etc.). Fig. 4.1 shows where the borders are chosen. The shoreface nourishment is located in the middle four stretches (C, D, E and F). Use was made of measurements that were performed every 200 m along the coast (the measurements with a smaller spacing often did not cover the entire area). Therefore the y-value of a 1.2 km stretch is the average of 6 y-values (6 times 200 m = 1200 m). Table 4.1 shows the division of the measuring lanes (relative to the RSP poles) over the defined stretches of coast. The division into three zones was also made. This division is the same as in Section 3.4.3. For example, C1, C2 and C3 represent respectively the upper, middle and lower zone of stretch C. For clearness' sake they are referred to as box C1, box C2, etc.

The shoreface nourishment is located in the middle zone (box C2, D2, E2 and F2). For each box the development of the average y-values was calculated. The method of calculation of the y-values in the three zones has been explained in Section 3.4. The development of the y-values is presented in a number of graphs. Linear trendlines
Fig. 4.1 Planview of Terschelling (above) and the positions of the borders between the different zones (below).
<table>
<thead>
<tr>
<th>Stretch of coast</th>
<th>Measuring lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stretch A</td>
<td>RSP 11.2 km - RSP 12.2 km</td>
</tr>
<tr>
<td>Stretch B</td>
<td>RSP 12.4 km - RSP 13.4 km</td>
</tr>
<tr>
<td>Stretch C</td>
<td>RSP 13.6 km - RSP 14.6 km</td>
</tr>
<tr>
<td>Stretch D</td>
<td>RSP 14.8 km - RSP 15.8 km</td>
</tr>
<tr>
<td>Stretch E</td>
<td>RSP 16.0 km - RSP 17.0 km</td>
</tr>
<tr>
<td>Stretch F</td>
<td>RSP 17.2 km - RSP 18.2 km</td>
</tr>
<tr>
<td>Stretch G</td>
<td>RSP 18.4 km - RSP 19.4 km</td>
</tr>
<tr>
<td>Stretch H</td>
<td>RSP 19.6 km - RSP 20.6 km</td>
</tr>
</tbody>
</table>

Table 4.1 Division of the measuring lanes over the defined stretches of coast.

were added to the graphs to make the general development more clear. These trendlines are based upon the development after execution of the nourishment. In the most western part of the project area the bathymetric measurements did not extend to NAP -9 m. Therefore the lower border of the boxes A3, B3 and C3 is at NAP -7 m instead of at NAP -9 m. These three boxes are presented to analyse the measured profile behaviour in the lower zone; they will not be compared with the three line model calculations because of the different zone heights. Graphs are also made of the development of the three zones all together for each 1.2 km stretch in order to calculate the total accretion or erosion per stretch of coast. There is referred to those as box A Total, box B Total, etc.

4.3 NOURTEC measurements

4.3.1 Introduction

In this section the graphs made of the development of the y-values in time in the different boxes will be evaluated. Section 4.3.2 will discuss the development in each of the boxes. In Section 4.3.3 a general evaluation will be made.

4.3.2 Development y-values in the different boxes

Two to four measurements were carried out just before execution of the nourishment. The average y-value of the measurements executed before the nourishment was set to \( y = 0 \). After the nourishment 9 to 11 measurements have been carried out. The final series taken into account was executed in December 1995. First the area where the shoreface nourishment is located (stretch C, D, E and F) is discussed. Next the area west of the nourishment (stretch A and B) and finally the area east of the nourishment (stretch G and H) are discussed.

Nourishment area: stretch C, D, E and F

Stretch C  (see Fig 4.2)

The most western part of the nourishment is located in the middle zone of stretch C
Fig. 4.2 Development measured y-values in the boxes of stretch C.

Fig. 4.3 Development measured y-values in the boxes of stretch D.
After execution of the nourishment there is an increase in y-value of the middle zone of about 80 m relative to the average y-value measured just before the nourishment. The nourishment was executed between May and November 1993. The y-value of box C2 decreases in the first year after the nourishment and remains stable in the next year. The y-value of the upper zone (box C1) shows a positive trend of about 11 m/year after the nourishment.

The lower zone (box C3) also shows a positive trend; about 6 m/year according to the trendline. The trendline of the development of the y-value of stretch C over the entire height (box C Total) shows an average increase in y-value of about 6 m/year.

**Stretch D** (see Fig 4.3)

The y-value of the middle zone (box D2) increases strongly after execution of the nourishment; about 150 m. From then on there is a steady decrease in y-value. The trendline indicates a decrease of -33 m/year. The graph of the upper zone of stretch D (box D1) shows a steady positive trend of about 19 m/year. The nourishment located in the middle zone probably behaved as a feeder for the upper zone. The y-value of the lower zone (box D3) has hardly changed after the nourishment; the y-value fluctuates around its original value. The y-value of stretch D (box D Total) has increased as an effect of the nourishment and remains almost stable in the two years after the nourishment.

**Stretch E** (see Fig 4.4)

The y-value of the middle zone of stretch E (box E2) has increased strongly due to the nourishment. The y-value has increased about 190 m. Although a decrease in y-value would have been expected in the period after the nourishment (because of redistribution of sediment over the cross-shore profile), an increase in y-value of about 9 m/year was measured. The y-value of the upper zone (box E1) also increases; about 14 m/year. The y-value of the lower zone (box E3) shows a small positive trend of about 2 m/year. The y-value of stretch E (box E Total) has increased strongly as an effect of the nourishment. In the period after the nourishment the y-value continues to increase at a rate of almost 10 m/year.

**Stretch F** (see Fig 4.5)

Stretch F is the most eastern part of the nourishment area. The behaviour of stretch F is comparable to the behaviour of stretch E. The y-value of the middle zone (box F2) has increased strongly after the nourishment; the increase amounts about 170 m. In the two year period after the nourishment the y-value still increases. The trendline shows a high increase rate of about 18 m/year. The y-value of the upper zone shows a positive trend of about 10 m/year. The lower zone shows a negative trend of about -5 m/year in the period after the nourishment.
Fig. 4.4  Development measured y-values in the boxes of stretch E.

Fig. 4.5  Development measured y-values in the boxes of stretch F.
The y-value of stretch F (box F Total) did increase right after the nourishment and continues to increase in the following period at a rate of about 8 m/year.

**Area west of nourishment: Stretch A and B**

**Stretch B (see Fig 4.6)**

Stretch B is located just west of the nourishment area. The middle zone (box B2) shows relative large fluctuations in y-value in time (up to 40 m). The trendline indicates an average increase in y-value of about 11 m/year. The upper zone of stretch B (box B1) also shows an increase in y-value in the period after the nourishment; about 9 m/year. The lower zone (box B3) shows a strong decrease in y-value of about -18 m/year. The lower zone of stretch B reaches only from NAP -6 m to NAP -7 m and has therefore little effect on the y-value of stretch B as a whole. The y-value of stretch B (box B Total) shows a positive trend of about 7 m/year.

**Stretch A (see Fig 4.7)**

Stretch A is the most western part of the evaluated area. The y-value of the middle zone (box A2) fluctuates around its original value. The y-value of the upper zone (box A1) shows a positive trend of about 7 m/year in the period after the nourishment. The lower zone of stretch A (box A3) shows large fluctuations in y-value. The trendline indicates an increase of about 19 m/year. The y-value of stretch A (box A Total) increases; the trendline shows an increase of about 6 m/year.

**Area east of shoreface nourishment**

**Stretch G (see Fig 4.8)**

The middle zone of stretch G (box G2) is located right east of the nourishment. Directly after the nourishment the y-value has decreased about 40 m compared to the situation before. From then on the y-value starts to increase rapidly. The trendline indicates that the increase is about 32 m/year. It has been noticed that the nourishment is moving eastward (Westlake, 1995). This eastward movement most likely causes the increase in y-value in box G2. The upper zone of stretch G (box G1) has increased slightly after execution of the nourishment and remains rather stable in the period after. The y-value of the lower zone fluctuates around its initial value. The trendline is almost horizontal. The y-value of stretch G as a whole (box G Total) shows an increase of about 7 m/year according to the trendline, caused by the increase in y-value in the middle zone.
Fig. 4.6 Development measured y-values in the boxes of stretch B.

Fig. 4.7 Development measured y-values in the boxes of stretch A.
Fig. 4.8 Development measured y-values in the boxes of stretch G.

Fig. 4.9 Development measured y-values in the boxes of stretch H.
Stretch H (see Fig 4.9)

Stretch H is the most eastward stretch of coast of the evaluated study area. Large fluctuations in y-value can be noticed in the middle zone of stretch H (box H2). The trendline indicates a large retreat of about -31 m/year.

The upper zone (box H1) shows a stable y-value in the two year period after the nourishment.

The lower zone of stretch H (box H3) shows a small negative trend of about -2 m/year in the period after the nourishment.

The y-value of stretch H (box H Total) shows a decrease of about -8 m/year according to the trendline.

4.3.3 General evaluation

In the period May to November 1993 a volume of about 2.1 million m$^3$ of sand has been nourished. With the used schematization the nourishment is located entirely in the boxes C2, D2, E2 and F2. The middle zone has a height of 3 m. Each box has a length of 1200 m. Therefore the average increase of these four boxes should be

$$2.1 \times 10^8 / 4 \times 1200 \times 3 \approx 146 \text{ m}.$$ 

The measured increase in y-value shows that the increase in the east is much larger than the increase in the west (from west to east: box C2 ≈ 80 m, box D2 ≈ 150 m, box E2 ≈ 190 m, box F2 ≈ 170 m). The average increase in the boxes is 147.5 m. Most sediment was nourished in the eastern part of the nourishment area. This is important for the schematization of the three-line model.

Calculations were made of the development of the y-values and the volume changes of each separate zone. The results\(^1\) are shown in Table 4.2.

The average increase in y-value of the upper zone is 8.7 m/year. Converted to volumes the upper zone volume has increased at a rate of about half a million m$^3$/year. Thus in the two year period after the supply the upper zone volume has increased with about 1 million m$^3$ of sediment.

In principle this could be nourishment sand which was redistributed over the cross-shore profile. In that case the volume of the middle zone (where the nourishment is located) should show a large decrease in sediment volume. The middle zone however does not show a large decrease in sediment volume, on the contrary, it has accreted slightly ($14 \times 10^3$ m$^3$/year). A calculation of the volume change of the boxes of the shoreface nourishment only (box C2, D2, E2 and F2) results in a decrease of $32 \times 10^3$ m$^3$/year. This is by no means near the amount of increase of the upper zone volume.

The lower zone shows a very small decrease in sediment volume: $-6 \times 10^3$ m$^3$/year.

It can be concluded that the volume change of all three zones together is dominated by the large increase in volume of the upper zone.

To be able to discuss the effect of the nourishment, the autonomous behaviour of the coast has to be taken into account. To analyse the trend prior to the nourishment the so called JARKUS measurements will be used. These yearly coastal profile measurements date from 1965. This will be discussed in Section 4.4.

\(^1\) The fact that the lower zones of stretch A, B, and C only have heights of 1 m (from NAP -6 m to NAP -7 m) instead of 3 m has been taken into account for the calculations.
<table>
<thead>
<tr>
<th>Zone</th>
<th>Volume change</th>
<th>Change in y-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper zone</td>
<td>$503 \times 10^3$ m$^3$/year</td>
<td>8.7 m/year</td>
</tr>
<tr>
<td>Middle zone</td>
<td>$14 \times 10^3$ m$^3$/year</td>
<td>0.5 m/year</td>
</tr>
<tr>
<td>Lower zone</td>
<td>$-6 \times 10^3$ m$^3$/year</td>
<td>-0.3 m/year</td>
</tr>
<tr>
<td>Total</td>
<td>$511 \times 10^3$ m$^3$/year</td>
<td>4.7 m/year</td>
</tr>
</tbody>
</table>

Table 4.2 Change of sediment volumes and y-values in the different zones in the period after the nourishment.

4.4 JARKUS measurements

4.4.1 Introduction

Since 1965 JARKUS measurements have been performed along the coast of Terschelling. JARKUS measurements are performed every year along the entire Dutch coast (JARKUS is an acronym of the Dutch expression for yearly coastal measurements: JAaRlijkse KUSTmetingen). The spacing between the measurements is 200 to 250 m (along the coast of Terschelling 200 m).

Section 4.4.2 will discuss the graphs that were made of the development of the y-values of the different boxes. The measurements of the NOURTEC period were appended to the JARKUS measurements. Section 4.4.2 will focus on the trend in the period prior to the nourishment. The trend after the nourishment has already been discussed in Section 4.3. Comments on differences between trends before and after the nourishment will also be made.

The periodicity of the bar system has affected the development of the y-values significantly. This will be discussed in Section 4.4.3. Section 4.4.4 discusses the profile development landward of the NAP +3 m border.

4.4.2 Development y-values in the different boxes

Graphs were made of the development of the y-values of the different boxes. The measurements of the NOURTEC period were appended to the JARKUS measurements. Linear trendlines were added to the graphs. A distinction is made between the period before the nourishment and the period after the nourishment. Both periods have their own trendlines.

Unfortunately, the early measurements in the period of 1965-1984 only extend in cross-shore direction to about 600 to 1000 m relative to the RSP line. This has troubled the analysis of the behaviour of the boxes of the middle and lower zone. The outer bar was often not measured completely. In those cases the most seaward lower border of the middle zone could not be found. Therefore it was not possible to use the data of this period for the analysis of the development of the y-values in the middle and lower zone. From 1985 on the measurements extend to about 2000 m offshore relative to the RSP line (apart from exceptions in 1990 and 1991). These measurements are useful for studying the behaviour of the middle and the lower zone. First the upper zone will be discussed and next the middle and lower zone.
Fig. 4.10  Development y-values in the upper zone in the period 1965-1995.
Upper zone

Fig. 4.10 shows the graphs of the development in y-value in the period 1965-1995. Before the nourishment there is a trend of accretion in the west and erosion in the east. Considering the development of the y-values a linear trend for the entire period before the nourishment seems appropriate. Fluctuations and (short) periods with apparently different trends occur, but in general there is no indication of a discontinuity in trend during the period before the nourishment.

