CHAPTER 141

RECONSTRUCTION OF THE HOLOCENE EVOLUTION OF THE DUTCH COAST

The Dutch Coast: Paper No. 2

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Abstract

In 1986 the TOW Coastal Engineering Research Programme was merged with the Coastal Genesis Research Programme. Rijkswaterstaat, the financer and initiator of these programmes, concluded that the growing interest in the longer term development of the coast in relation to sea-level rise and other climatic changes made it necessary to approach the research questions from a wider perspective than just the coastal engineering discipline. Geology, historical geography and physical geography were included as disciplines, and a multidisciplinary approach to a holistic understanding of the Dutch coast was undertaken. The results of the first phase of the Coastal Genesis Programme became available in 1987, comprising a reconstruction of the Holocene evolution of the Dutch coast, and a view on the available knowledge regarding the physical processes responsible for this evolution. A summary of the reported conclusions is given here.

1. Introduction

Since the early 1970's Rijkswaterstaat stimulated Dutch coastal research at Rijkswaterstaat, Delft University of Technology and Delft Hydraulics with the TOW Coastal Research Programme. This programme was mainly devoted to the study of coastal processes from the coastal engineering perspective.

Around 1985, initiated by coastal erosion management questions, an interest grew into larger scale, longer term coastal evolution processes and it was realized that the TOW Programme as such (i.e. focussing on coastal evolution processes of typical time- and length-scales of a year and a kilometer) was too limited in scope. In order to gain an understanding of large-scale, long-term coastal evolution, a variety of geo-morphological processes with a diversity of time- and length-scales needs to be considered, which, in turn, calls for the deployment of many specialisms. This approach has been applied in a new research programme, called Kustgenese (Coastal Genesis). In this programme, the fields of geo-morphology, hydro- and

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morphodynamics, physical and historical geography and geology have been linked in order to study and understand coastal evolution at the scales of interest and, subsequently, to arrive at a (physical-mathematical) tool for coastal erosion and eventually coastal zone management.

The present paper deals with the first phase of the Coastal Genesis Programme, which resulted in a reconstruction of the Holocene evolution of the Dutch coast and a view on the available knowledge regarding the physical processes responsible for this evolution. Based on this, the main research items for the second phase of Coastal Genesis were identified (Terwindt and Battjes, Paper No. 10, these proceedings).

2. Research strategy

The Dutch coast is a complex morphological system with a length-scale of hundreds of kilometers. Since length-scales and time-scales are coupled in the sense that the larger the length-scale, the larger the time-scale (De Vriend, 1988), it immediately follows that in order to unravel this system, a large time-scale has to be considered. Against this background, it was decided to focus the first phase of the Coastal Genesis Programme on the evolution of the entire Dutch coast over the past 5000 years.

In fact, ´typical´ time-scales of 100, 1000 and 5000 years were distinguished. For each of these time-scales, a working-group was formed and given the task to identify the physical processes dominating the coastal evolution at the given scale. The fields of geomorphology, hydrodynamics and physical geography took a leading position in the Working Group 100 and the activities in this group were mainly concerned with coastal modelling and gathering field data. Central in the Working Group 1000 were the fields of geology and historical geography and for the Working Group 5000 this position was taken by the field of geology.

The research strategy, applied in each of these working groups, is based on the rationale that the physical processes to be identified, form the link between the external conditions or constraints that influence coastal evolution (wave climate, currents, availability of sediment) and the corresponding morphological response in the coastal zone. In this respect, reconstructions of the external conditions and the actual coastal evolution have been made. These aspects, called Input and Output, respectively, were determined first. The natural link between the Input and the Output is formed by the (geo-)morphological processes and their interactions, shortly denoted as the System. Put together, this approach is called the ISO-method. Correlating the Input and the Output has led to hypotheses regarding the (potential) relevance of various morphological processes which fit in the System. In the description hereafter, the distinction between Input, System and Output is maintained.

