ELSEVIER

Coastal Engineering 47 (2002) 237–264

Coastal Engineering
An International Journal for Coastal, Harbour and Offshore Engineers

www.elsevier.com/locate/coastaleng

A summary of European experience with shore nourishment

L. Hamm[a,*], M. Capobianco[b], H.H. Dette[c], A. Lechuga[d], R. Spanhoff[e], M.J.F. Stive[f]

[a] *SOGREAH, B.P. 172, 38042 Grenoble Cedex 9, France*
[b] *Tecnomare, Venice, Italy*
[c] *Leichtweiss Institute, Brunswick, Germany*
[d] *CEPYC-CEDEX, Madrid, Spain*
[e] *RIKZ-Rijkswaterstaat, The Hague, Netherlands*
[f] *WL|Delft Hydraulics and Delft University of Technology, Delft, Netherlands*

Abstract

A recently completed European collaborative project focused on contributing to the improvement and harmonisation of present design practices for artificial nourishment schemes in Europe. An inventory of and a comparison between the major countries involved revealed significant differences between them regarding engineering methods and evaluation procedures, coastal zone management strategies and legal and financial frameworks. The design and evaluation methodologies were then reanalysed in order to provide harmonised recommendations. This analysis covered the monitoring and assessment of the performance of nourishment projects and the role of numerical models in design and evaluation. This paper summarises the conclusions obtained, uses two case studies as an illustration and gives a number of recommendations for achieving the objectives in the context of soft engineering works. The role of long-term monitoring at a regional scale is emphasised, advocating the use of innovative monitoring technologies together with the need for a better understanding and quantification of autonomous shoreline variability. Finally, suggestions for research are outlined, including such aspects as sediment grading and coupling between shoreline and profile change models.

Keywords: European experience; Shore nourishment; Soft engineering

1. Introduction

The traditional engineering response to coastal erosion has been to mitigate and where possible prevent erosion by coastal structures such as seawalls, groins and breakwaters. This attitude of counteracting instead of working in concert with natural processes is now referred to as "hard engineering". Nevertheless, the long-term monitoring of coastal changes around such structures frequently shows adverse environmental effects, in the vicinity (near field) as well as further away on adjacent shores (far field). Furthermore, the recognition in the early 1990s of the necessity for sustainable development of the coastal environment has led coastal engineers to the present interest in developing a "soft engineering" approach.

A central technique used in the soft engineering approach is shore nourishment. The use of the term shore nourishment rather than beach nourishment is preferred, since the nourishment location may vary

* Corresponding author. Fax: +33-4-76-33-43-33.
E-mail address: luc.hamm@sogreah.fr (L. Hamm).

0378-3839/02/$ - see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0378-3839(02)00127-8

considerably in the cross-shore direction (i.e. on the first dune row, at the duneface, on the beach, in the surf zone and/or at the shoreface). Today, periodic nourishment is regarded as an environmentally acceptable method of shore protection and restoration for short-term emergencies (i.e. storm-induced erosion) as well as long-term issues (i.e. structural erosion and sea level rise). The philosophy behind nourishment is based on the consideration that when a stretch of coast is sediment-starved, it could be more appropriate to import sediment and let nature do its job, rather than desperately try to counteract natural forcing factors to keep the remaining sediment.

This European collaborative project (Hamm, 1998) has focused on contributing to the improvement and harmonisation of present design practices for artificial nourishment schemes in Europe. The work has progressed in a series of steps, which can be summarised as follows:

1.1. Step 1

From an inventory of and a comparison between the major European countries practicing nourishment, significant differences have been found, viz. regarding engineering methods and evaluation procedures, coastal zone management strategies and legal and financial frameworks (Hanson et al., 2002).

1.2. Step 2

Acknowledging these differences, the project team aimed at establishing a common working framework linked with the soft engineering approach and structured around three principles:

- a preventive intervention strategy rather than a remedial approach to shore protection works (see, e.g. the dynamic preservation policy in the Netherlands),
- a comprehensive view of the morphodynamic processes at proper temporal and spatial scales by using of the concept of the coastal cell (Komar, 1996),
- a willingness to work with and not against natural processes, which implies a better understanding and quantification of autonomous coastal variability based on long-term monitoring efforts (Stive et al., 2002).

A major consequence of this point of view is the need to update conceptual issues for functional and technical design most particularly regarding the use of numerical models in design and evaluation (Capobianco et al., 2000, this issue).

1.3. Step 3

The various design and evaluation processes were then reanalysed in order to provide harmonised recommendations. Meanwhile, they have been applied in the field through monitoring campaigns at six locations in Europe where nourishments has taken place quite recently (Hamm, 1998).

1.4. Step 4

Research needs were also considered and part of the project was devoted to:

- the measurement and quantification of sediment grading effects, which play an important role in practice when the borrow sand is different from the native sand (De Meijer et al., 2002),
- the contribution of large-scale flume tests to the understanding and quantification of the physics of surf zone processes, along a beach profile (Dette et al., submitted for publication, this issue),
- the improvement of behaviour-oriented numerical models to help in the design (Capobianco et al., 2000, this issue),
- the development of analysis techniques by means of video images of the surf zone as a way to synoptically monitoring natural and man-made changes in beach morphology.

The five papers cited above in the description of the four steps are included in this Special Issue to provide a detailed view of the major results of this project. The aim of the present paper is to summarise the work carried out and to place it into a broader context in order to provide the reader with an overview of European experience with shore nourishment, including a description of two successful field cases not found in the other contributions.

The paper is organised as follows. The inventory of and comparison between shore nourishment practices in Europe is summarised first. Next, the design issues and objectives of shore nourishment are discussed. Section 4 discusses the prediction capabilities of numerical models and Section 5 gives the authors' views on performance assessment. Section 6 describes two nourishment cases illustrating the most advanced practices found in Europe. Section 7 is a plea for developing monitoring strategy and techniques. Finally, recommendations conclude this paper.

2. Present practice of shore nourishment in Europe

An inventory of the practices and objectives of beach fill projects in Europe (Hanson et al., 2002) has revealed different attitudes among the various countries. Table 1 summarises a few basic facts from different European countries.

Given the traditional strategy of using hard engineering, it is not surprising that the history of beach nourishment in Europe is pretty recent. As far as our information goes, it started in 1950 at Estoril, near Lisbon, Portugal, with a nourishment scheme involving some 15,000 m^3, which was soon followed by another in 1951 on the island of Norderney, Germany. Also, the United Kingdom started nourishment in the early 1950s. France followed in the early 1960s, Belgium and Italy in the late 1960s, the Netherlands in 1970, Denmark in 1974 and Spain in the early 1980s. Currently, the total annual rate of nourishment in Europe adds up to about 28M m^3, which is about the same volume as that for federal projects in the USA, i.e. in which the US Army Corps of Engineers is involved. It should be noted that quite a different degree of experience exists in the various countries: Germany, Spain and the Netherlands have performed tens to hundreds of nourishment schemes, while that at Rosslare Strand is the one and only case in Ireland so far.

The comparison of national practices and policies has also revealed significant differences closely linked to the main coastal issues of each country. Spain, Italy and France have an interest in coastal development projects and apply a strategy of remediation when negative impacts induced by these projects require coastal stabilisation. Furthermore, these countries seem to suffer from a lack of an overall long-term coastal management strategy and regular monitoring of the coastline. On the other hand, the use of soft protection techniques is quite different between these countries. In France and Italy, no overall strategy has been established, and funds are lacking, but engineering studies of implemented projects seem to be more advanced than in other countries, with the use of physical and numerical models.

Along the Mediterranean coast of Spain, artificial nourishment has become the principal remedial answer to coastal erosion problems over the last 20 years, even if the causes of the erosion (littoral drift intercepted by port jetties) are not treated. Monitoring by aerial photography was systematically used to detect vulnerable sections of the coast and to assess qualitatively the overall performance of the restoration works undertaken (MOPU, 1988; MIMAM, 1998).

Table 1
European nourishment practices—a few facts

Country	Date of the first recorded nourishment project	Number of nourished sites	Total fill volume (millions of m^3)	Mean annual rate of projects	Long-term strategy	Origin of funding
France	1962	26	12	< 1	No	Local
Italy	1969	36	15	1	No	National/Regional
Germany	1951	60	50	3	Yes	Federal/National
The Netherlands	1970	30	110	6	Yes	National
Spain	1985	400	110	10	No	National
Denmark	1974	13	31	3	Yes	National/Local
United Kingdom	1950s	32	20	4	No	National/Local
Total Europe				27.5		
USA	1922			30	No	Federal/Local

Fig. 1 presents a typical picture of a Spanish nourishment scheme at El Maresme.

In the Netherlands, Denmark (west coast of Jutland), the United Kingdom and Germany (North Sea coast), coastal protection against flooding by storm surges is a vital issue and has given rise to the development of long-term intervention strategies, which are implemented through follow-up programmes. This was made possible, thanks to a regular effort at monitoring long-term changes in the shoreline. The Netherlands seems to be a pioneering country in this respect and records of the position of the dune foot, mean high and low water levels are thus available in this country going as far back as 1840.

This variety of attitudes illustrates three types of societal responses found in Europe (Capobianco and Stive, 1997), namely:

- Resistance and maintenance—where no change is allowed and the status quo is maintained, if at all possible—is a typical attitude in France and Italy. Here, supporting structures (groins, breakwaters) are significant in the design of nourishment schemes, with the objective of zero-maintenance and no significant variability of beaches.
- Change at the margins—where the underlying assumptions are kept but symptoms are treated—is typical of the Spanish philosophy. This implies that a soft engineering technique such as artificial nourishment can be used in a hard engineering context.
- Openness and adaptability—where the underlying assumptions change and fundamental problems are treated—can be found in the Netherlands, the United Kingdom, Denmark and Germany.

3. Design issues and objectives

3.1. Design issues

In order to support proper decision-making and implementation of beach nourishment, several manuals or guidelines have been published, viz. the Dutch

Fig. 1. Typical Nourishment development in Spain at S. Vicente de Montalt' (El Maresme, Barcelona).

"Manual on artificial beach nourishment" (CUR, 1987), the German "Empfehlungen für Küstenschutzwerke" (EAK, 1993), the US book on "Beach Nourishment and Protection" (NRC, 1995) and the British "Beach Management Manual" (CIRIA, 1996a,b). Additionally, a more specific manual on "Beach Nourishments and Shore Parallel Structures" was published (CUR, 1997). Each of these sources pays attention to aspects such as problem analysis, nourishment design, implementation, monitoring, environmental impact and evaluation. While these manuals also contain elements of national interest only, they are largely of a generic nature and thus of international value. Also, from these sources, it seems that whereas in the USA, a debate on recognising beach nourishment as a sound engineering response to coastal erosion is ongoing (NRC, 1995), in Europe, confidence has been established in shore nourishment as a central technique in the soft engineering strategy.

Designing and evaluating shore nourishment is no mean task, for which there are no universal concepts. There are some general recommendations based on experience, such as NRC (1995): "Beach nourishment projects can be used effectively. . .within human time scales (decades, not centuries) when:

- Projects are carried out on sites at which the erosion processes are understood,
- Uncertainties in design and prediction are accounted for realistically, and
- State-of-the-art engineering standards of planning and design are used."

The methodology for project planning, design, monitoring, and evaluation should at least consist of (NRC, 1995):

- establishing objectives (goals and expectations) of the project and its continuation as a long-term programme in an effective and efficient manner;
- establishing a clear and quantifiable appraisal method;
- establishing and maintaining effective monitoring;
- evaluating the suitability of borrow locations and material;
- developing and maintaining a public awareness program;
- accounting for the uncertainties in design, prediction and project continuation.

Experience teaches that while economic and ecological considerations are important, the combination of effectiveness (design objective aspect) and the public perception of this effectiveness is often the most important issues.