Box A1 in the west shows a positive trend of about 4 m/year. This positive trend decreases in Box B1 (2 m/year) and box C1 (1 m/year). Box D1 shows a negative trend of -1 m/year. A negative trend also appears in box E1 (-3 m/year), box F1 (-3 m/year), box G1 (-3 m/year) and box H1 (-2 m/year). According to these trends the volume of the entire upper zone would decrease with an amount of about \(-41 \times 10^3 \text{ m}^3/\text{year}\).

After the nourishment in 1993 the trends in the different boxes change. The y-values start to increase in all the boxes except box G1. In section 4.3.3 (page 31) the results of a calculation showed an increase in the upper zone of over \(500 \times 10^3 \text{ m}^3/\text{year}\) in the after nourishment period. It seems that the nourishment has had a large impact on the upper zone. Before the nourishment the upper zone eroded. After the nourishment the development is totally different. There is accretion in almost the entire upper zone.

It is expected that the longshore transport in the upper zone is also affected by the nourishment. Landward of the nourishment the wave heights will be reduced. As a result the longshore transport will also be reduced. The wave driven current is mainly in eastern direction. Landward of the westside of the nourishment strong accretion occurs (box C1 and D1). This accretion is of the same magnitude as the accretion in box E1 and F1, although much less sand was nourished in box C2 and D2 than in box E2 and F2. This might be the effect of the change in longshore transport. At the leaside of the nourishment (box G1) the longshore sediment transport in the upper zone can increase again. Box G1 is the only box where erosion in the period after the nourishment still occurs. These are indications that the nourishment has a considerable impact on the longshore sediment transport.

Middle zone

Less data is available for the middle zone. As explained earlier in this section, only the measurements from 1985 on are useful. The analysis of the development of the y-values in the middle zone shows the remarkable picture of a very strong increase in y-value in all the boxes in the period 1985-1993 (see Fig. 4.11). The trends in the different boxes range from 16 to 27 m/year. There is no clear difference in trend visible from the east to the west as in the upper zone. There simply is a sharp increase in y-value in the entire middle zone in the period 1985-1993. It is stressed that this strong increase is partly caused by the movement of the outer bar in offshore direction. This will be discussed in Section 4.4.3 after the analysis of the y-values of the lower zone and of the three zones together. It has to be stated that the trendlines in the different boxes are based on much less data as was available for the upper zone. The measurements in the years 1990 and 1991 often did not extend far enough offshore.
Fig. 4.11 Development y-values in the middle zone in the period 1985-1995.
The outer bar often did not reach the NAP -6 m level in 1988 and 1989. (The effect on the analysis has been described in Section 3.4.2). In those cases the measurements were not taken into account.

A calculation of the net change in sediment volume indicates an average increase of $596 \times 10^3$ m$^3$/year in the period 1985-1993.

In the period after the nourishment the total volume has remained almost the same. A small change in sediment volume of $+14 \times 10^3$ m$^3$/year was calculated (Section 4.3.3). The volume of the middle zone did increase strongly by the nourishment. This sudden increase might have tempered the trend of accretion in the period after.

**Lower zone**

The y-values of the lower zone in the period 1985-1993 show a different behaviour than the y-values of the middle zone (see Fig. 4.12). In the most western part the measurements did not extend to NAP -9 m. Like for the NOURTEC period the lower border of box A3, B3 and C3 is at NAP -7 m. In the western part the fluctuations in y-value are large. The trendline of box A3 shows a decrease of -4 m/year in the period 1985-1993. The y-value of box B3 shows similar fluctuations but the trend is slightly positive (less than 1 m/year). Box C3 shows a decrease in y-value of -4 m/year. Box D3 shows a small positive trend of about 1 m/year. Box E3 shows a small negative trend (-4 m/year) and this negative trend gets stronger in the more eastern boxes (box F3: -13 m/year, box G3: -10 m/year and box H3: -14 m/year). A calculation of the change of volume of the lower zone indicates an average change of about $-140 \times 10^3$ m$^3$/year.

It is stressed that the development of the y-values of the lower zone is probably affected by the cyclic behaviour of the bar system. This will be explained in Section 4.4.3.

In the period after the nourishment the volume of the lower zone hardly changes. Out of the changes in y-value a volume change of $-6 \times 10^3$ m$^3$/year was calculated (Section 4.3.3).

**Development y-value three zones together**

Fig. 4.13 shows the development of the y-values per 1.2 km stretch of coast in the joint three zones. Measurements which did not cover the entire three zones could not be taken into account (e.g., the measurements before 1985 did only cover the upper zone entirely). Therefore a calculation of volume change based on the trendlines of the joint three zones will yield slightly different results than a calculation based on the sum of each separate zone.

The western part of the evaluated area shows a steady increase in y-value. The increase in y-value in box A Total and box B Total in the period before and after the nourishment is more or less the same: about 7 m/year.
Fig. 4.12 Development y-values in the lower zone since 1985.
Development measured y-values
Period 1986-1995
Box A Total

Development measured y-values
Period 1985-1996
Box B Total

Development measured y-values
Period 1985-1996
Box C Total

Development measured y-values
Period 1985-1996
Box D Total

Development measured y-values
Period 1985-1996
Box E Total

Development measured y-values
Period 1985-1996
Box F Total

Development measured y-values
Period 1985-1996
Box G Total

Development measured y-values
Period 1985-1996
Box H Total

Fig. 4.13  Development y-values in the three zones together since 1985.
Box C Total shows a positive trend of 9.3 m/year in the period before the nourishment. The nourishment causes a small jump in y-value. The y-value decreases in the period right after the nourishment and the positive pre-nourishment trend seems to be re-established.

Box D Total shows a positive trend of about 8 m before the nourishment. The nourishments causes a jump in y-value. From then on the y-value hardly changes. The trendline indicates a small positive trend of slightly more than 1 m/year.

Box E Total shows a positive trend of almost 4 m/year before the nourishment. Like for the stretch C and D, the nourishment causes a sudden increase in y-value. After the supply the y-value increases even faster: about 10 m/year.

Box F Total shows a similar picture as box E Total. The positive trend in y-value after the supply is larger than before: from over 1 m/year to over 8 m/year.

Box G Total shows a small positive trend of almost 2 m/year before the nourishment. After the nourishment the y-value increases faster at a rate of about 7 m/year. This is probably mainly caused by the eastward movement of the nourishment.

The trend of the box H Total before the nourishment is based on a very limited number of measurements. The trendline indicates a positive change in y-value of 4 m/year but the reliability is very small due to natural fluctuations and measurement errors. In the period after the nourishment a negative trend occurs of about -8 m/year.

4.4.3 Effect of periodicity of the bar system on analysis.

The analysis of the trends in the different zones showed that the behaviour of the middle zone is surprising at first sight. The large increase in y-value (respectively volume) is partly the effect of the periodicity of the bar system. The bars are generated close to the shoreline and migrate in an offshore direction. The return period of the bars in the order of 12-15 years. A more detailed description of the bar system is given by Ruessink and Kroon, 1994.

The effect of the periodical behaviour on the volume analysis will be explained by an example. Fig. 4.14 shows the profile at RSP 16600 in 1985 and 1986. It is obvious that the bar system is migrating in offshore direction. The outer bar is decreasing in height. The volume of water below the NAP -6 m border (area W) is increasing (see definition of area W in Section 3.4.2). As a result the volume of the middle zone in 1986 is smaller than in 1985. The volume of the lower zone has increased in the period 1985 - 1986 because of an offshore shift of the profile seaward of the seaward NAP -6 m border and the increased contribution of W.

A comparison between the 1985 and the 1991 profile (see Fig. 4.15) shows that the outer bar of 1985 has disappeared in 1991 and thus that the inner bar of 1985 has become the outer bar of 1991 (the profiles of the years in between also show a seaward migration of the bar). The effect on the volume analysis is quite clear. In 1991 the volume of water below the NAP -6 m level (indicated with a '-' ) is much smaller than in 1985 (see Figs. 4.16, 4.17 and 4.18). There is hardly any difference between the surface areas of the outer bar in 1985 and 1991 that exceed the NAP -6 m level. As a result of all this, the volume of the middle zone in 1991 is much larger than in 1985. It can also be seen that the profile seaward of the seaward -6 m border has shifted in landward direction in the period 1985 - 1991. The volume of the lower zone has decreased in time.
It can be concluded that the periodical behaviour of the bar system has a considerable effect on the volume analysis. Upon the general trend of accretion or erosion fluctuations in time will occur caused by the migration of the bars. The period of these fluctuations is linked to the period in which the bar system reaches a similar stage as before.

A comparison between volumes i.e. y-values of one particular zone in time is therefore complicated. A true measure for an indication of the long term behaviour is the change in the three zones all together. The sum of these zones is not affected by the periodical behaviour of the bar system. This is mainly important for the middle and lower zone. The bars that develop in the upper zone are relatively small and their migration offshore will not affect the volume analysis as much as in the middle and lower zone. The graphs of the upper zone in the period 1965-1993 indeed show rather small fluctuations compared to the general trend.

Because the limited amount of useful data for the middle and lower zone, from 1985 on instead of 1965, it is more difficult to determine the general trend of the middle and lower zone separately. As explained above, fluctuations caused by the periodicity of the bar system muddy the view of the general behaviour. Therefore the development of the volume of the middle and lower zone together presents a much more reliable picture of the general trend in the lower part of the profile. The sum of the volumes in the middle and lower zone based on the trendlines indicate a large increase in volume in time. According to the trendlines the volume of the middle zone increased with a rate of $596 \times 10^3$ m$^3$/year and the volume of the lower zone decreased: $-140 \times 10^3$ m$^3$/year. The increase in the middle zone is much larger than the decrease in the lower zone. There is a net average increase of about $456 \times 10^3$ m$^3$/year in the middle and lower zone together.

It can be concluded that the lower part of the profile (from NAP -3 m to NAP -9 m) has accreted strongly in the period 1985-1993. The amount of $456 \times 10^3$ m$^3$/year causes

![Cross-shore profiles at RSP 16600 in 1985-1986.](image)

*Fig. 4.14 Cross-shore profiles at RSP 16600 in 1985-1986.*
Fig. 4.16 Cross-shore profiles at RSP 16600 in 1985-1991.

Fig. 4.17 Cross-shore profiles at RSP 16600 in 1985.
an average increase in y-value of about 8 m/year in the middle and lower zone, or in other words, an increase of 50 m³/m/year. In the period 1985 - 1993 there has been an increase of $8 \times 456 \times 10^3$ m³/year $\approx 3.6$ million m³. Taking the trend of the entire upper zone also into account ($-41 \times 10^3$ m³/year) the average change from NAP +3 m to NAP -9 m amounts $415 \times 10^3$ m³/year. Thus in the period 1985 - 1993 the total volume in the evaluated area (length 9600 m) has increased approximately $8 \times 415 \times 10^3 \approx 3.3$ million m³ (about 1.5 times the nourishment volume).

### 4.4.4 Profile development landward of NAP +3 m border

Knowledge of the behaviour of the profile landward of the NAP +3 m border is important for the understanding of the behaviour of the entire coast. The dunes play an active role in the total sediment budget analysis. Aeolian transport is one of the transport mechanisms for the existence of dunes. At the North Sea coast of Terschelling winds are mainly from seaward direction. These winds transport sediment in landward direction: from the beach to the dunes. Transport in opposite direction also takes place, e.g., heavy storms can cause erosion of the dunefoot. The ‘lost’ sediment will settle in lower parts of the cross-shore profile.

The dunes play an active role and are therefore important when analysing the profile development and the sediment budget.

Unfortunately, during the NOURTEC period the profile measurements often did not reach the top of the first dune. The JARKUS measurements often do cover the entire first dune, especially in more recent years. JARKUS measurements have also been
Fig. 4.19  Upper part of profile at RSP 17000 with most landward border.

Fig. 4.20  Definition of borders for calculation surface area landward of NAP + 3m border.
executed during the NOURTEC period (independently of the NOURTEC measurements). These measurements provide information about the behaviour landward of the NAP +3 m border and the effect on the total sediment budget.

Graphs were made of the development of the volumes landward of the NAP +3 m border. The NAP +3 m border is the most seaward NAP +3 m crossing which is the same as the upper border of the upper zone. The position of the landward border was chosen such that beyond this border no significant profile development occurs. This criterion made many of the earlier JARKUS measurements unsuitable for volume calculations. The measurements often did not extend far enough in onshore direction. The landward border is different for every measurement ray.

Fig. 4.19 shows as example some profiles measured at RSP 17000. Fig. 4.19 clearly shows that the earlier measurements, in this case the measurements of 1983, 1985, 1987 (the dashed lines) do not extend far enough in landward direction to be suitable for volume calculations. The more recent measurements extend much further in landward direction. The fixed border is chosen at a point where the sediment transport is relatively negligible.

Fig. 4.20 shows two surface areas to be calculated. Area A is the volume of sediment above the NAP +3 m border. Area B represents the volume of air (read: absence of sediment) below the NAP +3 m border and in between of the two vertical borders. Area B is subtracted from area A. If sediment moves from area A to B this will not affect the outcome of A minus B.

Not the absolute value of A minus B is important but the change in time.

The results are presented in Fig. 4.21. Graphs were made of the development in the different stretches of coast (A through H). The horizontal axes of every graph are at the same scale to make a visual comparison of the trendlines possible. The amount of useful data varies strongly from one part of the coast to the other. For stretch C data since 1970 were useful while for stretch A, D, E and F only data since 1989 were useful. The validity of the trendlines is less secure in case of a relatively small number of data.