3. Output: Reconstruction of the actual coastal evolution

A summary calendar of the Dutch Coastal evolution in the Holocene is given in Table 1. A more detailed description is as follows.

geologicol time		yeors BP	yeors AD	sea level (m)	event in coastol evolution
Pleistocene					
HOLOCENE		10000			
	Preboreol				
		9000		– 25	8700 BP: Southern North Seo is formed
	Boreol				8300 BP: Connection between southern and northern North Sea
		8000	5500 BC	– 15	7800 BP: Coostline oppr. 25 km west of present locotion
	Atlontic	7000			On average, the coastline retreats and barrier islands are formed in the eastern part of the country
		6000			
		5000	3850 BC	– 4.5	5000 BP: Interconnection of borrier islonds in the eost; formation of old dunes; mouth of river Rhine becomes active; coastline 8 km east of present position and odvoncing
	Subboreal	4000		– 3.0	
		3000	1100 BC	– 1.7	3200 BP: Closure of the inlet neor Bergen
					Coastal advance comes to an end and retreat begins; the mouth of the river Rhine becomes inactive
	Sublontic	2000	AD	– 1.0	
					+ 500 AD: Break–through of dunes in the south
		1000			+1100 AD: Break–through of dunes in the north–west
					1000–1600 AD: Formation of the young dunes
		0	1987	NAP	

Table 1 Time table with the main events in the development of the Dutch coast (after Stive, 1987)

At the end of the last Glacial (Pleistocene), some 10,000 years ago, the area presently known as the southern North Sea was completely dry. It took about 2000 years before this area started to flood (Fig. 1). At first, the water came in from the south, through the English Channel. In the meantime, the northern North Sea was formed immediately south of the retreating polar ice. The separation between the southern and northern parts of the North Sea extended from the present Dutch Wadden island Texel in western direction. It flooded approximately 8300 BP (BP stands for carbon-14 years before present). As the icecaps continued to melt, the sea transgraded. About 7500 BP, the Dutch coastline was situated some 25 kilometers west of its present position and migrated in eastern direction.

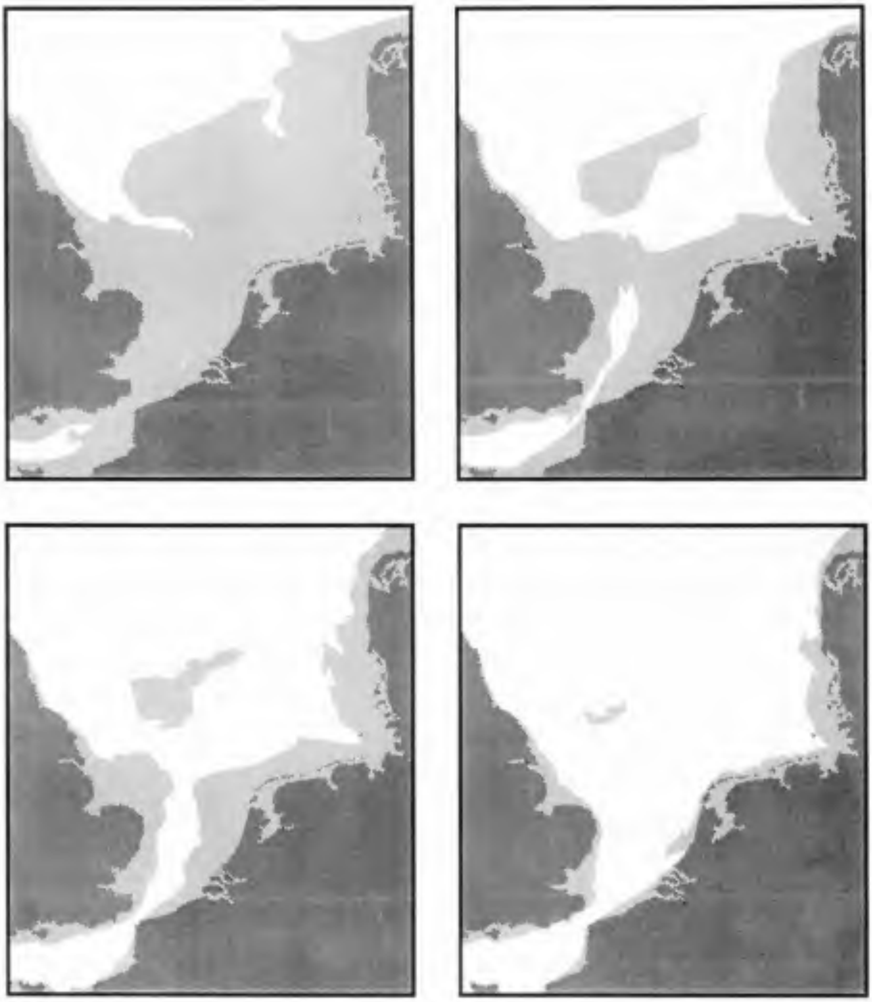

Figure 1 Four stages in the formation of the North Sea (after Zagwijn, 1986) at 9000 BP (a), 8700 BP (b), 8300 BP (c) and 7800 BP (d).