3.2. Design objectives and parameters

Performing a nourishment is a deliberate and costly act based on the expectation of some desired effect, the design objective. Examples of basic design objectives are (Table 2): (1) improving coastal stability; (2) improving coastal protection; (3) increasing beach width. In many cases, beach nourishments have been considered as successful, although mainly on qualita-

Table 2
Suggested design objectives and parameters

Purpose of the nourishment	Improving coastal stability	Improving coastal protection	Increasing beach width for recreational purposes
Design parameter	MKL position	Dune or upper beach volume[a]	Dry beach width before summer season
Parameter trend (erosion rate)	Linear fit of annual positions of MKL over 10 years	Linear fit of annual upper beach volume over 10 years	Linear fit of annual widths over 10 years
Design criterion (lifetime)	MKL stays seaward of a reference line after *y* years	Dune or upper beach volume stays over a reference volume after *y* years	Dry beach width stays larger than a minimum width after *y* years
Performance indicator	Ratio between actual and design lifetime. Ratio of erosion rate before and after nourishment	Ratio between actual and design lifetime	Ratio between actual and design lifetime

[a] The upper beach volume is often used as an indicator for the dune volume when measured data concerning the latter are missing.

tive grounds. With the feasibility of coastal maintenance no longer being an issue, a more rigorous approach with quantitative design goals is appropriate, for example, as has been proposed in the NOURTEC project (NOURTEC, 1997). Ideally, these goals shall be expressed in terms of design parameters, which then can be used to formulate design criteria, as illustrated hereafter. These parameters and criteria provide an objective basis to set up performance indicators for various nourishments, which in turn will give empirical insight into critical factors in nourishment performance (see Section 5).

The first objective (improving coastal stability) implies preventing the coastline from retreating landward from a selected position. A suitable design parameter for this purpose is the momentary coastline

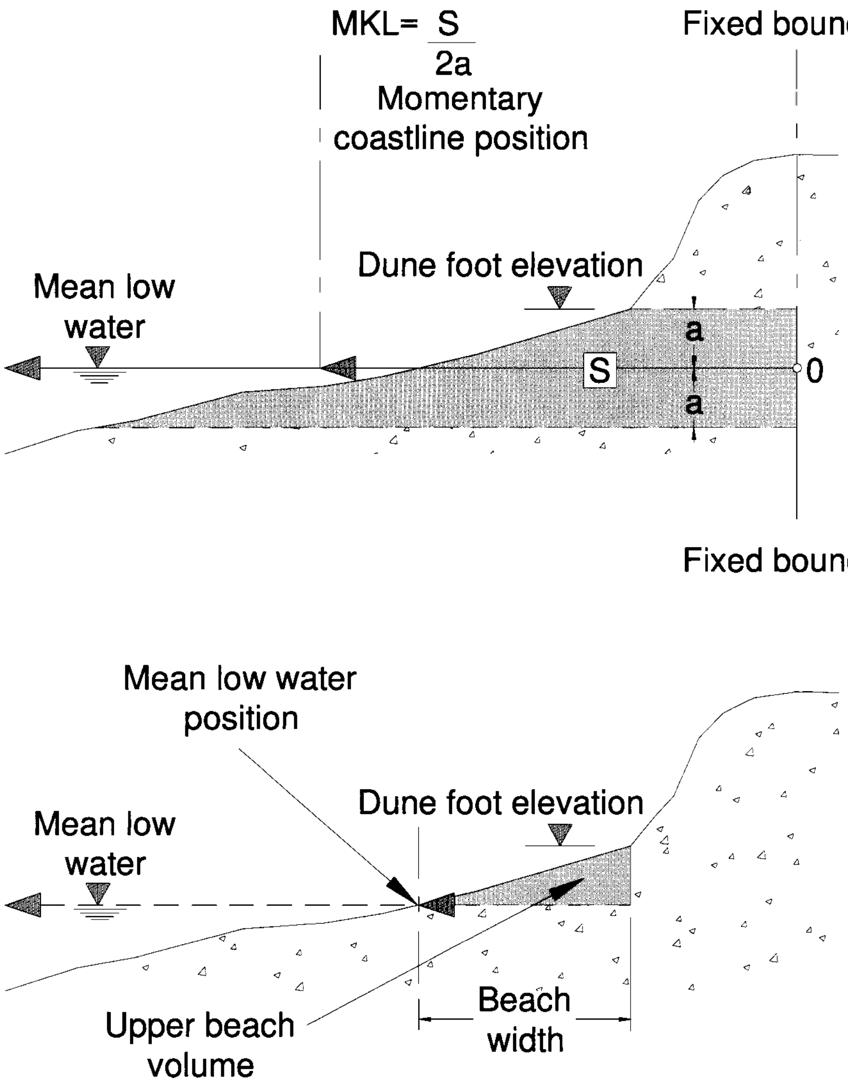


Fig. 2. Definition Momentary Coastline MKL. Positions and measurements are relative to a fixed (in time) co-ordinate system, here indicated by the reference line that connects the RSP beach poles ("Rijks Strand Palen"in Dutch). The MKL volume is shaded (see text). The MKL position lies a distance MKL volume/2H seaward from the fixed boundary. Other design parameters are obtained similarly: Upper Beach Volume can, e.g. be taken as the part of the shaded area above MLW (upper half layer) as far as the dune foot position, and Beach Width is distance MLW-dune foot position.

position taken from the Dutch coastline preservation policy of 1990 and referred in this paper as the MKL position ("kustlijn" is Dutch for coastline). The MKL volume, per (longshore) linear metre (Fig. 2), is bounded by (i) two horizontal planes at equal distances above and below the Mean Low Water (MLW) datum plane (this distance being that from the level of the dune foot to the MLW plane), by (ii) the profile and by (iii) an arbitrary vertical reference line landward of the foot of the dune. This reference line shall be chosen landward enough not to be reached by future possible retreat of the dune foot position. Dividing the volume by its height gives the position of the coastline relative to the reference line (MKL position). In practice, it will be close to the MLW line, albeit showing less scatter over relatively short periods (weeks). A design criterion for coastal stability is that as a result of the nourishment the MKL position remains seaward of a selected position for a well-defined period (y years), also called the lifetime of the nourishment.

The second objective (coastal protection) implies protection against flooding by storm surges. Standard safety assessment procedures consider sand volumes in the upper part of the profile, notably that of the dunes, as the proper design parameter. However, in most cases, monitoring does not cover all of the dunes. Therefore, the volume, per linear metre, of the upper part of the beach profile bounded by (i) the datum plane of MLW, (ii) the profile and (iii) a vertical line through the dune foot, is taken as the design parameter for coastal protection. In the presence of a seawall, a vertical line through the (foot of the) seawall may be taken as the landward boundary of the volume. The design criterion for coastal protection is that the nourishment maintains $\times$ m^3/m of sand in the control volume for y years.

The third objective (widening of beaches) usually serves recreational purposes. The associated design parameter is the width of the beach, in general with emphasis on the dry beach. For instance, it could be defined as the distance between the foot of the dune and the MLW line. The design criterion for beach widening is that as a result of the nourishment, a beach width of x metres is maintained for a period of y years. Table 2 summarises these nourishment objectives and parameters.

Finally, we note that many alternative design objectives and parameters are possible, and should also be considered. We would advocate that ample consideration should be given at the beginning of the preliminary design phase to establishing the design objectives and associated design parameters and criteria, which may be multiple if necessary, and tailored to the specific coastal problem.

4. Predicting the future of a shore nourishment

Predicting the behaviour of the nourishment is essential in the decision-making process of such a project. Given the complexity of coastal processes, efforts to understand and predict the fate of nourishment will always be grounded on coastal experience and expertise. On the other hand, models are given an increasing role in the design and appraisal of shore nourishment working in concert with field observations, and performing predictions and hindcasts. In this section, shore nourishment behaviour is summarised. The role of numerical models is then discussed and practical advice is provided.

4.1. Shore nourishment behaviour

Our current insights into the way shore nourishment schemes evolve may be summarised as follows.

First, consider a nourishment with borrow material equal (i.e. with at least the same median grain size) to native material along an unbounded stretch of coast. Any shore nourishment basically consists of a spatially localised volumetric enlargement of the shoreface sediment body. This may be considered as a local perturbation on a coast in a particular dynamic state. Over a long enough time scale and large enough spatial scale, the perturbation will be diffused in the cross-shore and longshore directions. The extent of the diffusion is dependent on the 'amplitude and wavelength' of the perturbation relative to the natural scales, and on the hydrodynamic climate. Generally speaking, the larger the amplitude and the shorter the wavelength and the more energetic the hydrodynamic climate, the stronger the diffusion. When significant net longshore or cross-shore transport is present, the perturbation will also undergo advection (or rather combined diffusion and advection) in the longshore or cross-shore directions, respectively.

Second, the stretch of coast influenced by the nourishment may be bounded in either longshore or cross-shore directions, naturally (e.g. geological controls) or by man-made structures. This will reduce the strength of diffusion and/or limit, i.e. prevent advection. If new structures are introduced to constrain the nourishment, new erosion problems may be introduced outside the domain.

Third, the nourishment may consist of sediment with a different grain size from the native sediment. Since sediment is commonly borrowed from offshore, the chances are that the borrow material is finer than the native material. In that case, the finer the material, the stronger are the diffusion and advection.

To sum up, the general situation is such that the nourishment is at least diffused (along- and cross-shore) in time. Whether the diffusion is interpreted as a volumetric loss depends on the defined boundaries of the nourishment domain considered and on the time span considered. It is important to realise that diffusion is inevitable. In particular, diffusion due to cross-shore processes in the case of subaerial nourishment has an enormous impact on public perception.

Besides this process of diffusion, the nourishment volume may be advected (or rather its centre of gravity may move along or across the shore, while diffusion may simultaneously take place), if no additional measures are undertaken.

Another degree of complexity is added by the fact that there will be autonomous shore variations over annual and decadal scales, which will be superimposed onto and may interact with the nourishment works. Stive et al. (2002) discuss a broad variety of time and space scales for natural and human-induced causes or factors (forcing or input) and the resulting shoreline changes (response or output). While forcing at all scales can exist, it is typically at decadal scales (years to tens of years) that human-induced forcing is exerted. At these scales the shoreline can exhibit spatially and temporally uniform and fluctuating motions of significant magnitude. Specifically, these fluctuating motions can be larger than uniform decadal motions and structural longer-term trends. These fluctuations should be clearly acknowledged in order to design shore nourishment works properly, i.e. so as not to fall into the trap of nourishing a coast which would accrete anyway, or more generally not to under- or overnourish a coast, which exhibits oscillatory behaviour. These arguments deal with the success and efficiency of nourishment. Since it may be expected that the intervention scales are of similar magnitude, scale interactions may occur leading to unforeseen changes (Capobianco et al., in press). If we understand the reasons behind decadal variability, we may design shore nourishments such that natural processes work in concert with such operations, rather than counteract them.

At shorter scales, the magnitudes of seasonal and annual variability should be taken into account when designing shore nourishments. In principle, if the nourishment source material does not differ too much from the native material, this variability may be expected to remain approximately the same. Typically, this variability has elements of unpredictability, due among other things to the stochastic nature of the hydrodynamic climate (Southgate and Capobianco, 1997). This well-recognised source of variability is taken into account in Europe in the overall framework of the North Atlantic Oscillation. This issue of probabilistic behaviour deserves more attention than it has received so far (Capobianco et al., 2000).

At a longer time scale, observations collected in the Climate Changes programmes and the associated predictions for the next 50 years should also be taken into account in analysing the behaviour of a nourishment scheme. As an example, Dette (1997) analysed the frequency and importance of storm surges at Sylt island in the North Sea, and found not only stochastic variations but also a long-term trend spanning a century.

4.2. Use of numerical models in design

In practice, a fill design (a single project as well as an overall nourishment plan) addresses a number of technical questions. Through the use of models, improvements may be expected in solving technical questions connected with fill design, namely:

- definition of the shape of the platform,
- assessment of the longshore distribution of the beach fill,
- definition of the minimum fill and of volumetric requirements,

- definition of the length of the project,
- possible need for terminal structures.

At the same time, better assessment of the problems connected with temporal aspects of the design may be expected, i.e.:

- post-fill balancing of the profile;
- design life; frequency for intermediate fills;
- needs for maintenance;
- risk connected with uncertainty;
- window of vulnerability and post-storm scenarios.

The fundamental roles of models is to assist the design in a trial and error iteration procedure (Kamphuis, 2000a, Chapter 13) thereby reducing unexpected changes as much as possible. A fundamental need exists to handle and properly communicate uncertainties, an important component of which is validation (Kamphuis, 2000b). Also, there is a need to assess the economic and environmental implications of modelling failures properly. Furthermore, the present tendency of moving from nourishment projects to nourishment plans (see, e.g. Dette et al., 1994) requires more significant prediction skills for planning nourishment in time than were available in the past.