The evaluated stretches all show a positive trend in change of sediment volume. The trendlines indicate increases varying from a minimum of 9.1 m$^3$/m/year at stretch F to a maximum of 23.9 m$^3$/m/year at stretch B. There’s not a clear trend in longshore direction like in the upper zone i.e. accretion in the west and erosion in the east.

No distinction was made between the period before and after the nourishment because of the limited amount of data. Only two measurements of the period after the nourishment are available (1994 and 1995). The 1993 measurement was performed before the nourishment. The measurements of 1994 and 1995 do not show a significantly different trend from the period before. In the period 1993-1995 the volumes of all the stretches have increased. It can be concluded that the strong increase of the upper zone volume in the period after the nourishment is not caused by a loss of sediment from above NAP +3 m. On the contrary it is most likely that sediment from or via the upper zone has been transported to the dune area.

A calculation of the volume change based on the trendlines shows there is an average increase of 139*10$^3$ m$^3$/year.
Fig. 4.21  Development landward of the NAP + 3m border.
Since 1967 coastal authorities have enlarged the dune volume by shifting sand from the upper part of the beach to the dunes. This has caused a retreat of the dunes and a widening of the beaches. This policy has lasted until 1992. It is however difficult to determine the magnitude and effect of these human operations. There is no obvious change in trend in the period after 1992. Also the fact that the shoreface nourishment might have affected the dune area in the period 1993-1995 (like it affected the upper zone) makes it very difficult to distinguish between autonomous behaviour, effects of human operations and effects of the shoreface nourishment. No further analysis of this aspect is made in this study.

4.5 General evaluation

The analysis of the bathymetric measurements has resulted in more insight in the autonomous behaviour and in the behaviour of the nourishment. This increased insight can be used for calibration of the three-line model. A short summary of the analysis of the bathymetric data is given in this section.

Behaviour coast before the nourishment

In the period 1965-1993 the upper zone was accreting in the west and eroding in the east. A net change in sediment volume of \(-41 \times 10^3 \text{ m}^3/\text{year}\) was calculated for the entire upper zone. The development of the middle and lower zone was affected by the cyclic behaviour of the bars (see Section 4.4.3). The middle zone volume has increased strongly in the period 1985-1993: \(+596 \times 10^3 \text{ m}^3/\text{year}\). There was no clear difference in trend from the west to the east. The lower zone has been eroding in the period 1985-1993: \(-140 \times 10^3 \text{ m}^3/\text{year}\). Most of the erosion took place in the eastern part of the evaluated area. Because of the cyclic behaviour of the bar system the sum of the volume change in middle and lower zone will give a better impression of the behaviour in the lower part of the profile (from NAP -3 m to NAP -9 m). The sum indicates a strong increase in sediment volume \(+456 \times 10^3 \text{ m}^3/\text{year}\).

The total evaluated area (without considering the area landward of the NAP + 3 m border) has accreted strongly in the period before the nourishment. Based on the trendlines of the separate zones a volume change of \(+415 \times 10^3 \text{ m}^3/\text{year}\) was calculated.

The trends of the different zones are not equal which implies that the cross-shore profiles are not uniform in time. This is in contradiction to one of the basic assumptions of the three-line model, viz. the existence of an equilibrium profile in cross-shore direction.

The nourishment design was based on the behaviour of the BKL zone (NOURTEC, 1994). The BKL zone ranges from NAP + 3 m to NAP - 5.24 m. The present analysis has showed that the increase in sediment volume in the period before the nourishment particularly took place in the lower part of the profile. Erosion mainly appeared in the eastern part of the upper zone.

The position of the horizontal borders, in this case especially the lower border of the BKL, does have a large impact on the volume analysis. If for instance the behaviour
of the by Rijkswaterstaat defined 'active zone volume' (defined as volume between NAP +3 m and NAP -7 m) would have been the design criterion, no nourishment would have been necessary.

*Behaviour coast after the nourishment*

The nourishment caused a sudden increase of the volume of the middle four boxes of the middle zone. The behaviour of the coast after the nourishment differs strongly from the behaviour before. The upper zone volume suddenly starts to increase rapidly. Calculations resulted in an average increase of $503 \times 10^3$ m$^3$/year. The middle zone where the nourishment is located does not show a volume decrease. It is therefore doubted whether sediment has moved from the nourishment area to the upper zone. A possible explanation for the increase of the upper zone volume can be that the shoreface nourishment has caused an increased amount of breaking. More waves will break further offshore. This could very well have affected the longshore transport in the upper zone. A decreased amount of breaking will result in a decrease of the longshore sediment transport rate which might cause accretion in that area. The accretion landward of the nourishment in the western part seems relatively large. Erosion occurs in the upper zone of stretch G. This can be the effect of an increasing longshore transport rate towards the east.

The lower zone volume has hardly changed in the period after the nourishment. A small amount of erosion was calculated ($-6 \times 10^3$ m$^3$/year).

The volume change in the three zones together is $+511 \times 10^3$ m$^3$/year. This is more than during the evaluated period before the nourishment ($+415 \times 10^3$ m$^3$/year) but the values are of the same order.

Further it has been noticed that the nourishment is migrating in eastern direction.
CHAPTER 5  LONGSHORE COASTAL CONSTANTS

5.1  Introduction

The longshore coastal constants determine the magnitude of transport in longshore direction. Kersting (1995a) already made a calculation of these constants in his forecast study of the Terschelling supply. The method of the derivation of the longshore coastal constants and the results of the calculations made by Kersting are presented in this chapter.

In order to determine the longshore coastal constants for the line modelling use was made of the CERC formula and the assumptions of Svašek (1968). A special computer program was written by Bakker & Kersting to do this. That program was also used for the Norderney case (Kersting, 1995b) and the Torsminde case (Groenewoud, 1996). Section 5.2 will explain the principles of transport calculation on which the program is based. Section 5.3 discusses the application for the Terschelling case. The longshore constants and the results of a calculation of the longshore transport, as calculated by Kersting, are presented.

5.2  Principles of transport computation

5.2.1  Assumptions

The transport computation in this report is based on the CERC formula. The most important assumptions are:

- The longshore sand transport capacity is proportional to the component of the energy flux in longshore direction at the outer edge of the surf zone (Fig. 5.1).

![Fig. 5.1: Longshore component of energy flux at breaker line.](image)

Energy flux: $1/8 \rho g H_0^2 n_c c_0 \cos \varphi_0$
Contour lines

Energy flux: $1/8 \rho g H_b^2 n_c c_0 \cos \varphi_b$
Breaker depth

Longshore component

Coastline
- The energy flux can be determined by linear refraction theory.
- The formula is valid for beaches with sand with a mean diameter ($D_{50}$) between 175 μm and 1000 μm.
- The wave energy losses only take place by breaking and take place in the breaker zone, so there is no transport outside the breaker zone.
- The breaker wave height $H_{b,\text{sig}}$ is proportional to the breaker depth $h_b$.

### 5.2.2 CERC transport formula

The following equation can be derived from the assumption of a proportional relation between the longshore transport and the component of the energy flux.

$$S_x = A \cdot H_{b,\text{sig}}^2 \cdot n_b \cdot c_b \cdot \cos(\phi_b) \cdot \sin(\phi_b) \quad (5.1)$$

- $S_x$ = longshore sand transport (m$^3$/s)
- $H_{b,\text{sig}}$ = significant wave height at the breaker line (m)
- $c_b$ = wave celerity at the breaker line (m/s) (-)
- $n_b$ = ratio (group celerity/ wave celerity) (-)
- $\phi_b$ = angle of wave incidence at the breaker line (-)
- $A$ = proportionality constant (-)

The proportionality constant, $A$, depends on physical parameters like for instance the characteristics of sand. For Dutch conditions a value of 0.040 is considered as appropriate.

### 5.2.3 Refraction

A usual assumption for the wave height calculation based on the refraction theory is that there is no energy loss before the waves break. The wave energy between two wave rays outside the breaker zone remains constant:

$$E_0 \cdot n_0 \cdot c_0 \cdot b_0 = E_b \cdot n_b \cdot c_b \cdot b_b \quad (5.2)$$

- $E$ = wave energy per square m of surface (J/m$^2$)
- $n_0$ = ratio ($c_{\text{group}}$/$c_{\text{wave}}$) (-)
- $c_0$ = wave celerity (m/s)
- $b_0$ = width between two wave rays (m)

The subscripts ‘$0$’ and ‘$b$’ indicate respectively the position of the wave at deep water and the position of the wave at the breaker line.

Assuming depth contours to be parallel to the coastline, refraction theory gives:
In Eq. 5.1 the parameter \( \sin \left( \phi_b \right) \) can be substituted using Snel’s Law:

\[
\frac{\sin \left( \phi_b \right)}{\sin \left( \phi_b \right)} = \frac{c_0}{c_h}
\]

(5.4)

giving:

\[
S_x = 0.040 \times H_{h,avg}^2 \times n_b \times \frac{c_h^2}{c_0} \times \sin \left( \phi_b \right) \times \cos \left( \phi_b \right)
\]

(5.5)

with:

\[
n_b = \frac{1}{2} + \frac{k h_b}{\sinh \left( 2 k h_b \right)}
\]

(5.6)

\[
c_h = c_0 \times \tanh \left( k h_b \right)
\]

(5.7)

\[
L = \frac{g T^2}{2 \pi} \times \tanh \left( k h_b \right)
\]

(5.8)

\[
k = \frac{2 \pi}{L}
\]

(5.9)

Assuming that wave breaking takes place in relative shallow water gives:

\[
c_h = \sqrt{g \times h_b}
\]

(5.10)

\( h_b \) = depth at breaker line (m)

\( g \) = acceleration of gravity (m/s^2)

The ratio between wave height and water depth at the breaker line can be substituted in Eq. 5.5:

\[
\frac{H_{h,avg}}{h_b} = \gamma
\]

(5.11)

This gives with Eq. 5.10:
\[ S_x = 0.040 \left( \gamma \cdot h_b \right)^2 \cdot e \cdot \frac{(\sqrt{g \cdot h_b})^2}{c_0} \cdot \sin(\phi) \cdot \cos(\phi) \]  

resulting in:

\[ S_x = 0.040 \cdot g \cdot \gamma^2 \cdot h_b \cdot e \cdot \frac{\sin(\phi) \cdot \cos(\phi)}{c_0} \]  

5.2.4 Distribution of sand transport capacity over the depth

For the distribution over the profile use is made of the adaption of the CERC formula as proposed by Svasek and Bijker (1969). The transport capacity, \( S_i \), in the zone above a depth \( h_i \), is proportional to the ratio \((h_i / h_b)^3 \cdot S_x\). For the detailed derivation and background is referred to Bakker (1969) and Bakker et al. (1972). In formula:

\[ S_i = \frac{h_i^3}{h_b^3} \cdot S_x \]  

\[ S_i = 0.040 \cdot g \cdot \gamma^2 \cdot h_b^3 \cdot e \cdot \frac{\sin(\phi) \cdot \cos(\phi)}{c_0} \]  

\( h_i \) = depth at depth contour i \( S_i \) = transport capacity in the zone higher than depth \( h_i \)

The transport in the zone between the breaker line and the depth contour \( h_i \) is therefore:

\[ S_{h \rightarrow h} = 0.040 \cdot g \cdot \gamma^2 \cdot \left( h_b^3 - h_i^3 \right) \cdot e \cdot \frac{\sin(\phi) \cdot \cos(\phi)}{c_0} \]  

This concept has been extended to more zones.

5.2.5 Computation of breaker depth and wave height

The wave energy per unit surface is:

\[ E = \frac{1}{8} \cdot \rho \cdot g \cdot H_{rms}^2 \]  

From Eq. 5.2 and Eq. 5.17 can be derived:
\[ H_{\text{rms}}^2 = H_{0,\text{rms}}^2 \cdot \frac{n_0 \cdot c_0 \cdot b_0}{n_h \cdot c_h \cdot b_h} \quad (5.18) \]

For deep water \( n_0 \) is 0.5.

For a relative small spectrum:

\[ H_{\text{sig}}^2 = 2 \cdot H_{\text{rms}}^2 \quad (5.19) \]

Combination of Eqs 5.3, 5.10, 5.11, 5.18 and 5.19 yields:

\[ (\gamma \cdot h_h)^2 = H_{0,\text{sig}}^2 \cdot \left( \frac{1}{2} \cdot c_0 \cdot \cos(\phi) \right)^{0.4} \cdot \left( \frac{1}{n_h \cdot \cos(\phi)} \right)^{0.4} \quad (5.20) \]

And so:

\[ h_h = \left( \frac{H_{0,\text{sig}}^2 \cdot c_0 \cdot \cos(\phi)}{2 \cdot g \cdot \gamma^2} \right)^{0.4} \cdot \left( \frac{1}{n_h \cdot \cos(\phi)} \right)^{0.4} \quad (5.21) \]

The first factor on the right hand side is constant. By first assuming \( n_h \cdot \cos(\phi) = 1 \), the breaker depth can be determined by iteration.

5.3 Application for the Terschelling case

In order to determine the longshore coastal constants \( (s_1, s_2 \text{ and } s_3) \) the CERC computer program was used by Kersting. The CERC program is written in Turbo Pascal 7.0. A flow diagram and a listing of the program can be found in Appendix B. The program uses wave data as input. These data consist of tables of probability of occurrence of a certain combination of wave height and wave period and tables of probability of occurrence of a certain combination of wave height and water level. The wave and water level measurements are from SON, a measurement station in the neighbourhood of Schiermonnikoog (island east of Terschelling). Wave and water level data of the period 1979-1991 were used. More recent data are not available at the moment. Kersting made a division in 7 segments of angles of wave approach (see Fig. 5.2). For each combination of angle of approach, wave height, wave period and wave period the longshore transport can be calculated. After this computation the computed transport is multiplied by the probability of occurrence of that particular combination. The sum of these calculated transports is the total transport for that specific mean wave angle.

