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# Monitoring in the western part of the Dutch Wadden Sea – sea level and morphology*

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ABSTRACT: This paper deals with the methods and results of monitoring sea level (tidal gauges) and with the analysis of depth sounding data. Possible future monitoring by means of remote sensing techniques will be presented. Some trends, based on water level and morphological monitoring, have been established in the western part of the Dutch Wadden sea: (a) the relative mean sea level is rising persistently by 15 cm/century, observed since the middle of the 19th century. The tidal range is increasing as well; (b) the cross-sectional areas of the most western Dutch Wadden tidal inlets have been increasing over the last two centuries; (c) the intertidal zones of the Texelstroom and Vliestroom tidal basins have shown an increase of surface area over the last decades. The Borndiep tidal basin shows a decrease of 4 % of the area shallower than 5 m – Dutch Ordinance Level (DOL) over the last two centuries. Several factors prevent serious predictions about future morphological developments of the tidal Wadden flats: (a) man induced interfering factors, e.g. the construction of the harbour revetments of Den Helder, the construction of the Enclosure Dike and construction of sand drift dikes stabilising the Wadden islands; (b) the limited scope of the present analysis that deals only with the western part of the Dutch Wadden Sea.

## INTRODUCTION

Monitoring is the process of repetitive observing for defined purposes on element(s) of the environment according to prearranged schedules in space and time. Monitoring provides information concerning present state and past trends (Meyers, 1986).

This paper concerns water level monitoring (van Malde, unpubl.) and morphological monitoring (Glim et al., 1987, 1988) of the Dutch Wadden Sea (Fig. 1).

The results of the latter are based on depth sounding with survey vessels. These depth surveys are executed for navigational and management reasons.

A characteristic phenomenon of the Wadden Sea area is a general accumulation of sediments, which depends on: hydraulic forces (tides and waves), sediment transport, availability of sediments. Besides these physical parameters, biological activities play a role as well (Dijkema et al., 1983). Accumulation of fine sediments is stimulated by salt marsh vegetation and by mussels (Misdorp et al., 1984). Benthic diatoms increase the critical erosion velocities and stimulate sedimentation of tidal flats (Vos et al., 1988).

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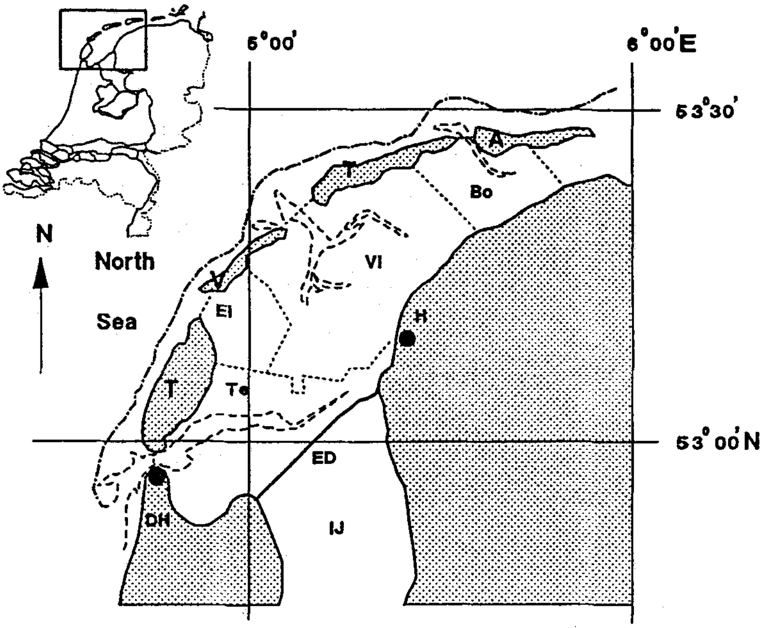


Fig. 1. Map of Western Dutch Wadden Sea area. Tidal basins: Te = Texelstroom (610 km$^2$); Ei = Eierlandse Gat (160 km$^2$); Vl = Vliestroom (704 km$^2$); Bo = Borndiep (320 km$^2$). Towns: DH = Den Helder; H = Harlingen. Wadden islands: T = Texel; V = Vlieland; T = Terschelling; A = Ameland. ED = Enclosure Dike (1032); IJ = IJsselmeer; DOL = Dutch Ordinance Level. Dotted line: tidal basin boundary; dash-and-dot line: depth contour (1980) 10 m – DOL

Tidal flats are important habitats for macrozoobenthos. This is illustrated by the relation between the density of macrozoobenthos of the intertidal flats of the western Dutch Wadden Sea and the mean tidal level (Fig. 2; Beukema, unpubl.). The maximum density is reached in the zone between low water and mean sea level. If the future sedimentation of the tidal flats cannot keep pace with the increase of sea level, shifts in the Wadden ecosystem might be expected.

Furthermore, society needs information about future morphological developments that will affect several functional uses such as shipping, fisheries, recreation and nature.

On the one hand, fear of dramatic changes related to future sea level increase gives rise to the thought (at provincial council level) of an ultimate solution: closing off the Wadden Sea!

On the other hand, a futuristic study shows that in the Netherlands an imaginary 5-m sea level rise can be coped with, involving a large amount of investment and maintenance costs (de Ronde & de Ruyter, 1987).

In order to make well balanced management decisions concerning possible measures, an increase in knowledge on future morphological developments of the Wadden Sea area, the tidal flats and island dunes is necessary.

The following paragraphs are concerned with the methods, results and possible future monitoring techniques of water levels and depth sounding data.