Moreover, one has to consider that the use of models in practical design situations could also be linked to economic and financial considerations when a benefit–cost approach is part of the design or, conversely, models can help in examining the economic implications of a design. In practice, the two aspects should be considered together since different models can lead to different conclusions on the economics of the project, as shown by Hanson and Kraus (1993).

4.3. The practical aspects of modelling shore nourishment

Considering on the one hand the increased use of models in the design of shore nourishments and on the other hand the recent development of morphodynamic modelling, which is still in its infancy, it is worth considering in this section the dissemination of basic practical rules in order to avoid major modelling failures. For a more comprehensive discussion of this topic in the context of coastal engineering, refer to Kamphuis (2000a).

The most popular engineering models currently in use are shoreline (one line) evolution models and profile evolution models. Hanson and Kraus (1993), Work and Dean (1995), Gravens (1997) and Browder and Dean (2000) reported practical applications of shoreline models to shore nourishment projects. Modelling of the response of nourished profiles to storm events was reported by Kraus and Wise (1993), Newe and Dette (1995) and Zheng and Dean (1997), while the medium-term response of such profiles was reported by Roelvink et al. (1996), Work and Dean (1995) and Larson et al. (1999a,b).

Capobianco et al. (2000) reviewed the main classes of models currently available, including the shoreline and profile change models mentioned above, but also multi-layer models such as a hybrid combination of previous types (Larson et al., 1990; Hanson and Larson, 1999) and quasi-3D models describing the three-dimensional evolution of a stretch of coast. They focussed their discussions on various aspects that can now be considered as the main sources of error while developing and using models for nourishment planning, as well as the main limits to their predictive strengths:

- equilibrium profile and depth of closure, with their time-scale related aspects;
- granulometry changes, with their effects on the dynamics of a nourished coast;
- the estimation of erosion rate, with its implications on the definition of the "basic state" or the "basic trend" of the coastal system;
- lateral spreading and beach fill transition;
- calibration and verification, with the additional degrees of freedom that might be introduced into the model development.

The recommendation that can be given here is not to underestimate the role and the implications of such aspects while setting up a model. Their careful consideration can help to define the uncertainty connected with the prediction of nourishment performance and can help to take more informed, transparent and efficient decisions in relation with the available "degrees of freedom" for the definition of a nourishment project. Sensitivity analysis should be used here to evaluate how model output changes with changes in input variables (see, e.g. Van Alphen et al., 1990), and uncertainty propagation can be analysed to examine how uncertainty in individual parameters can affect the overall uncertainty of the answers to technical questions.

Furthermore, the following situations should be properly identified:

- Nourishment is undertaken in the vicinity of inlets.
- Nourishment and native sands are different.
- Profile or shoreface nourishment is undertaken.
- Large seasonal variations occur.

In all such situations, predictability is traditionally more limited. Situations where complex structures are present probably need to be examined by adopting a different approach. Multi-line and quasi-3D models can play an important role here in the near future.

Finally, the assessment of existing models performed in this project has shown that such tools are in general not generic enough to be applied by non-specialists. Several input parameters are site-specific and need adjustment after careful calibration of the model. Calibration procedures themselves are not currently standardised and modellers' experience plays a dominant role in the process. The variability of the forcing factors (waves, wind, storm surges) is also a difficulty when analysing past situations and forecasting future changes.

5. Appraisal

While it is difficult to predict how shore nourishment will evolve, it is nowadays generally realised (due to the growing importance of public perception) that it is absolutely necessary to have an indication of the changes expected given the design objectives formulated. Implicitly, such an indication contains elements of the effectiveness of the nourishment. These expectations need to be checked, and that is why over the last decade, post-nourishment monitoring has become nearly a standard.

However, there is no single method for assessing the performance and effectiveness of nourishment. This is because the choice of suitable parameters for estimating the performance and effectiveness of nourishment is clearly linked to the definition of the objectives (expressed from a morphodynamic point of view) formulated during the design process.

In the USA, performance evaluation has become a key issue and comprehensive performance evaluations are regularly published (see, e.g. Stauble and Kraus, 1993; Kana et al., 1997; Bokuniewicz, 1998; Browder and Dean, 2000). In Europe, a few appraisals have been published so far (see, e.g. Cooper, 1998 reporting an appraisal of a beach nourishment plan at Poole Bay, UK).The Netherlands and Denmark are the only countries where a serious overall performance evaluation program has been integrated into their legal framework (Hanson et al., 2002). In the Netherlands, Roelse (1996) reported an evaluation of Dutch nourishment practice between 1975 and 1994, where seven possible performance indicators in relation to the objectives of the nourishment were discussed. Five of them are shown in Table 3. Except for the first indicator (E), they are all related to design objectives for achieving user functions. Only the first is an explicit effectiveness indicator; in the other four, effectiveness is implicit.

A feature of this table is the fact that the first indicator E is generally below 1, which means that the post-nourishment rates are in general higher than the pre-nourishment rates.[1] This is the expected change without any additional existing or new structures to constrain the nourishment volume. It is obviously due to the diffusion effect, but additionally it may be due to the increased structural erosion mechanisms resulting from perturbation of the geometry. For instance, it is believed in Egmond (Netherlands) that a perturbed geometry may increase the size and strength of rip currents (and thus increase offshore "diffusion"). It is interesting to note that this latter aspect is the probable reason for the recommendation by NRC (1995) that a short re-nourishment frequency should be chosen.

We also note that in estimations of the 'lifetime' of a nourishment, the remaining volume is generally related to the initial situation, thus relating the volume of the fill to a static condition. It might be

[1] An exception is the Ameland nourishment of 1980. Another similar case is the underwater nourishment of Terschelling (1997), which nourishment acts as an offshore breakwater trapping alongshore sediment transport (see Section 6).

Table 3
Performance indicators of nourishments in the Netherlands (adapted from Roelse, 1996)

Project	Year	Design life span (year)	Volume		Type[a]	Characteristic parameters[b]				
			Mm^3	m^3/m		E	C	R	N	F
Ameland	1980	8–10	2.20	365	d	>2	1.6	0.9	1.4	1.5
Eierland	1979	5	3.05	510	bb	0.7	0.9	0.9	0.8	0.9
Eierland	1985	5	2.85	480	bb	0.9	0.7	0.9	0.7	0.8
De Koog	1984	10	3.02	500	bb	0.6	0.7	1.1	0.8	1.0
Callantsoog	1986	13	1.30	440	b + d	0.3	0.5	1.1	0.7	n[c]
Zwanenw.	1987	15–20	1.70	400	bb	0.8	0.7	1.0	0.7	1.0
Goeree	1977	5	1.27	420	bd	n[c]	1.4	n[c]	n[c]	n[c]
Goeree	1985	5	0.86	290	b	n[c]	2.4	n[c]	n[c]	n[c]
Schouwen	1987	5	1.83	1080	b + s	0.8	1.9	1.3	1.0	1.0
Cadzand	1989	5	1.02	560	b + s	0.3	2.1	2.4	>1	2.4

[a] d = Duneface; b = beach; bb = beach + banquet; s = shoreface.

[b] E = Effectiveness factor of nourished sand, E is ratio of observed rates of erosion before and after nourishment; C = preservation of adopted boundary coastline (usually that of 1990), C is ratio of actual life time and design life time; R = recreation, R is ratio of the averaged beach width during the lifetime of the nourishment and the averaged width during the same time span before nourishment; N = natural values, N is ratio of actual and design life times of dune foot stabilisation; F = flood protection, F is ratio of actual and design life time of maintaining the dune profile.

[c] n = cannot be determined.

more appropriate to measure it against the zero-condition, i.e. the actual volume of the stretch of coast without the nourishment. Then, the actual loss of fill should be the difference between the two decreasing volumes (project–no project) and not (project–no change).

Finally, it should be stressed that the shift towards shoreface nourishment, possibly in combination with beach nourishment, introduces the concept of efficiency (from an economic and financial point of view) along with effectiveness. Recently, in situ experiments took place in the Netherlands, Denmark and Germany with scientific monitoring in order to increase our understanding of this technique (NOURTEC, 1997). Following the relative success of these experiments, several subsequent nourishment projects were implemented including shoreface nourishment. For instance, in 1999 at Egmond (Netherlands), a nourishment was implemented, combining a shoreface nourishment (400 m^3/m over a distance of 2250 m, placed during the summer season) with a beach nourishment (200 m^3/m over a distance of 1500 m, placed during the previous spring). In this case, not only the post-nourishment rate itself is relevant, but also how much the nourishment cost. If supplying the outer surf zone is substantially cheaper per unit volume, it may be more efficient to accept a higher post-nourishment rate compared to one resulting from nourishment of the beach.

6. Two field cases

Two nourished sites from among the six sites monitored during the project are described in more detail here. They illustrate the most advanced practices found in Europe. Both are located on the North Sea barrier islands, which experience similar environmental conditions. Yet the technical choices made are quite different because classical beach nourishments are regularly carried out at Sylt island, Germany, whereas an experimental shoreface nourishment was tested at Terschelling in the Netherlands.

6.1. The island of Sylt (Germany)

The island of Sylt in the North Sea is the northernmost island of Germany. Its 36-km-long North–South sandy west coast of mainly unprotected dunes with cliffs up to 25 m high (Fig. 3) is fully exposed to westerly North Sea waves and tides up to about 2 m high. Due to the geometry of the German Bight, the coast is also affected by storm tides, which can cause a rise in MHW level of up to 3.5 m. The

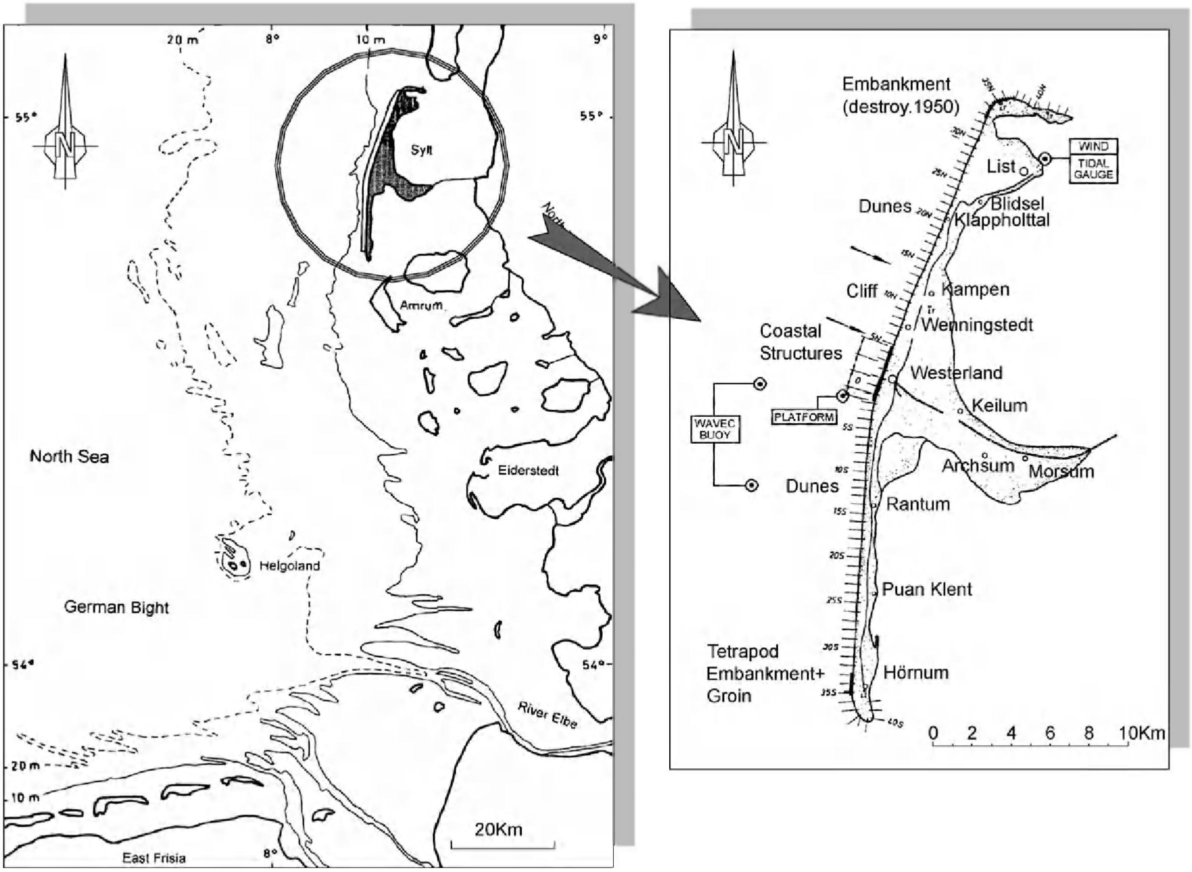


Fig. 3. The island of Sylt with the locations of the 500-m spaced measuring transects. The North Sea is to the West of the island.

nearshore area is characterised by a longshore bar, which is located approximately 300 m seaward of the shoreline. High waves break there as plunging breakers. During storm surges, with a water level rise of more than 2 m, the protective effect of the bar (crest height approx. MSL—3 m) is lost and waves pass over the bar without breaking. According to geological estimates, the west coast of Sylt has receded approximately 13 km over a period of 7000 years (1.8 m/year). Since monitoring started (1870) the recession rate has been 0.9 m/year. Over this period, the underwater profile has been shifted eastwards, probably without much change in shape. The eroded material has created spits to the north and south of the centre of the island. These are now curtailed by major tidal channels. Tidal currents carry the sand that arrives at the ends of the spits away from the island. Thus, Sylt is a typical example of an open sand system, because eroded material is not returned to the island.