The CERC program is also able to make a division of the transport over the three zones. To obtain the coastal constants for each direction two extra computations with a positive and an equally negative angle \( \delta \) have to be made. This angle \( \delta \) denotes the
Fig. 5.2  Schematization of the coast of Terschelling and directions of wave approach.

Fig. 5.3  Schematization of the coastal zone.
angle between the parallel depth contours of one zone and another. Fig. 5.3 shows this for the upper zone. By turning a zone over an angle δ the effect of a rotation of a zone on the total transport in that zone can be calculated. This strategy is used for all three zones separately. The final result is that a relation between change in angle of a zone and change in sediment transport can be derived. Kersting used a positive and a negative angle δ of 2 degrees. Table 5.1 presents the results of the calculations made by Kersting. The effect of a rotation of the lower zone on the sediment transport has not been calculated. The amount of sediment transport in the lower zone is negligible compared to the upper and the middle zone. Therefore the assumption was made that the transport in the lower zone is zero and thus the coastal constant $s_3$ is zero as well.

<table>
<thead>
<tr>
<th>Angle of wave approach (degrees)</th>
<th>Zone</th>
<th>δ</th>
<th>Sediment transport ($10^3 \text{ m}^3/\text{year}$)</th>
<th>ΣS ($10^3 \text{ m}^3/\text{year}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>82.5°</td>
<td>Upper zone</td>
<td>+2°</td>
<td>41.4 500.4 431.4 40.5 -114.6 -84.8 -10.1</td>
<td>804.2</td>
</tr>
<tr>
<td>30°</td>
<td>Upper zone</td>
<td>0°</td>
<td>40.6 478.3 377.3 0 -128.7 -87.9 -10.3</td>
<td>679.3</td>
</tr>
<tr>
<td>0°</td>
<td>Upper zone</td>
<td>-2°</td>
<td>39.5 453.8 341.2 -40.5 -142.1 -90.5 -10.3</td>
<td>551.0</td>
</tr>
<tr>
<td>-30°</td>
<td>Upper zone</td>
<td>+2°</td>
<td>0.0 68.4 161.9 15.2 -38.2 -8.8 0</td>
<td>198.5</td>
</tr>
<tr>
<td>-60°</td>
<td>Upper zone</td>
<td>0°</td>
<td>0.0 67.6 148.5 0 -42.0 -8.8 0</td>
<td>165.3</td>
</tr>
<tr>
<td>-82.5°</td>
<td>Upper zone</td>
<td>-2°</td>
<td>0.0 66.3 134.4 -15.2 -45.6 -8.7 0</td>
<td>131.2</td>
</tr>
<tr>
<td>Lower zone</td>
<td>0°</td>
<td>0°</td>
<td>5.5 0 0 -1.4 0 0</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Table 5.1  Calculated sediment transport in the three zones per angle of wave approach and for different zone rotation angles δ (δ).

The net sediment transport (in eastward direction) calculated by Kersting is:

$$S_x = (679.3 + 165.3 + 4.1) \times 10^3 = 848.7 \text{ m}^3/\text{year}.$$  

The coastal constants can be calculated now.

$$s_1 = \frac{804.2 - 551.0}{\frac{4}{360}} \times 10^3 = 3.63 \times 10^6 \text{ m}^3/\text{year}/\text{rad}$$

$$s_2 = \frac{198.5 - 131.2}{\frac{4}{360}} \times 10^3 = 0.964 \times 10^6 \text{ m}^3/\text{year}/\text{rad}$$

$$s_3 = 0 \text{ m}^3/\text{year}/\text{rad}$$

These constants will be used for the calculations with the three-line model.
6.1 Introduction

Cross-shore diffusivity will cause a deviation from the equilibrium shape (e.g. a nourishment) to finally spread out over the coastal profile. The cross-shore constants determine the rate of cross-shore diffusion in the model. It is therefore important to make a good estimate of these constants.

Section 6.2 discusses the cross-shore coastal constants in general. Chapter 4 presented an analysis of the bathymetric data. The results of this analysis will be used to determine the magnitude of the cross-shore constants. The n-line model is not capable of representing the autonomous behaviour. It can only be used to describe the effect of the nourishment. Therefore the measured nourishment behaviour should be corrected for the autonomous behaviour. This correction is discussed in section 6.3. First the upper zone will be discussed. The middle and lower zone will be discussed together because of the effect of the periodical behaviour of the bar system on the volume analysis (see Section 4.4.3).

Section 6.4 discusses the determination of the cross-shore coastal constants.

6.2 Cross-shore constants

In Chapter 3 the theory behind the three-line model has been explained. Smit (1987) proposed an analytical solution for the three line model without longshore transport. With the equations of Smit the values of $s_{y1}$ and $s_{y2}$ follow from:

$$s_{y1} = \frac{1}{T_{01}} \ast \left( \frac{h_1 \ast h_2}{h_1 + h_2} \right)$$

$$s_{y2} = \frac{1}{T_{02}} \ast \left( \frac{h_2 \ast h_3}{h_2 + h_3} \right)$$

with:

- $s_{y1}$ = cross-shore constant (m/year)
- $s_{y2}$ = cross-shore constant (m/year)
- $h_1$ = height of zone 1 (m)
- $h_2$ = height of zone 2 (m)
- $h_3$ = height of zone 3 (m)
- $T_{01}$ = time constant for diffusivity (year)
- $T_{02}$ = time constant for diffusivity (year)

The $T_{0}$-period is the period in which a certain value of deviation from the equilibrium distance of a zone will decrease with a factor e. The problem is shifted from determination of the cross-shore constant to determination of the $T_{0}$-period.
6.3 Correction measured development for autonomous behaviour

6.3.1 Correction upper zone development

The upper zone showed accretion in the west and erosion in the east in the period before the nourishment (1965-1993). The average change of the upper zone volume was \(-41 \times 10^3\) m\(^3\)/year. After the nourishment the upper zone volume increased rapidly: \(+503 \times 10^3\) m\(^3\)/year. It was decided to correct the trend of each box measured after the nourishment for the trend during the foregoing period. Of course, differences in trends before and after the nourishment can not only be contributed to the nourishment itself. Conditions during the NOURTEC period can differ from the average conditions and the autonomous behaviour has its fluctuations. The results of the correction are displayed in Fig. 6.1. The results of this correction seem logical. Box C1, D1, E1 and F1 are located right above the nourishment. Those boxes have had a larger profit of the nourishment than the boxes in the east (box G1 and H1) and the west (box A1 and B1). Box G1 has profited the least of all the boxes. This could be the effect of the nourishment on the longshore transport. With the predominantly north-western waves the longshore transport is in eastern direction. Due to the nourishment which causes more wave dissipation offshore, the longshore transport at the boxes C1, D1, E1 and F1 probably will be reduced. This can cause accretion landward of the nourishment. At the leeside of the nourishment the sediment transport will increase again. This might explain the much smaller positive trend of box G1 (see also Section 4.4.2). The fact that the boxes in the east and the west also seem to have had a benefit from the nourishment, indicates that also in longshore direction the nourishment has had its effect. The three-line model will in principle predict a symmetrical profile development in longshore direction in case of an alongshore symmetrical supply.

![Fig. 6.1 Trends upper zone prior to nourishment (a), after nourishment (b) and corrected (c).](image-url)
6.3.2 Correction middle and lower zone development

The middle zone showed a strong accretion in the period before the nourishment. There was not a clear difference in trend from the east to the west. The average calculated volume change was $+596\times10^3$ m$^3$/year. The lower zone showed an erosion of $-140\times10^3$ m$^3$/year. The periodical behaviour of the bar system had a significant effect on these numbers. It is difficult to determine the proper correction method for the autonomous behaviour. Two possible alternatives for correction for the autonomous behaviour are discussed.

Alternative 1

This alternative adjusts the measured trends of each box after the supply for the measured trend during the foregoing period. No adjustments are made for a possible effect of the periodical behaviour. The correction of the trends of the middle and lower zone is displayed in Fig. 6.2 and Fig. 6.3.

In the middle zone this results in a decrease in trend values in six of the eight boxes. Only box F2 and G2 show a positive trend in y-value. This is probably mainly caused by the eastward movement of the nourishment. This eastward movement can only partly be modelled with the three-line model. The correction for the positive development in trend values before the nourishment causes the negative trends for the period after the nourishment. The total decrease of the middle zone after correction is $-582\times10^3$ m$^3$/year ($=14\times10^3 - 596\times10^3$). A volume decrease of the boxes of the nourishment is expected in the period after the nourishment. The nourishment is supposed to spread out in longshore and cross-shore direction. As a result of the cross-shore transport the middle zone volume would decrease.

---

**Fig. 6.2** Trends middle zone prior to nourishment (a), after nourishment (b) and corrected (c).
The corrected lower zone behaviour (see Fig. 6.3.c) shows large fluctuations in the west caused by the sandwaves. Boxes A3, B3 and C3 will not be compared with the three-line model calculations because of the different zone heights. Towards the east the y-values are increasing. The average volume change of the lower zone is positive: $+134 \times 10^3 \text{ m}^3/\text{year} (= -6 \times 10^3 - (-140 \times 10^3))$. This increase of the lower zone after correction could be the result of nourishment sand spreading out in cross-shore direction.

The results of the corrections can be explained by the assumption that the disturbed equilibrium profile is being restored (decrease middle zone, increase upper and lower zone).

Alternative 2

This alternative corrects the behaviour of the middle and the lower zone in a different way. The trends of the middle and the lower zone prior to the nourishment are now combined. In this way the effect of the periodical behaviour of the bar system on the middle and lower zone development is filtered out. The average trend of middle and lower zone might give a better idea of the general trend below NAP -3 m. The trends in the middle and lower zone (prior to the nourishment) and the combination of both are shown in Fig. 6.4.

The combination of middle and lower zone results in a trend of accretion in the entire area (Fig. 6.4.c). The accretion in the west is larger than in the east. The trends in the middle and the lower zone after the nourishment can now be corrected.

The result of this correction for the middle zone is visible in Fig. 6.5. The two boxes of the shoreface nourishment in the west (box C2 and D2) show a large decrease in y-value. The more eastern boxes of the nourishment (box E2 and F2) show accretion. West of the nourishment erosion occurs (box A2 and B2). East of the nourishment there is a strong positive trend in box G2 and a sharp negative trend in box H2.
The correction of the lower zone is presented in Fig. 6.6. The correction has led to erosion in almost the entire lower zone, box A3 is an exception. The interpretation would be that the nourishment has caused erosion of the lower zone. Large erosion of the lower zone is not expected. The nourishment is supposed to spread out in cross-shore direction and that would lead to an increase of the lower zone volume. The correction for the autonomous behaviour seems therefore not right. This alternative divides the positive sediment balance of the middle plus lower zone equally over both zones. This correction for the periodical behaviour of the bar system is not useful for the three-line modelling.

Fig. 6.5  Average trends middle + lower zone prior to nourishment (a), middle zone after the nourishment (b) and corrected middle zone (c).
Fig. 6.6 Average trends middle + lower zone prior to nourishment (a), lower zone after the nourishment (b) and corrected lower zone (c).

Choice of alternative for middle and lower zone

The correction method of alternative 2 resulted in a strong decrease of the lower zone volume in the period after the nourishment. This is not expected in reality. The correction method of alternative 2 seems to have over-corrected the effect of the periodicity of the bar system. It was decided to use alternative 1 as correction method for the middle and lower zone behaviour. The effect of the periodicity of the bar system on the analysis of the trend is not taken into account. This is a shortcoming of the method. It is preferred to use alternative 1 while keeping in mind that no adjustment was made for the cyclic behaviour of the bar system.

6.4 Determination of the cross-shore constants

The calculated trends in the different boxes can now be used for the derivation of the coastal constants. Fig. 6.7 shows a 3D image of the calculated (corrected) trends in the different boxes. The trends of the boxes A3, B3, C3 of the lower zone are not shown in Fig. 6.7 because they will not be compared with the three-line model calculations. Boxes A3, B3, C3 only extend to NAP -7 m and therefore they do not correspond with the three-line model schematization. The assumption is made that after the nourishment the y-values of the boxes of the nourishment had increased as estimated in Section 4.3.2:

Increase y-value after nourishment of:  
Box C2: 80 m  
Box D2: 150 m  
Box E2: 190 m  
Box F2: 170 m

Fig. 6.8 shows the schematized development of the y-values right after the nourishment (defined as $T = 0$). With the calculated trends the development of the y-
Corrected trends of the different boxes in the period after the nourishment

Fig. 6.7 3D image of the corrected trends in the period after the nourishment.

Situation right after nourishment (T = 0 years)

Fig. 6.8 3D image of schematized situation after the nourishment.
Fig. 6.9  3D image of schematized situation 1 year after nourishment.

Fig. 6.10  3D image of schematized situation 2 years after nourishment.
values in time can be calculated. This development is linear. To give an impression of
the development the situation after 1 year and after 2 years was calculated. Fig. 6.9
and Fig. 6.10 show respectively the situation after 1 and after 2 years. The trendlines
of the period after the nourishment are based upon measurements during a period of
about two years (from November 1993 to December 1995). The calculated situation
after two years will be used for the derivation of the constants.

From the situation after two years, based on the measurement trendlines, the volume
changes of each zone can be calculated. The results are listed in Table 6.1. The aim is
to get the same volume changes in the different zones with the three-line model.
In Chapter 5 the longshore coastal constants were already calculated. It was decided to
run the three-line model with these constants and to vary the cross-shore coastal
constants.

<table>
<thead>
<tr>
<th>Volume change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper zone</td>
</tr>
<tr>
<td>Middle zone</td>
</tr>
<tr>
<td>Lower zone</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Table 6.1 Volume changes in the different zones after 2 years.

From Table 6.1 it appears that the sediment budget is not zero. Before the
nourishment there was an average increase in the total evaluated area of 415*10^3
m^3/year (see Section 4.5). After the nourishment the average calculated increase was
larger: 511*10^3 m^3/year (see Section 4.5 as well). There is a difference of 104*10^3
m^3/year. Therefore the sediment budget is positive after two years. Because of the
omission of the western boxes of the lower zone the sediment budget of Table 6.1 is
slightly different (not 2*104*10^3 m^3 = 208*10^3 m^3, but 177*10^3 m^3).