During the first 3000 years since the beginning of the Holocene, the rate of sea-level rise amounted approximately 1 meter/century.

This rate slightly decreased in the following 2000 years. A drastic decrease of this rate occurred around 5000 BP. Within a period of only a few centuries, the rate of sea-level rise almost decimated (Zagwijn, 1986).

These changes in the sea-level rise coincide with and are probably the cause of a turning point in the evolution of the Holland coast (Beets et al., 1990). When the rate of sea-level rise started to decrease significantly, the various tidal inletsystems were suppressed due to siltation processes in the direct vicinity of the main channel systems. As a result, barrier islands were formed originating from the sand reservoirs contained in the underwaterdeltas (from 7300 BP onwards). Interconnection of these islands took place around 5000 BP and led to a closed coastline at which, during the following 4000 years, the so-called old dunes were formed. In the meantime, the coastline advanced seaward, although the sea-level continued to rise.
The typical shape of a cross-section of these old dunes is low and wide. The amount of sediment contained in these dunes is appr. 62,000 m^3 per meter along the coast. The period between 3000 and 1800 BP is characterized by an inversion of the coastline migration. Since that period, the Dutch west-coast has retreated almost continuously and from 1000 to 400 BP the so-called young dunes were formed on top of the old ones. These young dunes are higher than the old dunes, but much narrower. They contain about 14,000 m^3 of sediment per meter in long-shore direction.

Before the interconnection of the barrier islands (i.e. before 5000 BP), the area behind these islands flooded with the tide (salt water) and with high river output (fresh water from the Rhine and Meusse). In this wet, brackish environment, peat started to grow and managed to keep pace with the rising sea-level. After the closure of the coastline, the brackish water was entirely replaced by fresh river water. This did not stop the growth of peat but merely caused a change in the type of peat (Van der Valk, 1990).

The retreat of the coastline (from 3000 BP onward) in combination with a continuously rising sea-level caused an increasing number of break-throughs in the dune coast. This initiated a chain of mutually intensifying processes. The first break-throughs caused the drainage of the peat area´s behind the dunes. The allied subsidence gave way to extensive flooding and, thus, erosion of the peat. This occurred primarily in the north and in the south-west of the Netherlands and resulted in the Waddensea (north) and the Zeeland estuaries (south-west). The excavation and burning of peat, performed by our ancestors, have intensified this process.

The resulting coastal system has not shown any dramatic changes during the past few centuries. Especially since approximately 1850, the coastline has been intensely regulated by man. The coastal system can roughly be divided into three sub-systems: the estuaries in the south-west (the Delta-coast), the closed dune coast in the west (the Holland coast) and the barrier islands in the north (the Waddensea coast). The estuaries at the Delta-coast have been closed off almost completely after the flooding of 1953. The concave-shaped Holland-coast is slowly eroding at its outer ends, whereas the centre maintains a fairly stable position. However, the shoreface at the centre of this part of the coast is steepening, so that there is effectively a loss of sediment. The erosion at the northern end of the Holland-coast is related to a vast accretion in the near-by part of the Waddensea, which becomes gradually shallower. These sub-systems of the Dutch coast are indicated in Figure 2.

Human interventions have influenced the cóastal evolution since the early middle ages, when the first dykes were built. Especially during the past century this effect is noticeable.