Attempts since 1865 to slow down dune recession by various types of groins along large parts of the island have been fairly unsuccessful, as was a seawall (built in 1907) in the middle of the island (Westerland), that needed gradual reinforcement and extension. Since 1972, repeated beach nourishments have been carried out regularly to protect this seawall and its 3-km-long revetment against underscouring. Since 1950, greater storm surge frequency has caused the mean yearly recession rate to increase from 0.9 m/year (1870–1950) to 1.5 m/year (1950–1985), which is equivalent to an annual loss of 1.5 million m^3 of sand (1/3 to the south and 2/3 to the north, see Dette, 1997). This prompted the coastal authorities (‘Amt für ländliche Räume' in Husum) to initiate a specific coastal protection master plan in 1985, for a period of 35 years (1985–2020), which has recently been updated in 1997. This assumed that the increased storm surge frequency would continue, and with it, the erosion that would endanger the island if no counter-measures were undertaken. All possible alternatives for future coastal protection of the west coast were considered, and their technical, economic and environmental aspects indicated that repeated replenishments in the form of deposits on the beach and shoreface nourishments would provide the most favourable solution. In the updated nourishment concept, it is intended to maintain the coastline in its 1992 position by compensating for the mean yearly sand loss from the coast. The coastline is defined by the dune foot (3.75 m above mean sea level). The order in which various areas have to be nourished is determined by the degree to which the sites along the west coast are endangered. The authorities determine this from routine numerical simulations with a dune erosion model based on the theory of Kriebel and Dean (Newe and Dette, 1995).

In the period 1985–1996, 23 schemes were implemented, with a total amount of approximately 20M m^3 of sand from offshore borrow areas. Practical experience with the placement of beach fill, its effectiveness and life span has been gained over a period of more than 25 years (Dette et al., 1994). In the future, it is intended to increase the half-life of the fill sand on the beach to 6 years. In the master plan, it is emphasised that the pressure to nourish repeatedly could drop considerably if a strip at least 100 m wide along the west coast was kept free from buildings and other developments.

The master plan also includes detailed monitoring (land and sea surveys), e.g. before, during, and after the individual nourishments. The programme of field measurements at Sylt includes:

- Beach/dune and foreshore surveys and their analysis. Regular monitoring of the positions of dunes, cliffs and the dry beach (above MHW) was considered to be crucial to initiate timely preventive measures. This task was performed by means of land surveys extending from the MLW-line up to the dune crest along the entire 36 km stretch of coastline, with profiles spaced every 500 m. This survey of 70 profile lines (Fig. 3), which covers the entire system since 1986, is carried out twice a year. For sea surveys, mostly carried out for follow-up studies of individual beach nourishments, a standard profile spacing of 50 m was adopted and maintained during the monitoring period. An assessment of the sensitivity of volume calculations in relation to the spacing of profiles was carried out by using data from detailed beach surveys to compute differences between the results of the 100-m and wider spacing and those of the 50-m spacing. It was shown that for 100 m, the error is of the order of 10%, and 15% for 200 m. Up to 1000-m spacing, an increase towards 25% or even 30% is obvious. This analysis led to recommendations aiming at decreasing the distance between two profiles down to 250 or even 167 m to improve budget calculations, albeit at the expense of, respectively, doubling and tripling the survey time.
- Wave measurements with directional wave rider buoys and wave rider buoys in deep water. For the monitoring period over several years, up to seven wave rider buoys (two directional) were available for wave data recording in deep water (− 10 to − 15 m). They were employed as follows: a directional wave rider buoy was operated at a central island position as reference location over the monitoring period. In parallel, the other wave buoys were operated part-time at selected positions in a parallel to the shore along the − 10-m depth contour for the study of variability in wave characteristics along the west coast, and also perpendicular to the shore between − 15 and − 10 m for the study of wave transformation in shallow water.
- Long-term recording of waves, water levels, currents and wind collected from a fixed offshore measuring platform at − 10-m depth. A data set was also created consisting of time series of water levels, wave heights, wave directions, wind speeds and wind directions. This data set contains hourly values of these parameters since 1950. Gaps in the wave records were filled using a correlation between wind and wave data. The energy flux was added to this data set.
- Wave and current measuring campaigns in the nearshore and in the surf zone at two representative study sites in the north and south of Sylt, including

sediment sampling for analysis of sedimentological characteristics.

A report documenting the monitoring since 1984 was produced (Dette and Newe, 1999).

The actual nourishment schemes are based on sand losses calculated from concurrent profile data for the entire coast at the beginning and end of the yearly storm season. The recession is characterised by the loss of sand from the dunes and the upper beach. The underwater part of the surf zone profile can be considered as the main area from which sand is transported by longshore drift to the ends of the island. That is, the sand removed from the dune and beach by storm surges is initially deposited in the surf zone, from where it is transported to the tidal channels at the ends of the island. Only a small amount is returned to the beach.

We now focus on a specific area located near Wenningstedt and Kampen (Fig. 3) in the northern half of the west coast of the island. This area has a length of about 4 km between profiles 5N and 13N, and is mostly characterised by a cliff with heights up to nearly 35 m. The average yearly recession in this part of the coast was 0.7 m/year from 1870 to 1950 and 1.3 m/year from 1950 to 1984. In order to stop or at least to retard the recession of the coastline, a first beach nourishment was performed here in summer 1985, in the form of a raised berm in front of the cliff (Fig. 4). It consisted of a so-called security deposit (20 m wide, 5 m high; 100 m^3/m), meant to act as a long-lasting coastal reserve, and a recession deposit (comparable dimensions) designed to compensate for the autonomous erosion in the 6 years to come and possible exceptional events. In addition, at several places the beach was nourished as far as the waterline with some 100–200 m^3/m of sand.

A total of 2.0M m^3 of sand (borrowed offshore) was dumped (in 65 days by two hopper dredges, via a 1000-m sinker line) between profiles 5N and 13N.

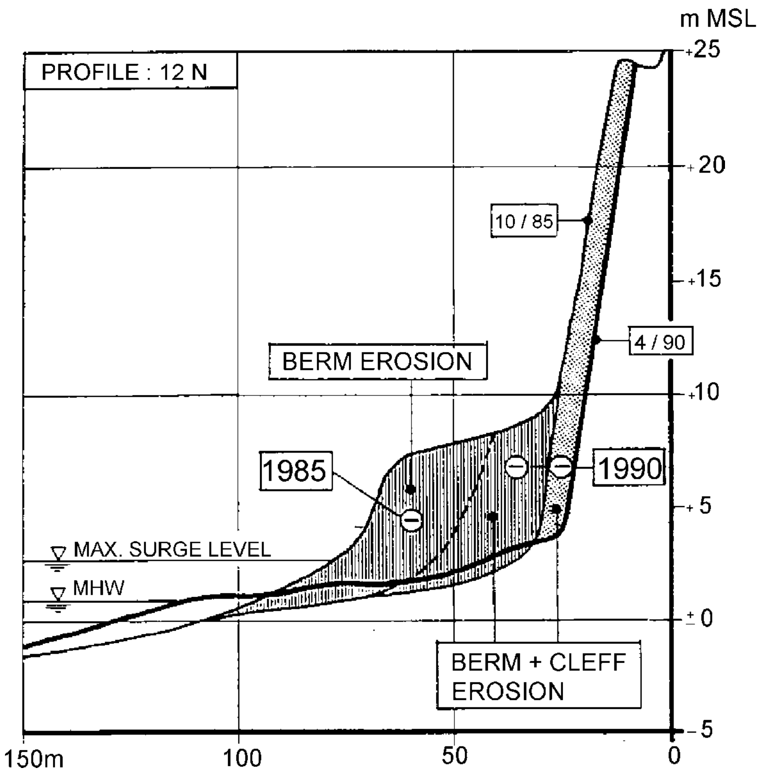


Fig. 4. Shape of beach nourishment (1985) and subsequent erosion at profile 12N. Serious losses by storms occurred in 1985 ("berm erosion"), shortly after the nourishment (see dashed profile), and in 1990 ("berm + cliff erosion").

The area was surveyed three times in 1985 from the cliff edge down to the waterline, in April (before the work), in October (just after it) and in November, after a severe storm ranked no. 16 of the 20th century according to Dette and Newe (1999). The losses due to the storm surge were high (50–90 m^3/m). After two more serious storm surges, in January and February 1990 (ranked nos. 4 and 5, respectively), even the security deposit eroded, as well as some 5 m of the original cliff (Fig. 4, profile 12N in the test area, see also Newe and Dette (1995) for a comprehensive description). So the design criterion of a "dune front" 6 years seaward of a permanent security deposit and a stable cliff was not met. This was attributed to the shape of the fill (40 m being too narrow and 7 m above MHW being too high). Still, the design parameter used here for coastline stability, the "dune volume" being the total volume above MLW with respect to a fixed vertical reference line landward of the dunes/cliff, remained significantly enhanced after the nourishment in the 5 years considered. This indicates that the nourishment was a partial success that can be described in terms of this design parameter. Because of the geometry of the nourishment and the cliff, the "standard" MKL design parameter for coastline stability was of no use, since nourishment and later also cliff sand was fed from above in its control volume.

Based on this experience, lower and broader nourishment berms were chosen, with a lower and wider security deposit and a larger recession deposit; also the slopes were optimised, notably that of the security deposit. An example of the performance of such a scheme is given in Fig. 5 for a nourishment in 1992 (in the southern half of Sylt). The initial fill geometry (1992) was altered considerably by a single storm surge within 1 year after the fill. The storm surge established an equilibrium profile for its raised water level (1993), which remained fairly stable even during a following storm surge of comparable strength (1994).

6.2. Terschelling

The island of Terschelling is part of a chain of barrier islands between the Wadden Sea and the North Sea (Fig. 6). With large quantities of sand bypassing its outer deltas (Vlie on its west side and Borndiep on its east side), Terschelling's concave central North Sea coast is considered as a throughflow system. This coast is fully exposed to the north–west, and thus to swell from the North Atlantic and to large-fetch wind waves from that direction. Prevailing winds are south-westerly. Tidal range is mesotidal (between 1.2 and 2.8 m). Tidal and residual currents are basically parallel to the shore (of the order of 0.3 and 0.03 m/s, respectively),

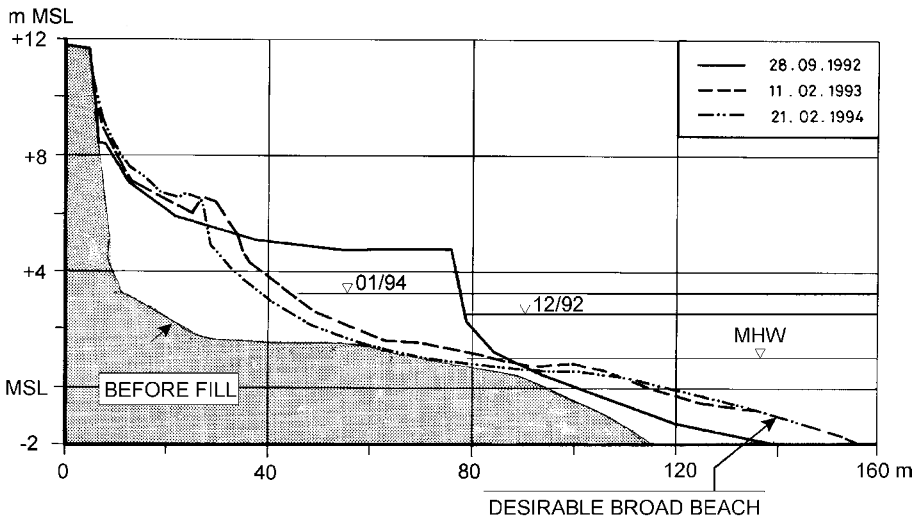


Fig. 5. Beach fill geometry (southern half of Sylt) after major storm surges in 2 consecutive years. The initial profile (1992) corresponds with the improved design.