To make a correction for this positive sediment budget it was decided to reduce the
positive development of the upper and the lower zone. The amount of reduction is
such that the decrease of the y-values of the upper and zone is the same. Converted to
volumes this results in a decrease of the upper and lower zone volume of respectively
135*10^3 m^3 and 42*10^3 m^3. The differences are caused by the fact that the upper zone
is twice as high as the lower zone and that the western boxes of the lower zone were
not taken into account. The modified sediment balance of the three zones is presented
in Table 6.2.

<table>
<thead>
<tr>
<th>Volume change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper zone</td>
</tr>
<tr>
<td>Middle zone</td>
</tr>
<tr>
<td>Lower zone</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Table 6.2 Modified volume changes in the different zones after 2 years.
The aim is to describe the volume increase of the upper and lower zone as well as possible. Therefore the volume changes as calculated by the model should give the same results as the figures in Table 6.2.

As described earlier, the $T_0$-period is the period in which a certain value of deviation from the equilibrium distance of a zone will decrease with a factor $e$. By trial and error the $T_0$-periods have been determined. The results for several combinations of $T_0$-periods are shown in Table 6.3.

**Remark:** The calculated volume changes of the lower zone as presented in Table 6.3, represent only the calculated volumes in the boxes D3 to H3. The three-line model also calculates volume changes in the western boxes of the lower zone (A3, B3 and C3). The calculated volume decrease of the middle zone is larger (absolute) than the increase of upper and lower zone together (as presented in Table 6.3) because sediment also moves to the boxes A3, B3 and C3. To avoid possible confusion about a sediment balance which is not zero, the changes in volume of the middle zone are not presented in Table 6.3. The focus is on the increase of the upper and the lower zone.

<table>
<thead>
<tr>
<th>zone</th>
<th>$T_{01} = 1.0$ year</th>
<th>$T_{01} = 1.5$ year</th>
<th>$T_{01} = 2.0$ year</th>
</tr>
</thead>
<tbody>
<tr>
<td>upper</td>
<td>$T_{02} = 3.0$ year</td>
<td>1083</td>
<td>916</td>
</tr>
<tr>
<td>lower</td>
<td></td>
<td>271</td>
<td>304</td>
</tr>
<tr>
<td>upper</td>
<td>$T_{02} = 5.0$ year</td>
<td>1133</td>
<td>960</td>
</tr>
<tr>
<td>lower</td>
<td></td>
<td>183</td>
<td>206</td>
</tr>
<tr>
<td>upper</td>
<td>$T_{02} = 7.0$ year</td>
<td>1158</td>
<td>983</td>
</tr>
<tr>
<td>lower</td>
<td></td>
<td>135</td>
<td>153</td>
</tr>
</tbody>
</table>

Table 6.3 **Calculated volume changes upper and lower zone after a period of 2 years for different combinations of $T_0$-periods.**

Table 6.3 shows the effect of the interaction between the $T_0$-periods. For instance a change in the $T_{01}$-period (relation upper-middle zone) will also affect the volume change of the lower zone even when the $T_{02}$-period (relation middle-lower zone) does not change.

It was decided to choose the following $T_0$-periods.

$T_{01} = 1.5$ year  
$T_{02} = 5.0$ year

Converted to cross-shore coastal constants with Eqs. 6.1 and 6.2:

$s_{y1} = 1.33$ m/year  
$s_{y2} = 0.30$ m/year
With these values the increase of the upper zone after two years is $960 \times 10^3$ m$^3$ and the increase of the lower zone $206 \times 10^3$ m$^3$ (see Table 6.3). These values are accurate enough for the calculations. The $T_0$-period of the relation between upper zone and middle zone is smaller than the $T_0$-period of the relation between middle and lower zone. This implies that the nourishment sand spreads out faster in onshore direction than in offshore direction. In the end the nourishment sand will be spread out equally over the entire profile.

The chosen $T_0$-periods are not necessarily the (only) right ones, much depends on the schematization of the presumed profile behaviour as an effect of the nourishment.

The values of the cross-shore constants differ strongly from the values used by Kersting in his forecast study of the Terschelling supply (1995a). Kersting used $T_0$-periods of 10 years. Kersting linked the $T_0$-periods intuitively to the cyclic period of the bar system. There was no real physical background for the values estimated by Kersting.

The results of the present study indicate much smaller $T_0$-periods. Cross-shore diffusion seems to take place at a higher rate than estimated by Kersting.

Bakker (1995) derived a $T_0$-period of 1.5 years for a two-line schematization of the Terschelling supply. The derivation of the $T_0$-period was based upon the measured profile development after the nourishment. His results are in good agreement with the present results.

Chapter 7 will compare the results of the corrected measurements and the three-line model calculations.
CHAPTER 7  RESULTS

7.1 Introduction

The three-line model was run with the constants derived in the previous two chapters. The results of the calculations with the three-line model are presented in two different ways. First the calculated development of the y-values per zone in time is showed in graphs. This is discussed in Section 7.2. The output of the three-line model is visualized by means of a spreadsheet program. The graphs show the profile development as an effect of the nourishment. Secondly the development of the y-values in the different boxes has been calculated and compared with the measurements. The results of this comparison between measured and calculated development will be discussed in Section 7.3. Finally in Section 7.4 conclusions about the three-line modelling of the Terschelling supply are drawn.

7.2 Nourishment behaviour

The three-line model was run with the constants derived in the previous two chapters.

The constants used for the longshore transport were:

\[ s_1 = 3.630 \times 10^6 \text{ m}^3/\text{year}/\text{rad} \]
\[ s_2 = 0.964 \times 10^6 \text{ m}^3/\text{year}/\text{rad} \]
\[ s_3 = 0 \text{ m}^3/\text{year}/\text{rad} \]

The constants used for the cross-shore transport were:

\[ s_{v1} = 1.33 \text{ m/year} \quad (T_{01} = 1.5 \text{ year}) \]
\[ s_{v2} = 0.30 \text{ m/year} \quad (T_{02} = 5.0 \text{ year}) \]

The 9.6 km stretch of coast used for the evaluation of the bathymetric measurements was simulated with the three-line model. Fig. 7.1 through Fig. 7.3 show the calculated profile development in the three zones. The scales of the y-axes are chosen such that the area below a curve enables an easy comparison of the amount of sand in the zone (the heights of the upper, middle and lower zone are resp. 6 m, 3 m and 3 m). The values at the x-axis are relative to the RSP-pole system.

The graphs show the diffusive character of the model. The nourishment is located in the middle zone (see Fig. 7.2). The sand of the nourishment spreads out in cross-shore and longshore direction. The distribution of the nourishment sand in cross-shore direction causes a decrease of the middle zone volume. The effect of the magnitude of the coastal constants can be noticed very well. Much more sediment is transported to the upper zone than to the lower zone because of the different cross-shore constants. The part of the sand of the shoreface nourishment that is transported to the upper zone

67
Fig. 7.1  Calculated development y-values in the upper zone.

Fig. 7.2  Calculated development y-values in the middle zone.
spreads out rather quickly. This is the effect of the relatively large longshore transport coefficient \( s_1 \). In the middle zone the distribution of the sand in longshore direction is less. The longshore coastal constant \( s_2 \) is much smaller. Sand that moves to the lower zone is not transported longshore \( s_3 = 0 \). However a small spread in longshore direction can be seen. This is caused by the fact that a certain amount of nourishment sand is first transported shore parallel in middle and upper zone and at a later stage shore perpendicular to the lower zone.

### 7.3 Comparison measurements and three-line model calculations

#### 7.3.1 Introduction

A comparison between results of the calculation and the measurements can now be made. This will be done in two different ways. First the development in the boxes after two years based on the trendlines will be compared with the three-line model calculations. Next the presumed autonomous behaviour (see Chapter 6) in the different boxes will be added to the three-line model calculation results. The outcome will be compared with the actual measurements.

#### 7.3.2 Comparison measured versus calculated situation after two years

The development in the boxes after two years based on the trendlines (referred to as “measured” development) can now be compared with the three-line model calculations. This will be done per zone. It is stressed that the method of correction
The results for the upper zone are very good (see Fig. 7.4). There is great similarity between the measured and calculated development. The boxes right above the nourishment have profited most of the nourishment. Due to the profile development along the coast the boxes in the east and the west also benefit from the nourishment. The calculated development in longshore direction matches very well with the measured development. Apparently the longshore coastal constant of the upper zone as calculated in Chapter 5 is of the right order of magnitude. The largest difference between measured and calculated development is observed at box G1. The measured increase is much smaller than the calculated increase. As explained earlier, this might be the effect of the shoreface nourishment on the longshore transport. The nourishment will cause wave breaking further offshore. The longshore transport might decrease landward of the nourishment. At the leeside of the nourishment the longshore transport in the upper zone could increase again. This might explain why the development of box G1 lags behind compared to the other boxes.

Remark: The comparison of the corrected measured versus calculated development after 2 years will give different results than a comparison for example of the situation 1 year after the nourishment. This is because the development according to the trendlines is linear and the development according to the three-line model is exponential. The measurement trendlines are based upon two years of measurement data. Therefore the situations after two years are compared.
Fig. 7.5 Corrected measured versus calculated development of the middle zone 2 years after nourishment.

The graph of the middle zone (Fig. 7.5) shows less convincing results. The difference between the measured and calculated developments of the boxes E2 and F2 is large. This eastern part of the nourishment is surprisingly stable (compare Fig. 7.2). This is in contradiction to the development of the boxes of the upper zone. Box E1 and F1 are supposed to have benefited from the boxes below. The y-values of the boxes E2 and F2 do not show such a large decrease. The western boxes of the nourishment (box C2 and D2) show a much larger decrease. A possible explanation is that the nourishment migrates in eastward direction. This can not be modelled with the three-line model. In case of an alongshore symmetrical supply, the longshore profile development will also be symmetrical alongshore. The used correction method resulted in negative y-values in the boxes A2, B2 and H2. The three-line model will never predict negative y-values.

In the lower zone the changes in y-value after 2 years are much smaller than in the upper and the middle zone (see Fig 7.6). With the used correction method the measured y-values in the east increase stronger than in the west. The three-line model predicts larger increases in y-value right below the nourishment. The relative differences between calculated and measured development are large.
7.3.3 Comparison measured versus calculated development

A comparison of the measurements and the three-line model calculations is also made in a different way. The profile development caused by the autonomous behaviour, as schematized in Chapter 6, is added to the three-line model calculations. In this way the results of the three-line model calculations can be compared with the actual (uncorrected) measurement points. Similar comments can be made as for the previous method of comparison. The advantage of this method of comparison is that it shows the scale of the fluctuations in the measurements compared to the general trend.

Fig. 7.7 shows the results for the upper zone. The results are satisfactory. It is stressed again that the used assumptions about the autonomous behaviour have a large effect on the comparison of the measurements and the calculations. The fluctuations of the measurements are relatively large. This makes it difficult to judge whether an exponential trend gives better results than a linear trend.

Fig. 7.8 shows the results for the middle zone. The differences between measurements and calculations are much larger than for the upper zone. In the boxes E2 and F2 the measured development differs most strongly from the three-line model calculations. A decrease in y-value would have been expected due to redistribution of the nourishment sand in longshore and cross-shore direction, rather than the observed almost constant values.

Fig. 7.9 presents the results for the lower zone. The fluctuations between the different measurement points are relatively large compared to the general trend in y-value.
Fig. 7.7  Measured versus calculated development in the boxes of the upper zone (autonomous behaviour is added to the three-line model calculations).
Fig. 7.8 Measured versus calculated development in the boxes of the middle zone (autonomous behaviour is added to the three-line model calculations).
Fig. 7.9  Measured versus calculated development in the boxes of the lower zone (autonomous behaviour is added to the three-line model calculations).
7.4 Conclusions

The aim of the three-line model as applied in this study is to describe the general trend of the bathymetric development after execution of a nourishment. The comparison between calculated and measured development of the y-values showed that the model predicts the development quite well but that also considerable differences occur. However, it should be kept in mind that the correction of the bathymetric measurements for autonomous behaviour may have a large effect on the outcome of the comparison.

The calculated development of the y-values of the upper zone is very similar to the measured development. The results for the middle zone are less good. The three-line model will in principle predict symmetrical profile development in longshore direction in case of an alongshore symmetrical supply. From observations it is clear that the nourishment is moving eastward. This can not be modelled with the present three-line model. The differences between measured and calculated development in the lower zone are also considerable.

It is difficult to distinguish between autonomous profile development and the effects of the nourishment.

The three-line model is based on the hypothesis that there exists an equilibrium profile in cross-shore direction. It can be questioned whether this concept is correct in case of a bar system with cyclic behaviour.

The question is also raised whether the nourishment has acted as a feeder berm or as a breakwater, or, more probably, as a combination of both. The effects of a shoreface nourishment behaving as a submerged breakwater can not be modelled with the present three-line model.

It can be concluded that some important features of the effects of a nourishment can not be modelled with the present three-line model.

The cross-shore constants were determined by studying the measured profile development, which is acceptable for research purposes. Because of the lack of a theoretical basis for these constants, the derived values are rather empirical and therefore not suited for an a priori predictive application of the model.

With the used schematizations the large volume increase in the upper zone is almost entirely caused by cross-shore transport. It can be questioned whether this is correct.