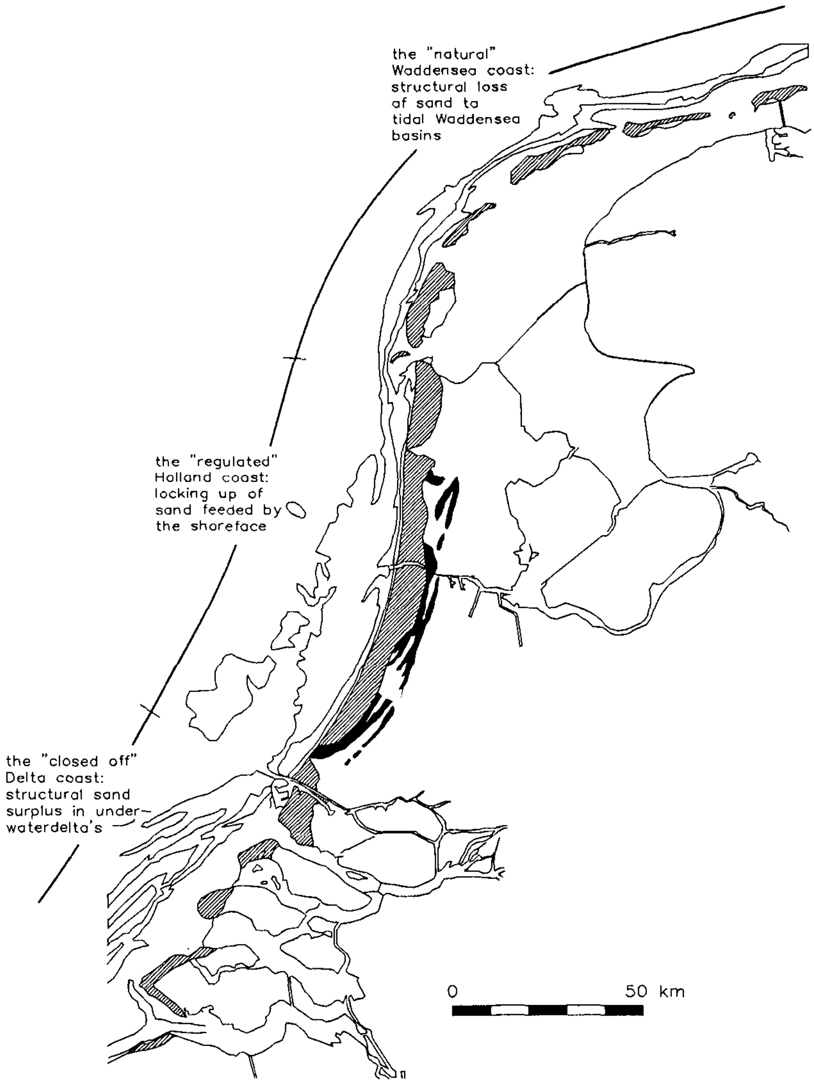

Figure 2 Subsystems of the Dutch Coast

4. Input: Reconstruction of the external conditions

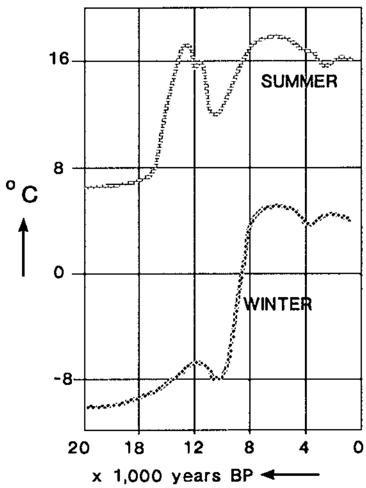

Figure 3 Supposed average summer and winter temperatures (after Lamb, 1982)

The end of the Pleistocene (appr. 10,000 BP) is marked by a sudden (on a geological time-scale) rise in the average winter temperature. Within a period of 2000 years, this temperature rose from appr. -8°C to appr. +3°C (Lamb, 1982; see Fig. 3). This change gave way to the melting of icecaps and, hence, to the formation of the North Sea.

The rise of the sea-level interacts with a number of supposedly important factors in coastal evolution. The horizontal sizes of the sea in combination with the bottom geometry and the water level clearly affects the propagation of the tidal wave and it has a vast influence on the generation and propagation of wind-waves in the (relatively shallow) coastal area.

The relation between various characteristics of the wind-wave field on the one hand and the sea-level on the other hand has been indicated by Stive (1987; see Fig. 4). Apparently, the significant wave height and the wave period have stabalised after the decrease in the sea-level rise (5000 BP) whereas the wave skewness, an important measure for wave-driven sediment transport, has increased continuously. Furthermore, model computations have been carried out to reconstruct the changes in the tidal conditions due to a rising level of the North Sea (Franken, 1987; see Fig. 5 for an example).

With the rising (average) air temperature, the atmospheric conditions have changed. The dominant wind direction as well as the distribution of the wind speed over time and directions has changed over the years (Kollen, 1987; Hoozemans, Paper No. 3, these proceedings). This has a direct effect on the transport of sediment (aeolic transport), but it has also an indirect effect (wind-induced waves and currents).