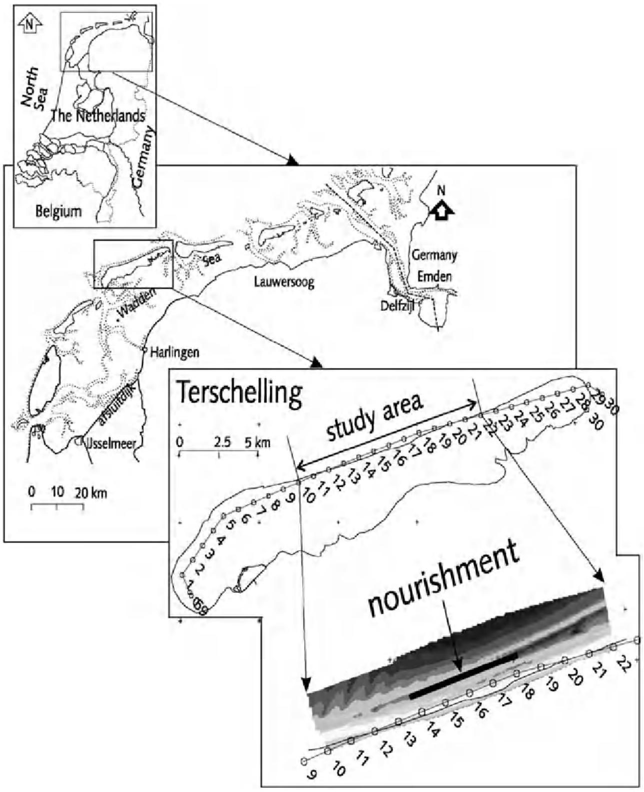


Fig. 6. Locations of Terschelling island, the study area and the shoreface nourishment. The 1-km spaced reference beach poles RSP are indicated. The lower figure shows the monitored area and the bathymetry (interpolated on a 20-m grid) with, e.g. shore-parallel breaker bars and sand waves. Depths are indicated with grey tones (max. depth: 11 m).

with occasionally relatively strong wind-driven currents (of the order of 0.5 m/s). The morphology is characterised by a cyclic, seaward moving three-bar system (Ruessink and Kroon, 1994). The level of the dune foot is +3.0 m NAP (NAP: Dutch ordnance level that approximately coincides with Mean Sea Level). Part of the centre of the island, notably to the east is retreating by about 2 m/year, without any obvious link to the behaviour of the bar.

As part of the Dutch policy to prevent all of its coastline from receding beyond the position it had in 1990, the central eroding part of the island of Terschelling was nourished in 1993 (May–November) with 2M m^3 of sand. The borrow site (20-m water depth) was at a distance of 10 km from the project site. Since the authorities wanted to assess the advantages of (possible future) shoreface nourishment schemes, a shoreface rather than a standard beach nourishment was performed in this case. The Terschelling nourishment was one of the three experimental underwater nourishments of the European (MAST-programme) NOURTEC project that aimed at assessing the potential of this type of scheme (Mulder et al., 1994; NOURTEC, 1997) Three small hopper dredges dumped the borrowed material directly at the required location. Down time due to wave action was 15%.

The shoreface nourishment at Terschelling was designed to compensate for the natural erosion at the nourished section of the coast over a period of 8 years. The average erosion in the area (2.9 m/year, i.e. 24 m^3 per linear metre) was derived using the standard procedure from linear regressions per transect to the MKL positions over a 10-year period (1982–1991). The nourishment was placed between km 13.6 and km 18.2, and thus the 8-year erosion amounts to about 1M m^3 ($8 \times 24 \times 4600$) of sand. The shoreface nourishment was placed in the trough between the two outer bars, largely below the MKL zone (Fig. 7), and it was anticipated (Mulder et al., 1994) that about half of the dumped sand would enter the MKL zone by cross-shore transport; therefore 2M m^3 was dumped.

The expected response of the system, in terms of sand volume in the MKL control volume, is depicted as follows (Spanhoff et al., 1997): The nourishment is dumped with a small fraction (top layer) directly in the MKL zone. Next, the profile will adapt according to a relaxation process, with a net transport of sand into the zone, higher up in the profile, until the volume gain in the zone equals about 50% of the nourishment volume. The rate of gain will initially be relatively high, subsequently decreasing monotonously to zero with time. Natural erosion will thus prevail in the later stages. Because of the experimental character of this nourishment, more sand was used than would usually be the case (a design life of 8 years instead of 4–5), to get a better "signal to noise" ratio, i.e. more easily detectable morphological changes. One of the reasons for choosing Terschelling as test site was that failure would involve no serious consequences, since the local dunes are no primary defence against the sea.

The monitoring programme was much more elaborate than normal. In addition, extensive process measurements were performed in various campaigns

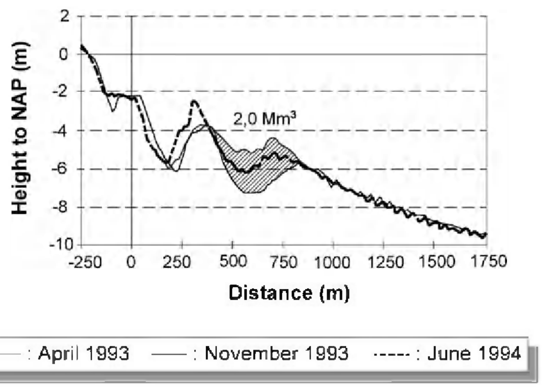


Fig. 7. Position of the Terschelling shoreface nourishment with respect to the profile. Sand of 2M m^3 has been dumped along a 4.6-km-long stretch of coast, largely below the MKL zone that ranges down to 5.2 m in depth.

to understand the changes in the coastal system and the impact of the nourishment better. The objectives of monitoring were threefold: (i) to assess whether the nourishment met its design goal, i.e. that the coastal volume of sand (MKL volume) remained larger than its 1990 value over the next 8 years, (ii) to gain a better understanding of the effect of such nourishment, and especially to judge whether this type of nourishment could be applied on a wider scale, and (iii) to provide a baseline database in a scientific experiment aimed at a more general and better understanding of coastal processes. The key parameters monitored were:

- Beach/dune and foreshore profiles. Apart from the yearly routine surveys performed along the entire Dutch coast as part of the Dutch coastal preservation policy, the shoreface nourishment at Terschelling, between km 13.6 and km 18.2, was surveyed a few (3 or 4) times a year (1993–1998). The total test area extended from km 10.0 to 22.0. All (cross-shore) profiles extended some 2000–2500 m offshore. Lane spacing was 200 m as usual but was decreased down to 25 m around the main measuring transect (km 17.0) in the centre of the experiment. The beach was surveyed up to the dune foot by a team of two to three persons who needed 1–2 weeks to cover the whole area.
- Tides are recorded by a standard gauge in the centre of the nourishment area as part of the national tidal network. The nearest wave-directional buoy is at the neighbouring island of Schiermonnikoog, some 50 km to the east. For NOURTEC, an extra wave-directional buoy was operated at 15-m depth in front of the nourishment in the main measuring transect, while wave and tide data were also obtained at two fixed poles in this transect. During the campaigns, four stand-alone frames at the bottom gathered wave information as well.
- Currents and suspended sediment concentrations are not usually measured in relation to (beach) nourishment operations. In the NOURTEC experiments, they were studied extensively, using some five stand-alone frames equipped with batteries, sensors, memories for data storage, and processors to steer the data gathering.
- Sediment sampling and grain size analysis always accompany nourishment operations, albeit on a

relatively moderate scale. The borrow areas, which should always be at more than 20-m depth according to Dutch practice, are selected with coarser sand than the native beach material. During NOURTEC, several hundred bottom samples were taken and analysed, mostly with a Van Veen grab from the sea bottom, and a few from the beach, both along cross-shore transects.

The performance of the nourishment was evaluated with the MKL position as the parameter for coastline preservation derived from soundings and levelling for the periods before the nourishment (annual JARKUS data 1965–1992) and after it (several surveys per year). Fig. 8 shows averaged values for the western part, eastern part and the whole of the nourished coastal sector, respectively. The absolute value of the vertical axis lost its meaning in the averaging. The data are scattered around the linear regressions, despite averaging over many transects. No obvious trend changes emerge from the data in the period 1965–1993 and regressions were performed over the entire period. Extending the reference period from 10 years (1982–1991, standard practice in the Netherlands) to 28 years revealed hidden long-term trends: the eastern half and the whole of the nourished sector are seen to erode less quickly than in the period 1982–1991. Furthermore, the western half is accreting somewhat, in contrast with its 1982–1991 trend. In the years since the nourishment, all trends have been strongly positive, of the order of 10–15 m/year, and hardly any saturation is noticed yet. The MKL coastline advance exceeds the 1982–1991 retreat, contrary to expectations, and it even surpasses its 1965 position, compensating for erosion over some 30 years. From a practical point of view, the nourishment has more than satisfied its goal (NOURTEC, 1997).

Indeed, this response of the system was so far from expectations that it was further investigated with GIS tools. First of all (Spanhoff et al., 1997), depth and height data were interpolated into a 2D grid (20-m grid size) and colour-coded, providing synoptic views of the bathymetry in the area. Morphological developments, both before and after nourishment, could be clearly highlighted in GIS by colour-coding differences between pairs of surveys. As quantitative measures of these developments,

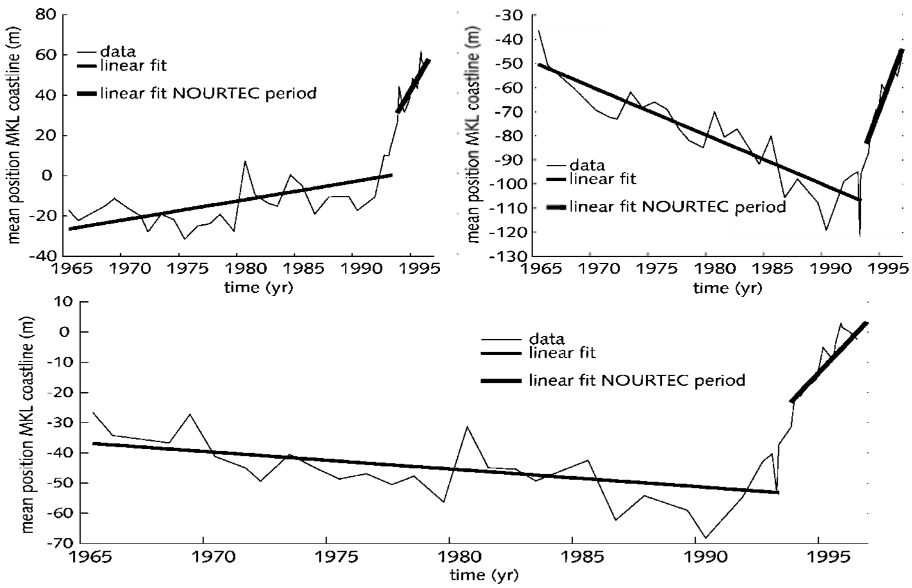
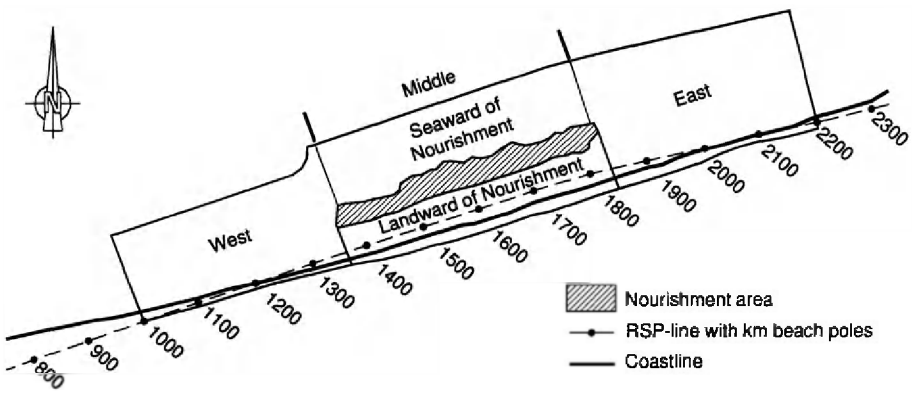


Fig. 8. Coastline positions at Terschelling as a function of time. Average MKL values are shown for the total nourishment area between 13.6 and 18.2 km (bottom), its western half (top left) and its eastern half (top right). Linear regressions for the pre- and post-nourishment periods, respectively, are shown.

sand volumes were calculated in GIS for selected boxes (spatially fixed areas). Fig. 9 shows results for three areas between cross-shore transects at beach poles RSP km 13.6 and km 18.2, namely the nourishment site and the areas landward and seaward of it. In addition, sand volumes in two reference areas are shown on either side, namely the areas monitored between transects at RSP km 10.0 and km 13.6 (west) and between km 18.2 and km 22.0 (east).