The validity of the used correction method of the bathymetric measurements for autonomous behaviour is very important. The three-line model is only capable of simulating the effect of the nourishment. The profile measurements therefore had to be corrected for the autonomous behaviour. This correction was based upon the trends in the foregoing period. The autonomous behaviour has its fluctuations in time. Different weather conditions, e.g., events like storms, affect the behaviour of the coast. The present knowledge of sediment transport is not that far developed that reliable corrections can be made for aberrant environmental conditions. It is yet not feasible to explain the profile development from measurement to measurement by studying the environmental conditions in between. Therefore models like the three-line model can be useful to describe the general trend of development as an effect of a nourishment.
The evaluation of the Terschelling case has certainly yielded an increased insight in the behaviour of the shoreface nourishment. The investigation of the autonomous behaviour has also resulted in more knowledge about the development of the coast during the period prior to the nourishment. The three-line model is capable to model some of the important features of the behaviour of a nourishment like cross-shore diffusivity and longshore dispersion. Other important aspects of nourishment behaviour like asymmetrical development in longshore direction and the functioning as submerged breakwater can not be modelled.
REFERENCES

- Bakker, W.T., 1969
  Computation of the longshore transport by waves with the method of parallel depth contours (in Dutch)
  (Berekening van het langstransport door golven met de methode van evenwijdige dieptelijnen)
  Rijkswaterstaat, Dir. Waterhuishouding en Waterbeweging
  Studierapport WWK 69-7

  Computation of the sediment transport by the method of Svašek in case of an angle between beach and shoreface (in Dutch)
  (Berekening van het zandtransport volgens de methode Svašek bij een strand en een vooroever die een hoek met elkaar maken)
  Rijkswaterstaat, Dir. Waterhuishouding en Waterbeweging
  Studierapport WWK 71-18

- Bakker, W.T., 1995
  The magnitude of cross-shore diffusivity
  Netherlands Centre for Coastal Research

- Groenewoud, M.D., 1996
  Three-line modelling of the Torsminde supplies
  Delft University of Technology, Faculty of Civil Engineering

- Guillén, J., 1995
  Sediment response in a littoral system affected by shoreface nourishment
  IMAU Report

  Proceedings Coastal Dynamics '94
  American Society of Civil Engineers (ASCE), 1994, pp. 402-416

- Kersting, N.F., 1995a
  Pilot study concerning the behaviour of coastal supply on the Dutch Wadden island of Terschelling
  Delft University of Technology, Faculty of Civil Engineering

- Kersting, N.F., 1995b
  Evaluation of a combined inshore and beach nourishment at the German Wadden island of Norderney
  Delft University of Technology, Faculty of Civil Engineering
- Noordstra, P., 1992
  Nourishment Terschelling (in Dutch)
  Kustsuppletie Terschelling 1993
  Rapport ANW 92.20, Rijkswaterstaat, Directie Friesland

- NOURTEC, 1994
  Design Report of the Three NOURTEC Test Sites
  National Institute for Coastal and Marine Management (RIKZ)
  The Hague, The Netherlands

- Pelnard Considère, R., 1954
  Essai de théorie de l’évolution de formes de rivages en plages de sable et de galets (in French)
  Quatrième Journées de l’Hydraulique, Paris
  Les Energies de la Mer, Question III

- Ruessink, B.G. and Kroon, A., 1994
  The behaviour of a multiple bar system in the nearshore zone of Terschelling, the Netherlands: 1965-1993
  Marine Geology 121 (1994), pp. 187-197

- Smit, E.S.P., 1987
  The role of cross-shore sediment transport on the development of the Dutch coast (in Dutch)
  (De rol van sediment-dwarstransport in de ontwikkeling van de Hollandse kust)
  Delft University of Technology, Faculty of Civil Engineering

- Svašek, J.N., 1968
  The effect of breaking waves on the stability of sandy coasts (in Dutch)
  (Invloed van brekende golven op de stabiliteit van zandige kusten)
  Rijkswaterstaat, Deltadienst, Waterloopkundige Afdeling, Nota W 68.083

- Svašek, J.N. and Bijker, E.W., 1969
  Two methods for determination of morphological changes induced by coastal structures
  XXIInd Int. Nav. Congress Paris, section II, item 4

- Westlake, S.J., 1995
  Behaviour of a Shoreface Nourishment, Terschelling, The Netherlands
  M. Sc. Thesis
  International Institute for Infrastructural, Hydraulic and Environmental Engineering, Delft, The Netherlands
APPENDIX A

Flow diagram and listing 3LINES computer program
Flow diagram 3LINES computer program

- Run program '3LINES'
- Default values for input parameters are shown on screen
- Possibility to change default values of input parameters
- Possibility to show longshore and cross-shore transport matrix on screen
- Initial y-values in the three zones are shown on screen
- Total calculation time and number of time steps are shown on screen
- Define output file
- Program starts calculation development y-values in time
- Calculated y-values per year are written to output file
- End of program '3LINES'
PROGRAM calculation_y_values (INPUT, outputfile);
USES CRT, GRAPH, VENSTERS, io_tools, tp_tools;

CONST path = 'c:\3lines\';
BGIPath = 'c:\tpascal\gbi';

TYPE matrix = ARRAY [1..3 , 1..3] OF REAL;
TwoDmatrix = ARRAY [1..3 , 1..500] OF REAL;
outputfilematrix = ARRAY [1..250 , 1..15] OF REAL;

VAR Cross , Long
     XYmatrix , Temporary
     i , j , p , n , k , d , xmax , xnumax , timemax , g
     S1 , S2 , S3 , sy1 , sy2 , h1 , h2 , h3 , dt , dx
     answer
     longterm , crossterm , q
     length , h , outdx , time
     str1 , screen , color
     nourlength , volume , dv , hoeksin , hoekcos
     year , Gd , Gm , Px , Qy , phi , t
     a , b , c
     by , by1 , by2 , by3 , by0 , P0 , Q0
     breakoff
     outmatrix
     pictures , outputl
     filename
     outputfile

PROCEDURE initialvalue;
BEGIN
S1  := 2650000 ;  \{m3 per year per rad\}
S2  := 222000  ;  \{m3 per year per rad\}
S3  := 0 ;       \{m3 per year per rad\}
sy1 := 1.60 ;    \{m/year\}
sy2 := 1.33 ;    \{m/year\}
h1  := 8 ;       \{meter\}
h2  := 2 ;       \{meter\}
h3  := 4 ;       \{meter\}
dt  := 1/2000 ;  \{year\} \{Must be a year divided by an INTEGER\}
dx  := 50 ;      \{meter\} \{Must be a km divided by an INTEGER.\}
length := 5000 ; \{meter\} \{Total length of calculation.\}
nourlength:= 1000 ; \{meter\} \{Total length of nourishment\}
volume := 250000 ; \{m3\}
time := 3 ;      \{year\}
outdx := 100 ;   \{meter\} \{For every 'outdx' there is an output value\}
FOR i:=1 TO 3 DO
BEGIN
  FOR j:=1 TO 500 DO
  BEGIN
    XYmatrix[i,j]:=0;
    Temporary[i,j]:=0;
  END;
END;
breakoff:=false;
output1:=false;
pictures:=false;
END; (** initial value ***)

PROCEDURE valuechange (VAR S1 , S2 , S3 , sy1 , sy2 , h1 , h2 , h3 , dt , dx : REAL;
                       VAR nourlength , length , volume , time , outdx : REAL);
BEGIN
  maakvenster(2,2,79,24,2);
  WRITELN('Please enter the values of the parameters.');
WRITELN('Type a zero if you want to use the default value of a parameter.');
a := 0;
{temporary variable}
WRITE('S1 (', S1:8:0, ',') ; readln(a); if a > 0 then S1 := a;
WRITE('S2 (', S2:8:0, ',') ; readln(a); if a > 0 then S2 := a;
WRITE('S3 (', S3:8:0, ',') ; readln(a); if a > 0 then S3 := a;
WRITE('Sy1 (', Sy1:8:2, ',') ; readln(a); if a > 0 then Sy1 := a;
WRITE('h1 (', h1:8:2, ',') ; readln(a); if a > 0 then h1 := a;
WRITE('h2 (', h2:8:2, ',') ; readln(a); if a > 0 then h2 := a;
WRITE('h3 (', h3:8:2, ',') ; readln(a); if a > 0 then h3 := a;
WRITE('dt (', dt:8:4, ',') ; readln(a); if a > 0 then dt := a;
WRITE('dx (', dx:8:2, ',') ; readln(a); if a > 0 then dx := a;
WRITE('length of calculation : (', length:8:0, ','));
READLN(a); IF a > 0 THEN length := a;
WRITE('amount of nourishment : (', volume:8:0, ','));
READLN(a); IF a > 0 THEN volume := a;
WRITE('length of nourishment : (', nourlength:8:0, ','));
READLN(a); IF a > 0 THEN nourlength := a;
WRITE('time period of calculation : (', time:8:2, ','));
READLN(a); IF a > 0 THEN time := a;
WRITE('output distance outdx : (', outdx:8:2, ','));
READLN(a); IF a > 0 THEN outdx := a;
WRITELN;
sliwitvenster;
CLRSCR;
END; {*** valuechange ***}

PROCEDURE matrixmaking(Sl, S2, S3, syl, sy2, hi, h2, h3 :REAL);
BEGIN
{*** Filling of the matrices with zeros ***}
FOR i:=1 TO 3 DO
BEGIN
  FOR j:=1 TO 3 DO
  BEGIN
    Long[i,j] := 0;
    Cross[i,j] := 0;
  END;
END;
{*** Input of values in the longshore transport matrix ***}
Long[1,1] := Sl / hi;
Long[2,2] := S2 / h2;
Long[3,3] := S3 / h3;
{*** Input of values in the cross-shore transport matrix ***}
Cross[1,1] := - syl / hi;
Cross[1,2] := syl / hi;
Cross[2,1] := syl / h2;
Cross[2,2] := -(syl + sy2) / h2;
Cross[3,2] := sy2 / h2;
Cross[3,3] := - sy2 / h3;
IF outputl = true THEN
BEGIN
  {Filling of the outmatrix}
  FOR i:=1 TO 250 DO
  BEGIN
    FOR j:=1 TO 15 DO
    BEGIN
      outmatrix[i,j] := 0;
    END;
  END;
END;
END; {*** matrixmaking ***}

PROCEDURE stability ( Long : matrix; q, dx : REAL);
BEGIN
FOR j:=1 TO 3 DO
BEGIN
END;
END; {*** stabi ...
IF \( q*\text{Long}[j,j] > 1/2 \) THEN \{stability check\}
BEGIN
CLRSCR;
WRITELN;
WRITELN('The calculation will be instable with the chosen dt, dx and');
WRITELN('longshore transport coefficients. Therefore choose a smaller');
WRITELN('dt-value or larger dx-value');
readln;
breakoff:=true;
END;

IF \( q*\text{Long}[j,j] / 1/6 > 1.5 \) THEN \{deviation of accuracy demand\}
BEGIN \{ is larger as 50 % \}
CLRSCR;
WRITELN('q*\text{Long}[j,j] = ', (q*Long_[j,j]) : 4 : 3, ' > 1/6 met j= ',j:2);
WRITELN('With the chosen values the calculation will not have the optimal');
WRITELN('accuracy. Choosing a smaller dt-value will improve the accuracy');
WRITELN('For example dt = 1/',round(1/(1/6 * dx*dx / Long_[j,j])):4,' year');
WRITELN('Would you like to continue anyway (y/n)?');
READLN(answer);
IF answer = 'n' THEN breakoff:=true;
END;
END; \{*** stability and accuracy ***\}

PROCEDURE matrixprinting( Long, Cross : matrix);
BEGIN
CLRSCR;
maakvenster(3,1,60,10,2);
WRITELN;
WRITELN(' Long-shore transport matrix:');
WRITELN;
FOR i:=1 TO 3 DO
BEGIN
WRITE(' ');
FOR j:=1 TO 3 DO
BEGIN
WRITE(Long_[i,j]:8:0,' ');
END;
WRITELN;
END;
maakvenster(3,12,60,21, 2);
WRITELN;
WRITELN(' Cross-shore transport matrix:');
WRITELN;
FOR i:=1 TO 3 DO
BEGIN
WRITE(' ');
FOR j:=1 TO 3 DO
BEGIN
WRITE(Cross[i,j]:8:2,' ');
END;
WRITELN;
END;
READLN;
sluitvenster;
sluitvenster;
clrscr;
END; \{*** matrixprinting ***\}

PROCEDURE calculate \( \{ q, dt \) : REAL \; \)
BEGIN \( \text{Long}, \text{Cross} : \text{matrix} \; \)
VAR Temporary : TwoDmatrix;
BEGIN \{calculation of the \( y_1, y_2, y_3 \)-values for every \( x \) and \( t=k*dt \}\)
FOR i:= 2 TO n DO \{ From \( x = dx \) to \( x = (\text{length-}dx) \}
BEGIN
FOR j:=1 TO 3 DO
BEGIN
longterm := q*Long[j,j]*(XYmatrix[j,j-1]-2*XYmatrix[j,j]+XYmatrix[j,j+1]);
crossterm := 0;
FOR d:= 1 TO 3 DO
BEGIN
  crossterm := crossterm + dt*(Cross[d,j]*(XYmatrix[d,j]));
END;
Temporary[j,i] := XYmatrix[j,j] + longterm + crossterm;
END;
END;
END; {*** calculate •*•}

PROCEDURE calculateborder1( q, dt : REAL;
  n : INTEGER;
  Long, Cross : matrix;
  XYmatrix : TwoDmatrix;
VAR Temporary : TwoDmatrix);
BEGIN (calculates for x=0 the y1, y2, y3-values for t=k*dt)
i:= 1;
FOR j:=1 TO 3 DO
BEGIN
  longterm := q*Long[j,j]*(-2*XYmatrix[j,i]+2*XYmatrix[j,i+1]);
crossterm := 0;
FOR d:= 1 TO 3 DO
BEGIN
  crossterm := crossterm + dt*(Cross[d,j]*(XYmatrix[d,j]));
END;
Temporary[j,i] := XYmatrix[j,i] + longterm + crossterm;
END;
END; {*** calculateborder1 ***}