5. Input-Output correlation

The purpose of correlating the reconstructed external conditions and the observed coastal evolution is to gain insight in the relevance of processes which determine the large-scale coastal evolution. In the long run, the morphological changes in the coastal zone are obviously determined by the availability of sediment. Hence, it is important to localize the potential sediment sources and sinks. Additionally, the intensity of the mechanisms that transport the sediment to and from these sources and sinks have to be determined.

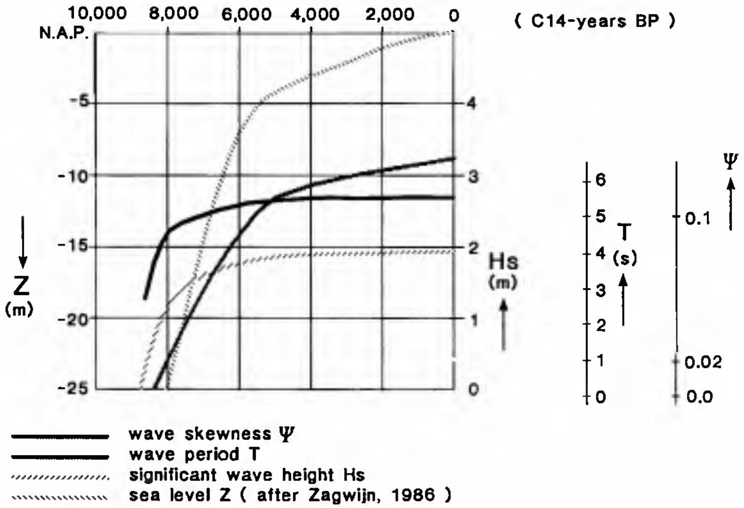

Figure 4 Changes in wave parameters in relation to the sea-level rise (after Stive, 1987).

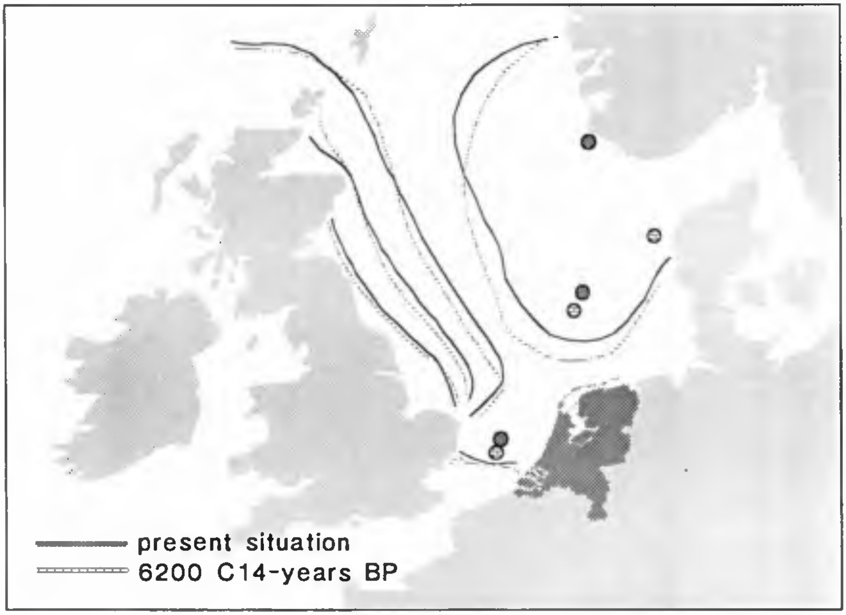

Figure 5 Iso-amplitude lines and amphidromic points cooresponding to the semi-diurnal tide (after Franken, 1987).

One of these sources or sinks may be formed by a seaward boundary of the coastal system. For example, such a boundary could act as a sink if sediment can only be transported across this boundary in offshore direction. Van Vessem and Stolk (Paper No. 4, these proceedings) have searched for such a boundary, but could not find clear indications for the existence of one.

Tidal basins can act as a sink, for instance if a near equilibrium situation is disturbed by sea-level rise (Eysink, Paper No. 8, these proceedings). These basins appear to strive for an equilibrium ratio of their wet surface and their wet volume. A rising sea-level continuously disturbes this equilibrium in the sense that the basin becomes too deep in relation to its horizontal sizes. This results in accretion inside the basin at the expense of the nearby coastal area.

An important source is formed by sediment contained in river discharge. This way, material is brought into the coastal system at the river mouth and is distributed along the coast by longshore transport mechanisms. Before 5000 BP, the relatively high output of sediment from the rivers Rhine and Scheldt in combination with a transport of sediment from deeper towards the coast, has led to the formation of a delta. Later on, the sediment supply from these rivers decreased and the delta slowly eroded due to gradients in the longshore transport. This erosion process has also acted as a source of sediment.