The nourishment (2M m^3) is clearly visible. After October 1993 (end of the nourishment), the volume of the nourishment site decreases (1M m^3 at most), while that of the box landward of it increases much more (2M m^3). The seaward box remains constant in volume, at first sight, as does the eastern reference area till, around the end of 1997. The westward reference area is gradually gaining sand. Since the nourishment, the total area has received an extra 2M m^3 of sand which can only by explained by extending



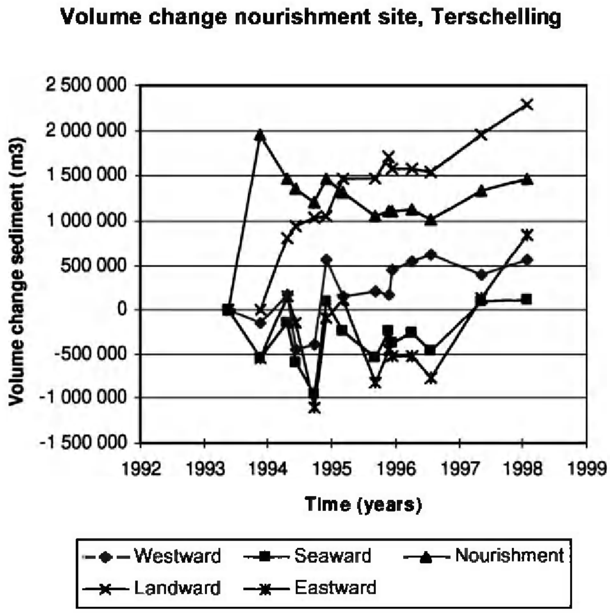


Fig. 9. Sand budgets (m^3) at Terschelling of selected boxes (fixed areas) as a function of time, derived from surveys: (i) nourishment site, (ii) area landward and (iii) area seaward of nourishment site, (iv) and (v) west and east monitored reference areas.

the study area to a larger scale including the two neighbouring outer deltas (Biegel and Spanhoff, 1999). The main conclusions of this study can be summarised as follows:

The shoreface nourishment has been designed as a feeder berm, with the idea that sand dumped at − 5 to − 7 m NAP in the trough of the two outer bars would be transported shoreward. Longshore transport quantities, or rather gradients therein, were deemed to be less significant. The system was considered to be homogeneous in a longshore direction, and at most some head effects were expected to occur near the western and eastern ends of the nourishment. Furthermore, it was assumed that the autonomous erosion would remain virtually the same, and that the amount of sand added was not that large that it could push the system to a basically different state. Obviously, reality differed from these expectations, since, for instance, the gain in sand volume of the area landward of the nourishment site is much larger than the "loss" of the nourishment area. The extra gain could be attributed on the one hand to the trapping of sand transported along the shore behind the nourishment, which acted as a berm reducing the wave energy responsible for littoral drift (a gain of 0.5M m^3/year, corresponding to half of the annual littoral drift, was discussed by Spanhoff et al., 1997) and on the other hand by a strong modification of the large-scale changes in the two outer deltas (see the apparent change in trend in the period 1990–1993 in Fig. 8) which act now as sediment sources for the Terschelling coastline.

This last analysis clearly shows the importance of extensive post-nourishment surveys at large scale to reduce uncertainties over the major system parameters. This point is now developed below.

7. Plea for monitoring

7.1. Organising a monitoring strategy at regional scale

Conducting field surveys before implementing a coastal defence scheme is a basic task for coastal engineers. It generally includes a bathymetric and topographic survey at the site, the sampling and analysis of surface sediments, and the collection of meteorological and oceanographic data (wind, waves, sea levels, currents). In the case of shore nourishment projects, a detailed local bathymetric survey is usually carried out just after the completion of the works for contractual reasons, in order to check the volume and position of the dumped sand. Specific technologies for local scale data collection are now fairly well established and potentially available for application. Recent extensive reviews of the possibilities are available in the literature (Gorman et al., 1998; Larson et al., 1997; Morang et al., 1997a,b).

The weak point of this approach is that surveys are usually planned shortly before the beginning of works, and just after, and cover too limited an area. As a consequence, their analysis cannot provide a reliable picture of the long-term and large-scale trends and variability of the stretch of coast to be nourished. In the absence of such an assessment, the performance of the nourishment scheme cannot be properly predicted. The case of Terschelling described in the previous section is a typical illustration of this point. The authorities are usually much more interested in the extent of the success and economic gains, than in why they occur. Performing a larger number of shoreface nourishments will automatically reveal when they work, and when not, and possibly why that is the case. However, this process can be speeded up and unnecessary project failures and waste of money can be avoided, by proper monitoring and analysis of previous and ongoing projects, as illustrated by the two field cases presented above.

In the soft engineering approach, the aim is different and more ambitious: a preventive approach is encouraged, leading to the implementation of a long-term routine monitoring and analysis programme covering the topography of the beach and bathymetry of the shoreface well before the works in order to follow the dynamic changes in the coast at seasonal, yearly and decadal time scales. The spatial extent of such a programme is also broader than the most exposed site itself, covering the entire coastal cell. It should also be accompanied by the collection of data related to the forcing (sea levels, meteorological data).

In Europe, the Dutch coast is a leading example of long-term monitoring. The positions of the dune foot, low- and high-waterline have been recorded since the 1850s. In the same way as for Sylt, a fixed reference frame is used, of so-called RSP (spatially fixed reference points) beach poles with spaced 200–250 m apart along the shore. At receding coasts, new poles are placed from time to time, but still the original positions are used as a reference. Two or three poles are positioned cross-shore to indicate measuring transects. Since 1965, cross-shore profiles at the RSP poles have been measured yearly (in so-called JARKUS surveys), with standard echo sounding of the sea bottom and, originally, levelling of the dry beach and dunes. Soon, from the 1970s onwards, levelling was replaced by aerial (pseudo-stereo, i.e. with overlapping consecutive images) photography. Since 1998, laser altimetry from an aircraft has been used for the dry parts of the profile after comparing it with aerial photographs (1996, 1997). The sounding lanes extended some 800 m seaward of the reference poles, from 1965. Every 5 years, much longer lanes were recorded. Since the end of the 1980s, the yearly lanes have been extended to 2000 m. The data are stored in the JARKUS database and used to implement the Dutch preservation policy in the field (Rijkswaterstaat, 1994). Waves and tides are also routinely monitored at several places in the North Sea along the Dutch coast, typically with frequency storages of 1 h and 10 min, respectively. Some 10 wave-directional buoys lie at water depths greater than 15 m, while some fixed stations at comparable depths are also in use. Tens of tidal gauges are placed all along the Dutch coast. Thus, usually enough information is available to guide standard nourishment operations.

Another example of such a long-term monitoring programme has been described at Sylt in the previous section. In our analysis, it is noted that project-related surveys are too often given a higher priority than long-term surveys, leading to a lack of any comprehensive understanding of the dynamics of the system as a whole. It is also shown that long-term surveys could provide more relevant information on the effectiveness of a shore nourishment scheme than a detailed, local survey.

7.2. The role of new monitoring technologies

Recognition of the need for a monitoring strategy at regional scale calls for the use of efficient monitoring techniques at reasonable cost. This is now achieved in Europe when hydrodynamic forcing is considered (air pressure, wind, waves, sea levels, tidal currents, storm surges). It has been obtained through a combination of field data and large-scale operational models.

On the other hand, regional hydrographic surveys are too often considered to be expensive and time-consuming, and few regions have established a routine monitoring programme. Yet, research and technological innovations related to remote sensing have rapidly developed in recent years, and produced operational techniques that are not well disseminated in Europe. Table 4 summarises available techniques, their uses and the expected vertical accuracy. Most of these techniques have been reviewed by Parson (1997).

For our purposes, the most promising techniques include the use of high precision global positioning systems (GPS), airborne laser mapping, video imaging and amphibious vehicles.

Basic GPS (global positioning system) is reputed to be the most accurate radio-based navigation system ever developed. It is accurate enough for many applications. Differential GPS (DGPS), an updated version, can yield measurements of the horizontal position that are accurate to a couple of metres in stationary and moving situations. With its improved

Table 4
Monitoring techniques in the nearshore (adapted from Parson, 1997)

Technique	Uses	Vertical accuracy
Rod and Transit	Dune, beach and foreshore (less than 1-m water depth)	± 1 to 10 cm
Single or multiple beam fathometer	Sea bottom outside the surf zone	± 15 to 30 cm
Differential GPS	Land or sea surveys in conjunction with the other methods	Land survey: ± 2 to ± 10 cm
Survey sea sled	Sandy beaches, inside the surfzone	± 3 cm
Airborne Lidar	Dune, beach, coastal zone and structures	± 5 cm (topography), ± 15 to 30 cm (bathymetry)
Video imaging	Shoreline, nearshore bars	
Amphibious vehicles	Beach and foreshore inside the surf zone	± 3 cm

accuracy, DGPS has become a universal measurement system capable of horizontally positioning features at a very precise scale. Also, the vertical co-ordinate of the receiving antenna, and thus of everything related to it (like the echo-sounded sea bottom) can be measured relatively accurately (± 5 cm), thanks to the RTK (real time kinematics) technique (Kaminsky and Gelfenbaum, 1988). DGPS involves the co-operation of two receivers, one that is stationary and one that is roving around while making position measurements. The stationary receiver is the key that ties all the satellite measurements into a solid local reference frame. The roving receiver merely needs to record all of its measured positions and the exact time each measurement was made. Later, these data can be merged with corrections recorded at the reference receiver for a final clean up. In Europe, Levoy (1994) reported its use since 1991 for seasonal monitoring of the west coast of Cotentin in Normandy, France. This regional survey is performed three times per year. It consists of 75 transects covering a stretch of coast 110 km long and about 500 m wide from the top of the dune to the mean sea level. The large width of this intertidal area is the consequence of very large tidal ranges (10 to 14 m during spring tides). The instrument is mounted on a buggy, and is able to complete the survey within a week.

Several airborne laser mapping techniques are now operational, and have been used in recent years for regional monitoring. In the US, Parson et al. (1999) and Irish et al. (2000) reported the use of an airborne LIDAR (named SHOALS) for regional sediment management in Florida over a 217-km stretch of coast. This system makes use of multiple laser beams in order to cover the beach and the underwater shoreface down to 60-m depth. (Note: such a depth is a function of water turbidity. It corresponds to two to three times the Secchi depth.) SHOALS is also used by the US Army Corps of Engineers to monitor the evolution of beach nourishments. Experience gained in the USA with this system has also led to the conclusion that airborne laser surveys are not only useful for long-term monitoring, but also for assessing the consequences of a storm event which often requires a quick and comprehensive survey. In the Netherlands, the yearly topographic survey based on transects every 200/250 m by stereo photogrammetry over a coastal length of about 300 km has been replaced since 1997 by a laser scanning survey with an average point density of 1 point per 6 m^2 (Van de Kraats, 1999).