PROCEDURE calculateborder2( q, dt : REAL;
  n : INTEGER;
  Long, Cross : matrix;
  XYmatrix : TwoDmatrix;
VAR Temporary : TwoDmatrix);
BEGIN (calculates for x = length the y1, y2, y3-values for t=k*dt)
i:= n+1;
FOR j:=1 TO 3 DO
BEGIN
  longterm := q*Long[j,j]*(-2*XYmatrix[j,i]+2*XYmatrix[j,i-1]);
crossterm := 0;
FOR d:= 1 TO 3 DO
BEGIN
  crossterm := crossterm + dt*(Cross[d,j]*(XYmatrix[d,j]));
END;
Temporary[j,i] := XYmatrix[j,i] + longterm + crossterm;
END;
END; {*** calculateborder2 ***}

PROCEDURE initialsituation (VAR XYmatrix : TwoDmatrix;
  dx, nourlength, length, volume, dV, h2 : REAL);
BEGIN
xmax := round (nourlength / dx);
xnul := round (0.5*(length-nourlength)/dx);
dV := volume/(nourlength); (volume per running meter)
FOR i:= xnul TO (xnul + xmax) DO
BEGIN
  XYmatrix[2,i] := dV/h2; (initial values of y2 as result of nourishment)
  { XYmatrix[3,i] := dV/h3; } (nourishment in lower part)
  { XYmatrix[4,i] := dV/h4; } (nourishment in upper part)
END;
CLRSCR;
maakvenster(2,3,79,20,2);
WRITELN;
WRITELN('Initial values are defined.');
WRITELN('Some characteristic values: ');
WRITELN;
WRITELN('dx = ', dx: 6:2);
{ WRITELN('xmax = ', xmax: 6,
maal dx = ', (xmax*dx):8:1, ' m');
WRITELN('xnul = ', xnum: 6,
maal dx = ', (xnum*dx):8:1, ' m');
WRITELN('xnul+xmax = ', (xnum+xmax):6,
maal dx = ',((xnum+xmax)*dx):8:1); }
WRITELN('length = ',length:8:1, ' m');
WRITELN('nourlength = ',nourlength:8:1, ' m');
WRITELN('dV = ',dV:8:1, ' m3/m1');
WRITELN('volume = ',volume:8:1, ' m3');
{ WRITELN('XYmatrix[ Y2, xnum-1 ] = ',XYmatrix[2, (xnum-1)]:8:2);
WRITELN('XYmatrix[ Y2, xnum ] = ',XYmatrix[2, xnum]:8:2);
WRITELN('XYmatrix[ Y2, xnum+xmax ] = ',XYmatrix[2, (xnum+xmax)]:8:2);
WRITELN('XYmatrix[ Y2, xnum+xmax+1 ] = ',XYmatrix[2, (xnum+xmax+1)]:8:2); }
READLN;
sluitvenster;
END; {*** initialsituation ***}

PROCEDURE equalization(VAR XYmatrix, Temporary : TwoDmatrix; k : INTEGER);
BEGIN
FOR i:=1 TO 500 DO
BEGIN
FOR j:=1 TO 3 DO
BEGIN
XYmatrix[j,i]:=Temporary[j,i];
END;
END;
END; {*** equalization ***}

PROCEDURE filloutmatrix (XYmatrix : TwoDmatrix;
year, k, n : INTEGER
VAR t : INTEGER;
dx, outdx : REAL)
BEGIN
IF year=0 THEN {defining x-coordinates}
BEGIN
p:=1;
FOR j:=1 TO 3 DO
BEGIN
FOR i:=1 TO n+1 DO
BEGIN
IF frac((i-U*dx/outdx) = 0 THEN {only for every outdx}
BEGIN
outmatrix[p,1] := (i-1)*dx; {x-values}
outmatrix[p,2] := XYmatrix[j,i]; {y-values at t=0}
p:=p+1;
END;
END;
END;
END;
IF year <> 0 THEN IF year <= 10 THEN
BEGIN
BEGIN
END;
END;
END;
END; {for every y values }
BEGIN
BEGIN
END;
IF frac((i-1)*dx/outdx) = 0 THEN
BEGIN
   outmatrix[p,t] := XYmatrix[j,i];
   p := p+1;
END;
END;
END;
END; {*** fill outmatrix ***}

PROCEDURE outmatrixwriting (outmatrix : outputfilematrix;
                          n : INTEGER;
                          dx, outdx : REAL);
BEGIN
   p := 1;
   FOR j := 1 TO 3 DO
      BEGIN
         WRITELN(outputfile);
         WRITELN(outputfile);
         WRITELN(outputfile);
         WRITELN(outputfile);
         FOR i := 1 TO n+1 DO
            BEGIN
               IF frac((i-1)*dx/outdx) = 0 THEN
                  BEGIN
                     FOR g := 2 TO 12 DO
                        BEGIN
                           WRITE(outputfile, outmatrix[p,g] : 8:2, ' ');
                        END;
                     p := p+1;
                     WRITELN(outputfile, ' ', ((i-1)*dx/1000) : 8:2, ' km');
                  END;
               END;
            END;
      END;
END; {*** outmatrixwriting ***}

PROCEDURE toscreen (XYmatrix : TwoDmatrix; n : INTEGER; dx, outdx : REAL);
BEGIN
   maakvenster(2,1,79,24,2);
   WRITELN(' This is the initial situation:
            y1  y2  y3 ');
   FOR j := 1 TO 3 DO
      BEGIN
         WRITE(XYmatrix[j,1] : 8:2, ' ');
      END;
   WRITELN(' voor x = 0.00 km');
P := 3;
   FOR i := 2 TO n+1 DO
      BEGIN
         IF frac((i-1)*dx/250) = 0 THEN
            BEGIN
               IF frac(p/20) = 0 THEN
                  BEGIN
                     P := 1;
                     WRITELN;
                     WRITE(' Press enter ');
                     READLN;
                     WRITELN(' y1  y2  y3 ');
                  END;
               FOR j := 1 TO 3 DO
                  BEGIN
                     WRITE(XYmatrix[j,(i-1)] : 8:2, ' ');
                  END;
               WRITELN(' voor x = ', ((i-1)*dx/1000) : 4:2, ' km');
               P := P+1;
            END;
      END;
BEGIN
   TextAttr := $17;
   Checkbreak := true;
   CLRSCR;
   initialvalue;
   maakvenster(2,2,79,24,2);
   WRITELN(' The initial values are:
   WRITELN;' 'Sl = ', Sl, ' m3/year/rad');
   WRITELN('S2 = ', S2, ' m3/year/rad');
   WRITELN('S3 = ', S3, ' m3/year/rad');
   WRITELN('Sy1 = ', sy1, ' m/year');
   WRITELN('Sy2 = ', sy2, ' m/year');
   WRITELN('h1 = ', h1, ' meter');
   WRITELN('h2 = ', h2, ' meter');
   WRITELN('h3 = ', h3, ' meter');
   WRITELN('dt = ', dt, ' year');
   WRITELN('dx = ', dx, ' meter');
   WRITELN('The output distance -outdx- is : ', outdx, ' m');
   WRITELN('Length of area to be calculated : ', length, ' m');
   WRITELN('Amount of nourishment : ', volume, ' m3');
   WRITELN('Length of nourishment : ', nourlength, ' m');
   WRITELN('Total calculation time : ', time, ' year');
   WRITELN;
   WRITELN('Do you want to change some values ? (y/n) ');READLN(answer);
   sluitvenster;
   IF answer = 'y' THEN
      BEGIN
         valuechange(Sl, S2, S3, sy1, sy2, h1, h2, h3, dt, dx, nourlength, length, volume, time, outdx);
      END;
      matrixmaking(Sl, S2, S3, sy1, sy2, h1, h2, h3);
      WRITELN;
      maakvenster(8,5,72,9,1);
      WRITELN;
      WRITE('Do you want a screenprint of the matrices Long en Cross ? (y/n) ');READLN(answer);
      sluitvenster;
      IF answer = 'y' THEN
         BEGIN
            matrixprinting(Long, Cross);
         END;
         q:= dt / (dx*dx); {Timestep relative to the square of dx }
         stability(Long, q, dx); {Stability and accuracy check }
         n:= ROUND(length/dx); {Number of x-coordinates}
         IF n >= 500 THEN
            BEGIN
               CLRSCR;
               WRITELN('Either the length of the area that has to be calculated is too');
               WRITELN('big or the gridsize -dx- is too small. Please enter new values');
               WRITELN('for the length and/or dx ');breakoff := true;
               IF breakoff = false THEN WRITELN('breakoff = false 6');READLN;
               END;
               initialsituation(XYmatrix, dx, nourlength, length, volume, dv, h2);
toscreen(XYmatrix, n, dx, outdx);  \{initial XYmatrix to screen\}

timemax := round(time/dt);

maakvenster(3,3,79,24,2);

WRITELN('The calculation will be executed ',n:3,' times.');
WRITELN('The time of calculation is',time:6:0,' years.');
WRITELN('The number of timesteps is',timemax:6,'.');
WRITELN;

WRITE('Do you want a datafile ? (y/n) ');
READLN(answer);
if answer <> 'y' THEN outputl := false ELSE BEGIN
outputl:=true;
repeat
  GoToXY(3,5);
  filename:='c:\nourtec\output\';
  Write('Enter the path and name of the outputfile: ');
  Readstr(filename,35,true,true);
until Checkedoutputfile (filename,true);
Assign (outputfile,filename);
Rewrite (outputfile);
END;

WRITELN;
WRITELN;
WRITELN;
WRITELN;
WRITELN;
WRITELN;

sluitvenster;
pictures:=false;

IF outputl=true THEN BEGIN
\{the outputfilematrix is filled with initial values\}
t:=0;
year:=0;
filloutmatrix (XYmatrix, year, k, n, t, dx, outdx);
END;

IF outputl=false THEN IF pictures=false THEN BEGIN
CLRSCR;

\{You do not want any datafile. That is why the program now will be aborted. Bye bye\};
DELAY(3000);
breakoff:=true;

sluitvenster;
END;
WHILE NOT breakoff DO
BEGIN
  FOR k:=1 TO timemax DO {calculation for every timestep till maximum time}
  BEGIN
    calculate( q, dt, Long, Cross, n, XYmatrix, Temporary );
    {calculation for every x-coordinate till xmax }
    {except for i=1, because in that case x=0 }
    calculateborder1( q, dt, n, Long, Cross, XYmatrix, Temporary );
    calculateborder2( q, dt, n, Long, Cross, XYmatrix, Temporary );

    equalization(XYmatrix, Temporary, k);

    IF FRAC(k/round(1/dt)) = 0 THEN
    BEGIN
      year:= round(k*dt);
      IF output1=true THEN
      BEGIN
        filloutmatrix(XYmatrix, year, k, n, t, dx, outdx);
      END;
      IF pictures=false THEN
      BEGIN
        maakvenster(15,3,65,8,1);
        WRITELN(' The situation after ',year:3,' year');
        WRITELN(' has been calculated:');
        DELAY(1500);
        sluitvenster;
      END;
      IF year=time THEN breakoff:=true;
    END;
  END;
END;

IF output1=true THEN
BEGIN
  maakvenster(10,10,69,15,2);
  outmatrixwriting ( outmatrix, n, dx, outdx);
  CLOSE(outputfile);
  WRITELN(' The calculation has been executed.');
  WRITELN(' The calculated values are');
  WRITELN(' listed in: ', filename:9);
  READLN;
  sluitvenster;
END;

END. {*** Main programme ***}
APPENDIX B

Flow diagram and listing CERC computer program
Flow diagram CERC computer program

Run program 'CERC'

Select output file

Define delta (angle of rotation of zone)

Define angle of wave approach

Select input file (which contains tables with wave data)

Program starts calculation of longshore transport for each combination of wave height, wave period and water level. Transport is multiplied by its probability of occurrence. Total transport is calculated and a division over the three zones is made.

Results are presented on screen and written to output file

End of program 'CERC'
PROGRAM CERC (INPUT,outputfile);
USES CRT, DOS, GRAPH, io_tools, tp_tools;
CONST gamma = 0.6 ;
g = 9.81 ;
LABEL FINISH;
TYPE datamatrix = ARRAY [1..16, 1..6] OF REAL;
VAR h3, h2, h1, h0 : REAL ; { depth at the lines }
Ho_sig, Ho_rms : REAL ; { significant wave height }
hbr, Hb, Phi, Phi2 : REAL ; { angle at breakdepth }
Tmo, dS1, dS2, dS3 : REAL ; { wave period at deep water }
chance : REAL ; { total transport at the lines }
Co, Cbr : REAL ; { probability of occurence }
number, exponent : REAL ; { variable angle }
Phi : REAL ; { total transport }
x, Sx : REAL ; { waterlevelchange due to wind & tide }
delta : REAL ; { total transport }
dh : REAL ; { wave celerity }
case1, case2, case3 : BOOLEAN ; { case }
getal : INTEGER ;
x, nb : REAL ; { variable }
C2, cosphi2, Phi2 : REAL ;
dirfilename : STRING ;
filename, answer : STRING ;
inputfile, outputfile : TEXT ;
pHT, pHW : datamatrix ;
i, j, k, S1, S2, S3, dummy : INTEGER ;
S1W1T, S2W1T, S3W1T : REAL ;
S1H, S2H, S3H : REAL ;
S1W1TH, S2W1TH, S3W1TH : REAL ;
totpTWH, totpTW1H : REAL ;
jahr : REAL ;
hbrmax : REAL ;
p, q, r : integer ;
t, u, v : integer ;
a, b : integer ;
test : real ;

FUNCTION Power ( number:REAL; exponent:REAL) : REAL;
BEGIN
  IF number=0 THEN BEGIN POWER:=0 END ELSE
  Power := exp (exponent*ln(number));
END; (Power)

FUNCTION ArcCos ( Phi: REAL) : REAL;
BEGIN
  ArcCos := ArcTan (sqrt (1-sqr (Phi)) /Phi);
END; (ArcCos)