An important item in the correlation of Input and Output was to gain insight into the relative importance of cross-shore and longshore transport of sediment. A survey has shown that a considerable part of the observed coastal evolution cannot be explained if only longshore transport is taken into account (Zitman, 1987). From this it was concluded that cross-shore transport is at least as important as long-shore transport. However, this survey did not yield any indications regarding the relevance of the involved physical processes. This has been investigated later (Roelvink and Stive, Paper No. 5; Steetzel, Paper No. 6; Stive et al., Paper No. 9; all in these proceedings).

6. Summary of hypotheses

The correlation of the external conditions and the reconstructed (observed) coastal evolution (input and output, respectively) has led to hypotheses regarding the relative importance of physical processes that have played a dominant role in the coastal evolution. This relative importance is dependend on the considered time-scale. Stive (1987) has given an overview of the hypotheses and their relevance in relation to the various time-scales. A summary of this overview is given hereafter.

Exchange of sediment between the nearshore and the inner shelf is a process of which the physics are not fully understood. Nevertheless, it is believed to explain much of the observed coastal evolution. There are no hard indications that there is a seaward boundary to this exchange on a time-scale of 100 years. This cross-shore transport is believed to have provided a considerable part of the material needed in the building up of the coast since the beginning of the Holocene. Up to 5000 BP this building up kept pace with the rising sea-level. However, at that time the sea-level rise decreased. This, in combination with the earlier described closure of the tidal inlet system on the central Holland coast, yielded a sediment surplus in the nearshore which, eventually, resulted in the formation of barrier islands and the old dunes. Furthermore, cross-shore sediment transport is also believed to have played an important role in the formation of the young dunes, which started approximately 1000 years ago.

In contrast with the cross-shore sediment exchange, there is a good understanding of the physics behind the longshore transport of sediment in the nearshore zone. This type of transport is mainly wave-driven and takes place inside a comparatively narrow band along the coast. In this case, there is a closed system in which the sediment is redistributed along the coast due to gradients in the longshore transport. Examples of this process are the coastal retreat at the outer ends of the Holland coast (time-scale of 100 years) and the interrelation of the coastal advance and the erosion of the Rhine-Scheldt delta (from 5000 BP onwards).

On a time-scale of 1000 years, changes in the sea-level rise appear to be highly correlated with the formation of dunes. However, the understanding of this relation is insufficient to estimate its importance with respect to the observed coastal evolution.

The importance of (changes in) the tidal amplitude is even harder to estimate. The changes themselves can be roughly determined, but the knowledge regarding the physics behind the influence on coastal evolution is insufficient to determine its significance in this respect.

Human interventions in the coastal system are well-known. About 1000 years ago the peat areas behind the dunes were brought under cultivation. This has intensified the process of break-throughs of the dunes, especially in the northern and southern parts of the Dutch coast. This has contributed to the formation of the Wadden Sea (north) and the Zeeland estuaries (south). The effects of human interventions are also noticeable at a shorter time-scale. During the last 100 years, the Dutch coastline has been intensely regulated. Obviously, erosion control measures, the construction of defensive structures as dikes and dams have, at least locally, directed the coastal evolution.

7. Relation with subsequent phases of the coastal genesis programme

The first phase of the Coastal Genesis Project was completed at the end of 1987. It was concerned with a reconstruction of the Holocene evolution of the Dutch coast, the formulation of hypotheses on the physical processes behind this evolution and the, mainly qualitative, testing of these hypotheses. The research activities in this first phase have resulted in an overview of missing knowledge on relevant physical processes. Furthermore, an inventory was made of supplemental historical information required for understanding the observed coastal evolution. Phase I is reported in a main report (Stive, 1987) and five supporting reports (Kollen,1987; Wind, 1987; Stolk et al. 1987; Reinalda, 1987; Zitman, 1987).

The second phase of the programme is in progress now. It was started around mid 1989 with a consultation of the international scientific world in the form of a Colloquium (Terwindt and Battjes, Paper No. 10, these proceedingd). Consensus about the missing knowledge resulting from Phase I and this Colloquium has led to a research strategy for Phase II. Implementation of the gathered knowledge in partly conceptual physical-mathematical models, as well as the verification and testing of these models, is planned to be carried out in a third phase of the programme.

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