Surveying the sea–land interface is a challenge, especially in micro-tidal environments, and we would like to emphasise here the use of the video-imaging technique as developed by the Coastal Imaging Laboratory of Oregon State University (USA) and known as the ARGUS system (Holland et al., 1997). It has been developed to provide a synoptic view of the surf and swash zones over a length coast of a few kilometres on a daily basis. A tool of this kind is very useful for monitoring nourished coasts. Ten-minute time-averaged images show smooth, bright bands of higher intensities that indicate locations where waves have a greater tendency to break. As nearshore waves generally break due to depth limitation, these patterns can be shown to reflect the presence of underwater shoals such as sand bars or shoreface nourishments (Lippmann and Holman, 1989). In the Netherlands, shoreface nourishments are generally placed just seaward of the outer bar, at a depth of around 5 m. Therefore, if the wave conditions are sufficiently rough to generate wave breaking at these depths, time-averaged video images can be used to reveal the presence and evolution (movement) of a shoreface nourishment. In the spring of 1998, a 1.25M m^3 shoreface nourishment was placed immediately seaward of the outer bar at Noordwijk (Netherlands), at a depth of 5 to 7 m. The location and scale of the underwater nourishment could be identified from so-called merged images (Fig. 10), which are created by merging the views from the different cameras of an Argus station. The upper panel shows a 180° panoramic view of the beach, whereas the lower panel contains its associated rectified image. The latter is a plan view image of the nearshore area, covering a 5-km stretch of beach and reaching out to 1500 m offshore. Clearly, they show the presence of an underwater nourishment 3 km long, at about 900 m offshore. By investigating a sequence of merged plan view images, the morphodynamic behaviour of the nourishment can be monitored.

The ARGUS system was also implemented at Egmond beach in the Netherlands to monitor a nourishment and coupled with the recently built so-called Water and Strand Profiler (WESP) that is comparable

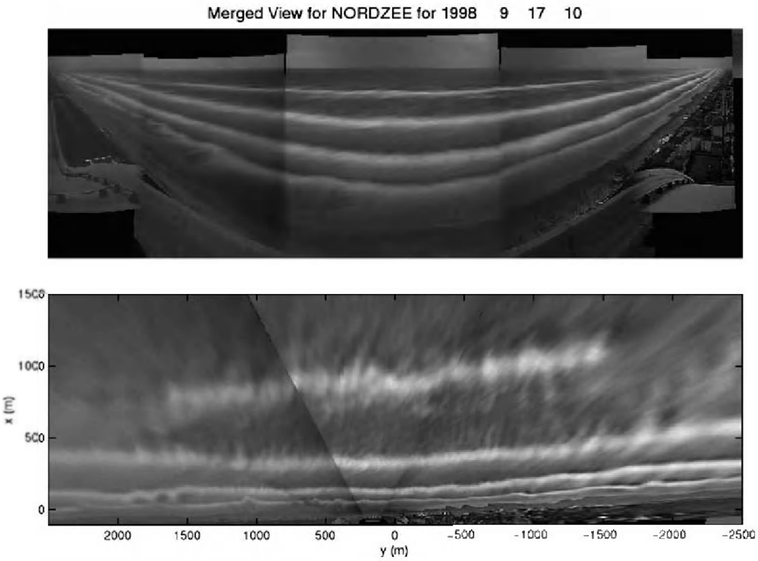


Fig. 10. Video-image of the shoreface nourishment at Noordwijk, Netherlands.

to the Coastal Research Amphibious Buggy (CRAB) developed previously by CERC (Birkemeier and Mason, 1984) to be used at the Field Research Facility at Duck, NC. The WESP has various advantages over more traditional techniques. First, the beach and underwater part are probed in one uninterrupted profile (uninterrupted from the dune foot to about 6-m water depth). Second, the data are independent of the water level, since the vertical position of the WESP, known by levelling with a laser on the beach or by vertical DGPS, determines the bottom elevation with respect to a fixed frame of reference. Third, the measurements can be done under relatively rough weather conditions. Finally, the WESP roves at a rate of about 5 km/h while measuring, enabling a suitable area to be probed in a day. As an option, the WESP can also tow a heavily instrumented sledge to its measuring positions (measurements of about 20 min at freely chosen locations, also to −6 m) and deploy and recover frames or assist in servicing instrumented poles, etc. WESP and ARGUS complement each other, and the combination of the two instruments seems to offer great potential for obtaining valuable monitoring data (Fig. 11).

Fig. 11. Schematic layout of a monitoring/measuring programme. From left to right: buoy, frame, pole, WESP, sledge, ARGUS tower, dune. In deep water, wave boundary conditions are measured by a buoy, while in shallow water, waves and water levels are measured from a pole. WESP and ARGUS monitor depths and heights. An instrumented sledge and a frame perform experimental process measurements.

8. Conclusions and recommendations

Nourishment techniques are widely regarded today as an environmentally acceptable method of beach and dune protection and restoration for short-term emergencies (viz. storm-induced erosion) as well as long-term issues (i.e. structural erosion and relative sea-level rise). Such developments, however, are neither easy to sustain nor well established yet, since a large variety of situations exists in Europe and a number of technical, scientific and public perception problems affect the design of nourishments.

Decision-making processes and legislative frameworks are certainly dominant in defining the objectives and constraints of nourishment projects, in their actual design, and also in the practices used. This is a clear example of the fact that proper management and planning of the Coastal Zone and its resources require concerted action at all levels. Local people, regional and national authorities, and socio-economic actors all have a role to play. All this considered, the views developed in the present paper lead to the following conclusions and recommendations:

(R1) Soft engineering implies a new attitude towards nature with the recognition of the value of natural systems (Capobianco and Stive, 1997) and the natural mobility of beaches. Its application to soft beach systems implies primarily a preventive approach based on the implementation of a long-term monitoring programme covering large-scale morphodynamic regions.

(R2) Traditional hydrographic survey techniques are expensive, time-consuming and slow down the development of monitoring programmes. Innovative survey techniques such as high precision GPS, airborne laser mapping, video-imaging and amphibious vehicles should be encouraged so that costs may be reduced and the frequency of surveys may increase.

(R3) Monitoring programmes provide a wealth of data, which should be properly documented and stored for future analysis and reference. A few databases are already available and their dissemination for scientific and engineering purposes should be encouraged as much as possible (see, e.g. a description of 12 field data sets in Hamm, 1999). It is suggested to include the maintenance costs of such databases in the design of the monitoring programme and to give it a high priority. Moreover, a proper organisation for collecting, handling and disseminating information and data on experience both at national and European levels should be promoted.

(R4) Analysis of such field data leads to a wider view of the morphodynamic processes and a better understanding of the variability of the shoreline as shown by the case study of Terschelling. Its recognition by coastal engineers is a prerequisite to proper soft engineering operations. Variability should be maintained as much as possible in order to minimise the impacts on adjacent shores. Practical tools to obtain a quantitative estimation of the variability of a shoreline are required. Coastal engineers are encouraged to use them in the process of designing shore nourishments.

(R5) Several manuals are currently available for providing recommendations in the design of shore nourishments. Conceptually, they cover the topic satisfactorily. Nevertheless, it is worthwhile noting that virtually no experience with shoreface nourishment has been explicitly discussed in the manuals. Yet this concept is receiving increased attention, especially with regard to upper shoreface nourishment (e.g. Jackson and Tomlinsen, 1990). In Europe, three experimental shoreface nourishments were implemented in the framework of the European (MAST-programme) NOURTEC project including Terschelling (Wadden island, North Sea coast of the Netherlands), Torsminde (North Sea coast of Denmark, north of Sylt) and at the Wadden island of Norderney (Germany, east of Terschelling). As potential advantages, shoreface nourishments can be carried out under a wider range of conditions than beach nourishments, without interfering with on-going recreation. The project may be even cheaper by avoiding additional handling such as borrow sand transfer to smaller vessels, coupling to pipelines, pumping and/or rainbowing, and bulldozing.

(R6) Numerical models are frequently used at a scientific level to explain collected field data. Their use in coastal engineering is no mean task and requires specialised skills. Their contribution to the design process is nevertheless considered essential. When properly calibrated and validated, they can provide comparative answers to several alternatives and optimise their efficiency in terms of costs, while providing indications on the uncertainty of coastal responses.

(R7) Models are sensitive to morphological as well as input (forcing) parameters, so it is imperative to use proper values and to perform sensitivity analyses. The modeller's experience plays a dominant role in this respect. Also, calibration procedures that are not currently standardised depend on such experience. Still, "nonexperts" are increasingly involved in applying models in the design of nourishments and in the decision-making process. Thus, all elements of subjectivity should be removed from calibrating and running models in order to make the results "reproducible", "transferable", and "recognisable".

Research efforts should be pursued along several lines:

(R8) Monitoring by video-imaging has proven to be efficient in providing comprehensive views of surf and swash zones. More intensive use of these images can be foreseen as a way of monitoring the shoreline and the surfzone bathymetry.

(R9) The effect of gradation in sediment transport and morphodynamics is still a key research issue. For instance, the effect of grain sizes on sand transport was shown at the Terschelling shoreface nourishment (Guillen and Hoekstra, 1996). In this issue, De Meijer et al. (2002) report flume experiments exploring the effect of gradation in grain-size and density on sediment transport induced by waves and waves plus currents. This still limited knowledge should be enlarged. Another important aspect in this context is the monitoring of sediment characteristics in nourishment projects. One of the novel techniques recently developed is the characterisation of sediments based on their natural radioactivity content (De Meijer, 1998). The method can be applied in the laboratory for sample analysis, but also in the field. A towable underwater detector system (MEDUSA) enables the mapping of synoptical sediment composition maps. The method is currently limited to discrimination between heavy minerals, quartz sand grains and mud. A future development of the system includes the use of a microphone that records the sound level generated by the detector casing and the sediment. Comparison of sound levels and the grain sizes of surface sediment samples showed a linear relation between median grain size and sound level (Koomans et al., 1998). This suggests the possibility of mapping grain sizes synoptically and in situ as part of a beach nourishment monitoring programme.

(R10) Numerical modelling is developing along two main lines:
- process-based models are used mainly for research purposes and cannot currently reproduce long-term morphodynamic changes. Most particularly, they require a better description of wave-related sediment transport and swash processes,
- behaviour-oriented models are more operational. At the moment, a clear distinction is made between cross-shore and longshore changes. Coupling between these two appears to be a promising way of providing a comprehensive view of the sediment budget.

Acknowledgements

This work was undertaken as part of the SAFE project, partly funded in the MAST programme by the European Commission, Directorate of Science, Research and Development (DG-XII), contract No. MAS3-CT95-0004. The first author acknowledges the funding provided the by Ministère de l'Equipement, des Transports et du Logement, Direction de la Recherche et des Affaires Scientifiques et Techniques, Service Technique des Ports Maritimes et des Voies Navigables (France), subvention No. 97 M/3. The other authors acknowledge their respective national funding parties.

Disclaimer

The facts and views presented in this paper are based on information available to the authors, and on their personal interpretations that do not necessarily correspond with the opinions of their institutes and governments, nor with those of the European Union.

References

Biegel, E.J., Spanhoff, R., 1999. Large and small scale coastal behaviour and the effect of the shoreface nourishment at Terschelling, the Netherlands—Final Report prepared for SAFE project National Institute for Coastal and Marine Management/RIKZ, The Hague, Netherlands, May 1999.

Birkemeier, W.A., Mason, C., 1984. The CRAB: a unique nearshore surveying vehicle. Journal of Surveying Engineering 110, 1–7.

Bokuniewicz, H.J., 1998. Monitoring beaches: conditions at the village of East Hampton, NY. Shore and Beach 66 (4), 12–17.

Browder, A.E., Dean, R.G., 2000. Monitoring and comparison to predictive models of the Perdido Key beach nourishment project, Florida, USA. Coastal Engineering 39, 173–191.

Capobianco, M., Stive, M.J.F., 1997. Soft protection technologies as a tool for integrated coastal zone management. Proc. 3rd Int. Conf. On the Mediterranean Coastal Environment (MEDCOAST '97), Malta, November 11–14, pp. 469–484.