FUNCTION tanh (x : REAL) : REAL;
VAR e2x : REAL ;
BEGIN
  e2x := exp(2*x);
\[
\tanh := \frac{e^{2x} - 1}{e^{2x} + 1};
\]

END; \{tanh\}

FUNCTION sinh (x : REAL) : REAL;
VAR ex : REAL;
BEGIN
  ex := exp(x);
  sinh := \frac{e^x - (1/e^x)}{2};
END; \{sinh\}

FUNCTION cosphi (C, Co, Phio : REAL) : REAL;
VAR var1, var2 : REAL;
BEGIN
  var1 := (C * sin(phio)) / Co;
  var2 := 1 - sqr(var1);
  cosphi := sqrt(var2);
END; \{cosphi\}

FUNCTION celerity (h, Tmo : REAL) : REAL;
VAR xn, a, Lo, f, fx : REAL;
BEGIN
  Lo := Tmo * Co;
  a := 2*pi * h / Lo;
  x := 0;
  xn := 1;
  i := 1;
  WHILE ABS(xn - x) > 0.00001 do
    BEGIN
      x := xn;
      f := x - tanh((a/x));
      fx := 1 + (a/sqr(x)) * (1 - sqr(tanh((a/x))));
      xn := x - (f/fx);
      i := i + 1;
    END;
  celerity := Co * xn;
END; \{celerity\}

FUNCTION n(hbr, c, Tmo : REAL) : REAL;
VAR lch2 : REAL;
BEGIN
  lch2 := (4 * pi * hbr) / (c * Tmo);
  n := 0.5 * (1 + (lch2 / sinh(lch2)));
END; \{n\}

PROCEDURE makematrixes(var pHT, pHW : datamatrix);
VAR i, j : INTEGER;
BEGIN
  FOR i := 1 TO 16 DO
    BEGIN
      FOR j := 1 TO 6 DO
        BEGIN
          READ(inputfile, dummy);
          pHT[i, j] := dummy;
          WRITE(pHT[i, j]:9:4);
        END;
      READLN(inputfile);
      WRITELN;
    END;
  READLN(inputfile);
  FOR i := 1 TO 16 DO
    BEGIN
      FOR j := 1 TO 6 DO
        BEGIN
          READ(inputfile, dummy);
          pHW[i, j] := dummy;
        END;
      READLN(inputfile);
      WRITELN;
    END;
  READLN(inputfile);
  READLN(inputfile);
END; \{makematrixes\}
PROCEDURE initialisation (var h2, h1, h0 : real);
BEGIN
  h3   := 0;
  h2   := 4;
  h1   := 6;
  h0   := 10;
  case1 := false;
  case2 := false;
  case3 := false;
END; {initialisation}

PROCEDURE brealcerdepth(Ho_rms, Phio, Tmo : REAL; var hbr, Phib, Co, nb : real);
VAR temp hbr, hbr const : REAL;
  var1, var2, var3 : REAL;
  cosphib, cosfrac : REAL;
  i,imax : INTEGER;
BEGIN
  var1 := sqr(Ho_rms);
  var2 := sqrt(gamma);
  var3 := sqrt(g);
  Co   := (g*Tmo)/(2*pi);
  hbr const := power(('(var1 * Co * cos(Phio)) / (2 * var2 * var3) ), 0.4);
  hbr := hbr const;
  imax := 50;
  FOR i:= 1 TO imax DO
  BEGIN
    Cbr := celerity(hbr, Tmo);
    cosphib := cosphi(Cbr, Co, Phio);
    Phib := arccos(cosphib);
    nb   := n (hbr, Cbr, Tmo);
    cosfrac := power((nb*cosphib),-0.4);
    hbr := hbr const * cosfrac;
  END;
END; {breakercerdepth}

PROCEDURE brealcerdepthdelta(Ho_rms, Phio, Tmo, delta : REAL; var hbr, Phib, Co, nb : real);
VAR temp hbr, hbr const : REAL;
  var1, var2, var3 : REAL;
  cosfrac, cosphib : REAL;
  i,imax : INTEGER;
BEGIN
  var1 := sqr(Ho_rms);
  var2 := sqrt(gamma);
  var3 := sqrt(g);
  Co   := (g*Tmo)/(2*pi);
  hbr const := power(('(var1 * Co * cos(Phio)) / (2 * var2 * var3) ), 0.4);
  hbr := hbr const;
  imax := 50;
  FOR i:= 1 TO imax DO
  BEGIN
    Cbr := celerity(hbr, Tmo);
    cosphib2 := cosphi(Cbr, Co, Phio);
    phi2 := arccos(cosphib2);
    FOR i:= 1 TO imax DO
    BEGIN
      Cbr := celerity(hbr, Tmo);
      cosphib := cosphi(Cbr, C2, (Phi2+delta)) ;
      Phib := arccos(cosphib);
      nb   := n (hbr, Cbr, Tmo);
      cosfrac := power((cos(Phi2+delta)) / (nb*(cos(Phi2)*cos(Phib))), 0.4);
    END;
  END;
END;
PROCEDURE BreakerCases( dh, h2, h1, h0, hbr : REAL);
BEGIN
  case1 := false;
  case2 := false;
  case3 := false;
  IF hbr < (h2 + dh) THEN BEGIN case1 := true; t:=t+1; END
  ELSE IF hbr < (h1 + dh) THEN BEGIN case2 := true; u:=u+1 END
  ELSE BEGIN case3 := true; v:=v+1 END;
END;

PROCEDURE Transport1(nb, Cbr, hbr, Phio, Co, Phib, delta : REAL;
VAR dS1, dS2, dS3 : REAL);
VAR var1, var2, var3, var4, var5 : REAL;
BEGIN
  dS1:=0; dS2:=0; dS3:=0;
  IF case1 THEN
  BEGIN
    var1 := sqrt(gamma);
    var2 := power(hbr, 3);
    dS1 := 0.080 * var1 * var2 * nb * g * sin(Phio) * cos(Phib) / Co;
  END
  ELSE IF case2 THEN
  BEGIN
    var1 := sqrt(gamma);
    var2 := power((h2+dh), 3);
    var3 := power(hbr, 3);
    var4 := celerity(h2, Tmo);
    cosphi2 := cosphi(C2, Co, Phio);
    phi2 := arccos(cosphi2);
    dS1 := 0.080 * var2 * nb * var1 * g * sin(Phio) * cos(Phib) / Co;
    test:=test+hbr;
  END
  ELSE IF case3 THEN
  BEGIN
    var1 := sqrt(gamma);
    var2 := power((h1+dh), 3);
    var3 := power((h2+dh), 3);
    var4 := power(hbr, 3);
    var 4 := celerity(h2, Tmo);
    cosphi2 := cosphi(C2, Co, Phio);
    phi2 := arccos(cosphi2);
    dS1 := 0.080 * var2 * nb * var1 * g * sin(Phio) * cos(Phib) / Co;
    dS2 := 0.080 * (var3-var2) * nb * var1 * g * sin(Phio) * cos(Phib) / Co;
    dS3 := 0.080 * (var4-var3) * nb * var1 * g * sin(Phio) * cos(Phib) / Co;
  END
END; {transport}

PROCEDURE Transport2(nb, Cbr, hbr, Phio, Co, Phib, delta : REAL;
VAR dS1, dS2, dS3 : REAL);
VAR var1, var2, var3 : REAL;
BEGIN
  dS1:=0; dS2:=0; dS3:=0;
  IF hbr > (h3+dh) THEN BEGIN
    h:=h+1;
    var1 := sqrt(gamma);
    var2 := power(hbr, 3);
    C2 := celerity(h2, Tmo);
    cosphi2 := cosphi(C2, Co, Phio);
    phi2 := arccos(cosphi2);
    dS1 := 0.080 * var2 * nb * var1 * g * sin(Phio) * cos(Phib) / Co;
    test:=test+hbr;
  END;
END; {transport}

Pay attention to the constant 0.040 for Hsig and 0.080 for Hrms !!!
BEGIN
  textattr := $17;
  clrscr;
  initialisation(h2,hi,ho);
  writeln ('This program needs an already existing outputfile. It appends the');
  writeln ('output data of this run at the end of the file');
  writeln ('');
  filename:='c:\nourtec\output\*.*';
  AskInputFile (filename,3,5,35,true);
  ASSIGN(outputfile,filename);
  APPEND(outputfile,'');
  writeln (outputfile,'');
  writeln (outputfile,'');
  Printheader (outputfile,filename);
  clrscr;
  WRITELN;
  WRITE('Open inputfile (y/n) ? ');
  READLN(answer);
  IF answer = 'y' THEN
    BEGIN
      WRITE('Which delta (degrees)? : ');
      READLN(dummy); delta := dummy * pi/180;
      WRITE('Which angle of approach (degrees)? : ');
      READLN(dummy); phio := dummy * pi/180;

      filename:='c:\nourtec\data\*.*';
      AskInputFile (filename,3,5,35,true);
      ASSIGN(inputfile,filename);
      RESET(inputfile);
      malcematrices (pHT, pHW);
      END
    ELSE
      BEGIN
        writeln ('The program is aborted.' );
        GOTO FINISH;
      END;
  END

  a:=0;b:=0;
  t:=0;u:=0;v:=0;
  r:=0;p:=0;q:=0;
  jaar := (60*60*24*365)/(sqr(1000.0)); { jaar • 10^-6 }
  S1:=0;S2:=0;S3:=0;
  FOR i:=1 TO 16 DO
    BEGIN
      SIWTIH :=0; S1H:=0;
      S2WTIH :=0; S2H:=0;
      S3WTIH :=0; S3H:=0; { transportrates for one H }
      totpWTIH :=0;
      Ho_sig := -0.25 + (i*0.50);
      Ho_rms := sqrt(0.5 * sqr(Ho_sig));
      FOR j:=2 TO 6 DO
        BEGIN
          S1WT :=0;
          S2WT :=0;
          S3WT :=0;
          for k:=1 to 6 do
            BEGIN
              dh := -1.25 + (k*0.5);
              Breakerdepth(Ho_rms, phio, Tmo, hbr, phib, Co, nb);
              IF hbr < (h2+dh) THEN
                BEGIN
                  IF delta <> (h2+dh) THEN
                    { hbr < (h2+dh) and delta <>0 }
BEGIN
  Breakerdepthdelta(Ho_rms, Phio, Tmo, delta, hbr, Phib, Co, nb);
  Transport2(nb, cbr, hbr, Phio, Co, Phib, delta, dS1, dS2, dS3);
  p:=p+1;
END
ELSE
BEGIN
  { hbr < (h2+dh) and delta = 0 }
  Breakercase(dh, h2, h1, h0, hbr);
  Transport1(nb, cbr, hbr, Phio, Co, Phib, delta, dS1, dS2, dS3);
  r:=r+1;
END
ELSE { hbr > (h2+dh) and all delta }
BEGIN
  Breakercase(dh, h2, hi, hO, hbr);
  Transport1(nb, cbr, hbr, Phio, Co, Phib, delta, dS1, dS2, dS3);
  q:=q+1;
END
END
FOR k
BEGIN
  SIWT := SIWT + (dSl * pHW[i,k] * 0.01);
  S2WT := S2WT + (dS2 * pHW[i,k] * 0.01);
  S3WT := S3WT + (dS3 * pHW[i,k] * 0.01);
END
FOR j
BEGIN
  totpTWlH := totpTWlH + pHT[i,j]*0.01;
  S1WH := (S1WT/H*totpTWlH)*jaar;
  S2WH := (S2WT/H*totpTWlH)*jaar;
  S3WH := (S3WT/H*totpTWlH)*jaar;
END
IF totpTWlH < 0.00001 THEN BEGIN totpTWlH := 0.000001 END;
  S1 := S1 + SIH;
  S2 := S2 + S2H;
  S3 := S3 + S3H;
  totpTWH := totpTWH + totpTWlH;
END
END
writeln(i:3);
END
writeln('sum total probability =', (100*totpTWH):12:3, ' %');
writeln('transport in upper zone: S1 = ', S1:10:6, ' m3/year');
writeln('transport in middle zone: S2 = ', S2:10:6, ' m3/year');
writeln('transport in lowest zone: S3 = ', S3:10:6, ' m3/year');
writeln('total transport := ', (S1+S2+S3):10:6, ' m3/year');
writeln('delta = ', (delta*180/pi):4:2, ' degrees');
writeln('phio = ', (phio*180/pi):5:1, ' degrees');
writeln('name inputfile = ', filename:15);
writeln('outputfile, sum total probability =', (100*totpTWH):12:3, ' %');
writeln('outputfile, transport in upper zone: S1 = ', S1:10:6, ' m3/year');
writeln('outputfile, transport in middle zone: S2 = ', S2:10:6, ' m3/year');
writeln('outputfile, transport in lowest zone: S3 = ', S3:10:6, ' m3/year');
writeln('outputfile, total transport := ', (S1+S2+S3):10:6, ' m3/year');
writeln('***** READY *****');
FINISH
READLN;
WRITELN(outputfile,'delta= ',(delta*180/pi):4:2,' degrees');
WRITELN(outputfile,'phio = ',(phio*180/pi):5:1,' degrees');
WRITELN(outputfile,'name inputfile = ', filename:IS);
WRITELN(outputfile, 'h0 = ',h0:4:1,' m');
WRITELN(outputfile, 'h1 = ',h1:4:1,' m');
WRITELN(outputfile, 'h2 = ',h2:4:1,' m');
WRITELN(outputfile, 'h3 = ',h3:4:1,' m');
WRITELN(outputfile, 'number of cases of waves breaking in zone 1 = ',t:3);
WRITELN(outputfile, 'number of cases of waves breaking in zone 2 = ',u:3);
WRITELN(outputfile, 'number of cases of waves breaking in zone 3 = ',v:3);
WRITELN(outputfile, 'total number of cases = ',(t+u+v):3);
CLOSE(outputfile);

END.