Capobianco, M., De Vriend, H.J., Stive, M.J.F., Southgate, H.N., Jimenez, J., Larson, M., Hanson, H., 1999. Large-scale coastal evolution: toward a robust model-based methodology. Journal of Coastal Research (in press).

Capobianco, M., Hanson, H., Larson, M., Steetzel, H., Stive, M.J.F., Chatelus, Y., Hamm, L., Aarninkhof, S., Karambas, T., 2000. Nourishment Design and Evaluation. Applicability of Model Concepts 47, 113–135.

CIRIA, 1996a. Beach Management Manual. In: Simm, J.D. (Ed.), Construction Industry Research and Information Association, Report 153, London, United Kingdom.

CIRIA, 1996b. Beach recharges material-demand and resources. Construction Industry Research and Information Association, Report 154, London, United Kingdom.

Cooper, N.J., 1998. Assessment and prediction of Poole Bay (UK) replenishment schemes: application of data to Führböter and Verhagen models. Journal of Coastal Research 14 (1), 353–359.

CUR, 1987. Manual on artificial beach nourishment. Center for Civil Engineering Research, codes and specifications—Report 130, Gouda, Netherlands.

CUR, 1997. Beach nourishments and rock structures. Center for Civil Engineering Research, codes and specifications—Report in press, Gouda, Netherlands.

De Meijer, R.J., 1998. Heavy minerals: from 'Edelstein' to Einstein. Journal of Geochemical Exploration 62, 81–103.

De Meijer, R., Bosboom, J., Cloin, B., Katopodi, I., Kitou, N., Koomans, R., Manso, F., 2002. Gradation effects in sediment transport. Coastal Engineering 47, 179–210.

Dette, H.H., 1997. Evaluation of long term dune recession data. Proc. Coastal Dynamics '97 Conf., Plymouth, UK, June 23–27. ASCE, New York, pp. 634–643.

Dette, H.H., Newe, J., 1999. Documentation of field data from Sylt/North Sea. Internal report no. 835. Leichtweiss Institute, Technical University of Braunschweig, Germany.

Dette, H.H, Führböter, A., Raudkivi, A.J., 1994. Interdependence of beach fill volumes and repetition intervals. Journal of Waterway, Port, Coastal, and Ocean Engineering 120 (6), 580–593.

Dette, H.H., Larson, M., Newe, J., Peters, K., Reniers, A., Steetzel, H., 2001. Application of prototype flume tests for beach nourishment assessment. Coastal Engineering (submitted for publication).

EAK, 1993. Empfehlungen für die Ausführung von Kstenschutzwerke (Recommendations for the design of coastal structures), Die Küste, Heft 55, Heide, Germany (in German).

Gorman, L., Morang, A., Larson, R., 1998. Monitoring the coastal environment; part IV: mapping, shoreline changes, and bathymetric analysis. Journal of Coastal Research 14 (1), 61–92.

Gravens, M.B., 1997. Wave resolution effects on predicted shoreline positions. Journal of Waterway, Port, Coastal, and Ocean Engineering 123 (1), 23–33.

Guillen, J., Hoekstra, P., 1996. The "equilibrium" distribution of grain size fractions and its implications for cross-shore sediment transport: a conceptual model. Marine Geology 135, 15–33.

Hamm, L., 1998. Performance of soft beach systems and nourishment measures for European coasts (project SAFE). Proc. 3rd European Marine Science and Technology Conf., Lisbon, 23–27 May 1998. Project Synopsis, vol. II, pp. 931–944.

Hamm, L. (Ed.), 1999. PACE project. Prediction of aggregate-scale coastal evolution. Task force on datasets. Summary of available datasets. Internal report no. 51 8906 R1, Sogreah, Grenoble, France.

Hanson, H., Kraus, N.C., 1993. Optimization of beach fill transitions. In: Stauble, D.K., Kraus, N.C. (Eds.), Beach Nourishment Engineering and Management Considerations. Proc. Coastal Zone '93. ASCE, New York, pp. 103–117.

Hanson, H., Larson, M., 1999. Extension of GENESIS into the cross-shore dimension-from 1-line. Proc. 5th Intl. Conference on Coastal and Port Engineering in Developing Countries, 312–323.

Hanson, H., Brampton, A., Capobianco, M., Dette, H.H., Hamm, L., Laustrup, C., Lechuga, A., Spanhoff, R., 2002. Beach nourishment projects, practices and objectives—a European overview. Coastal Engineering 47, 81–111.

Holland, K.T., Holman, R.A., Lippmann, T.C., Stanley, J., Plant, N.G., 1997. Practical use of video imagery in nearshore oceanographic field studies. IEEE Journal of Oceanic Engineering 22 (1), 81–92.

Irish, J.L., Mc Clung, J.K., Lillycrop, W.J., 2000. Airborne lidar bathymetry: the SHOALS system. P.I.A.N.C. Bulletin (3), 43–52.

Jackson, L.A., Tomlinsen, R.B., 1990. Nearshore nourishment implementation, monitoring and model studies of 1.5 Mm^3 at Kirra beach. Proc. 22nd Int. Conf. on Coastal Engineering, Delft, Netherlands. ASCE, New York, pp. 2241–2254.

Kaminsky, R., Gelfenbaum, R., 1988. Monitoring coastal change in Southwest Washington and Northwest Oregon during the 1997/98 El Nino. Shore and Beach 66 (3).

Kamphuis, J.W., 2000a. Introduction to coastal engineering and management. Advanced Series on Ocean Engineering, vol. 16. World Scientific Publishing, Singapore.

Kamphuis, J.W., 2000b. Designing with models. Keynote at the 27th International Conference on Coastal Engineering, Sydney, Australia. ASCE, New York, pp. 19–32.

Kana, T.W., Katmarian, R.E., McKee, P.A., 1997. The 1986–1995 Myrtle beach nourishment project ten-year performance summary. Shore and Beach 65 (1), 8–23.

Komar, P.D., 1996. The budget of littoral sediments, concepts and applications. Shore and Beach 64, 18–26.

Koomans, R.L., de Meijer, R.J., Venema, L.B., 1998. Cross-shore graded sediment transport: grain size and density effect. Proc. ICCE '98. ASCE, Reston, pp. 2463–2474.

Kraus, N.C., Wise, R.A., 1993. Simulation of January 4, 1992 storm erosion at Ocean City, Maryland. Shore and Beach 61 (1), 16–22.

Larson, M., Kraus, N.C., Hanson, H., 1990. Decoupled numerical model of three-dimensional beach change. Proc. 22nd Int. Conf. on Coastal Engrg. ASCE, New York, pp. 2173–2185.

Larson, R., Morang, A., Gorman, L., 1997. Monitoring the coastal environment: Part II. Sediment sampling and geotechnical methods. Journal of Coastal Research 13 (2), 308–330.

Larson, M., Capobianco, M., Wise, R.A., 1999a. Modelling cross-shore sediment transport at different scales using equilibrium beach profile theory. Proc. 4th Int. Symp. On Coastal Engineering and Science of Coastal Sediment Processes (Coastal Sediments '99), Hauppauge, Long Island (NY, USA). ASCE, Reston, pp. 1371–1387.

Larson, M., Kraus, N.C., Wise, R.A., 1999b. Equilibrium beach profiles under breaking and non-breaking waves. Coastal Engineering 36, 59–85.

Levoy, F., 1994. L'étude globale concernant la défense contre la mer du département de la Manche: vers une nouvelle politique de protection des côtes. Cahiers Nantais (41–42), 279–290.

Lippmann, T.C., Holman, R.A., 1989. Quantification of sand bar morphology: a video technique based on wave dissipation. Journal of Geophysical Research 94 (C1), 995–1011.

MIMAM/Ministerio de Medio Ambiente, 1998. La Costa de todos naturalmente. Secretaria de Estado de Aguas y Costas. Direccion General de Costas, NIPO: 310-98-024-4, Madrid, Spain.

MOPU, 1988. Coastal Actions. Direccion General de Puertos y Costas, Secretaria General Técnica, Centro de Publicacciones, ISBN: 84-505-7700-4, Madrid, Spain.

Morang, A., Larson, R., Gorman, L., 1997a. Monitoring the coastal Environment: Part I. Waves and currents. Journal of Coastal Research 13 (1), 111–133.

Morang, A., Larson, R., Gorman, L., 1997b. Monitoring the coastal environment: Part III. Geophysical and research methods. Journal of Coastal Research 13 (4), 1064–1085.

Mulder, J.P.M., Van De Kreeke, J., Van Vessem, P., 1994. Experimental shoreface nourishment, Terschelling (NL). Proc. 24th Coastal Engineering Conference. American Society of Civil Engineers, New York, pp. 2886–2899.

Newe, J., Dette, H.H., 1995. Simulation of Dune and Nourished Berm Erosion During Storm Surges. Proceedings Coastal Dynamics '95, Gdansk, Poland. ASCE, New York, pp. 850–861.

NOURTEC, 1997. Innovative nourishment techniques evaluation. Final report. Coord. Rijkswaterstaat, National Institute for Coastal and Marine Management/RIKZ, The Hague, Netherlands, 105 pp., with figures.

NRC/National Research Council, 1995. Beach Nourishment and Protection. Committee on Beach Nourishment and Protection. National Academic Press, Washington, DC, USA.

Parson, E.L., 1997. Beach and nearshore survey technology. Coastal Engineering Technical Note, CETN II-38, Waterways Experiment Station, US Army Corps of Engineers, Vicksburg, MS, USA.

Parson, E.L., Lillycrop, W.J., McClung, J.K., 1999. Regional sediment management using high density lidar data. Proc. Coastal Sediments, 99 Conf. ASCE, New York, pp. 2445–2456.

Rijkswaterstaat, 1994. Statistical analysis and prediction of Dutch Coastline (in Dutch). Rijkswaterstaat, National Institute for Coastal and Marine Management/RIKZ/94-045, The Hague, Netherlands.

Roelse, P., 1996. Evaluatie van Zandsuppleties aan de Nederlandse Kust. Report RIKZ-96.028, The Hague, Netherlands, ISBN 90-369-0455-2.

Roelvink, J.A., Meijer, Th.J.G.P., Houwman, K.T., Bakker, R., Spanhoff, R., 1996. Field validation of a coastal profile model. Proc. Coastal Dynamics '95. ASCE, New York, pp. 818–828.

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

Southgate, H.N., Capobianco, M., 1997. The role of chronology in long-term morphodynamics: theory, practice and evidence. Proc. Coastal Dynamics '97, Plymouth, UK, June 23–37. ASCE, New York, pp. 943–952.

Spanhoff, R., Biegel, E.J., Van de Graaff, J., Hoelstra, P., 1997. Shoreface nourishment at Terschelling, the Netherlands: feeder berm or breaker berm? Proc. Coastal Dynamics '97, Plymouth, June 23–27. ASCE, New York, pp. 863–872.

Stauble, D.K., Kraus, N.C., 1993. Project performance: Ocean city, Maryland beach nourishment; beach nourishment engineering and management considerations. Proc. Coastal Zone '93. ASCE, New York, pp. 1–15.

Stive, M.J.F., Aarninkhof, S.J.C., Hamm, L., Hanson, H., Larson, M., Winjberg, K., Nicholls, R.J., Capobianco, M., 2002. Variability of shore and shoreline evolution. Coastal Engineering 47, 211–235.

Van Alphen, J.S.L.J., Hallie, F.P., Ribberink, J.S., Roelvink, J.A., Louisse, C.J., 1990. Offshore sand and extraction and nearshore profile nourishment. Proc. 22nd Intern. Conf. on Coastal Eng. ASCE, New York, pp. 1998–2009.

Van de Kraats, E., 1999. Airborne laser scanning: an operational remote sensing technique for digital elevation mapping in coastal areas. Proc. Coast GIS '99 Conf., November 1999. Editions Ifremer, Brest, France.

Work, P.A., Dean, R.G., 1995. Assessment and prediction of beach-nourishment evolution. Journal of Waterway, Port, Coastal, and Ocean Engineering 121 (3), 182–189.

Zheng, J., Dean, R.G., 1997. Numerical models and intercomparison of beach profile evolution. Coastal Engineering 30, 169–201.