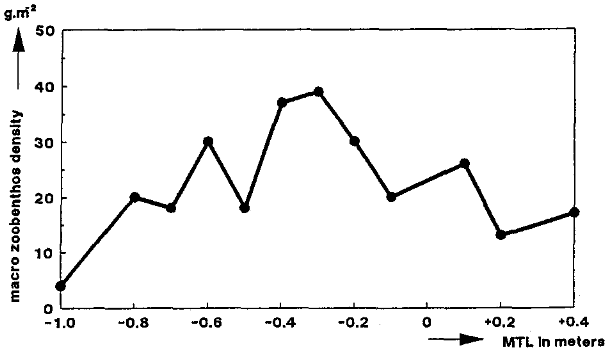


Fig. 2. Relation between biomass of macrozoobenthos and mean tidal level (MTL), western Dutch Wadden Sea (after Beukema, unpubl.)

## METHODS OF WATER LEVEL AND MORPHOLOGICAL MONITORING

The Rijkswaterstaat is monitoring water levels at 15 stations in the Dutch Wadden Sea. These stations form a part of the MSW-system – Monitoring System Water levels –, a recent nationwide water-level recording network. All the water level data are centrally stored in an easily accessible data base in our main office (The Hague).

Three stations have been recording water levels for more than a century: Delfzijl and Harlingen since 1865, Den Helder since 1832 (de Ronde, 1982). All the water levels are related to the fixed Dutch Ordinance Level – DOL.

The methods, frequencies and the "noise" of the water level observations at tidal gauges are described by van Malde (unpubl.).

The tidal inlets of the Dutch Wadden sea were systematically surveyed for the first time in 1796 (Rijzewijk, 1986).

The tidal basins of Texelstroom and Vliestroom (= 1300 km$^2$ = about a third of the entire Dutch Wadden Sea; Fig. 1) were surveyed six times between 1933 and 1983. The original depth sounding charts are presented on a scale of 1 : 10 000. These are converted to a density of 144 depth soundings/km$^2$. The ultimate result is a hydrographic chart on a scale of 1 : 125 000, with four averaged depth soundings/km$^2$ (Glim et al., 1987, 1988).

The depth sounding accuracy is divided into random and systematic errors (Nanninga, 1985). The random errors of depth sounding are relatively easy to estimate and show a strong tendency to decrease or even disappear in the averaged depth. An estimation of the systematic errors of a survey is much more difficult to make. Theoretically, the total systematic error in one survey amounts to 10 cm, depending on bottom slopes, water depth, instrumentation and the degree of conscientiousness of the surveys.

The presence of trends in time may be an indication of the reliability of the sounding charts, based on hundreds of thousands of depth soundings in each tidal basin.

The tidal volumes (= water volume between MHW and MLW) of the tidal basins are calculated on the basis of the hydrographic maps of 1933–1983 which were drawn to a scale of 1 : 125 000.

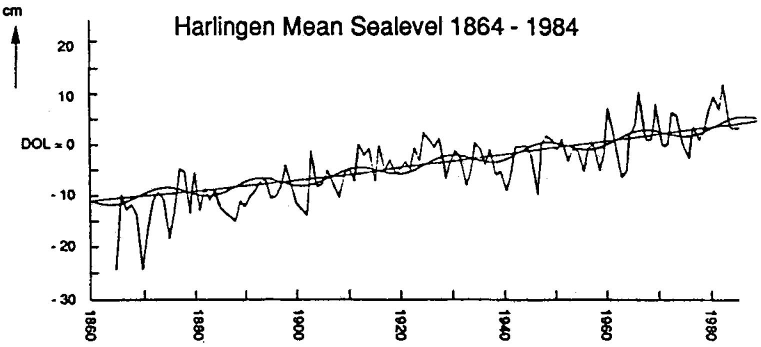
The computation of the cross-sectional area of the tidal inlets are based on the hydrographic charts drawn to a scale of 1 : 10 000 (Rijzewijk, 1986). The cross-sectional area of a tidal inlet is here defined as the surface of the cross-section with the smallest width. Lateral migration of the tidal channels in this area has no significant influence on the surface area trend.

The intertidal zone is defined as the surface area between mean low and mean high water level.

The sea level rise is included in the calculations of the tidal volumes, cross-sectional areas of the tidal inlets and of the surface area of the intertidal zones.

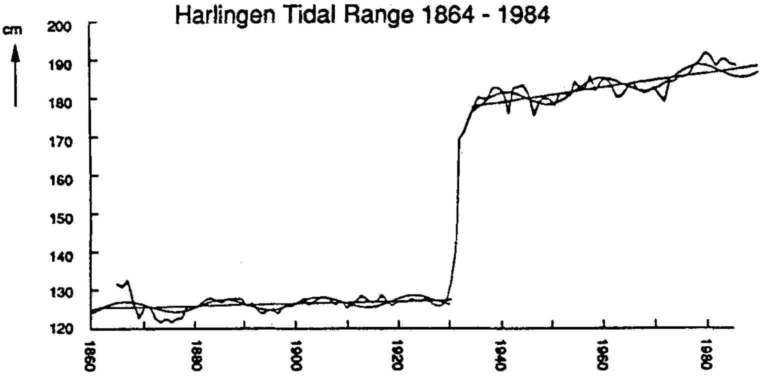
## RESULTS OF WATER LEVEL AND MORPHOLOGICAL ANALYSIS

The mean sea level has been rising consistently by 15 cm/century (de Ronde, 1982) since the existence of the tidal gauges of Den Helder und Harlingen (Fig. 3). The tidal ranges are increasing as well (de Ronde, 1982), however at a slower rate (Fig. 3).



$Y = AX + B \times \sin[(X + K)/S \times 2 x\pi] + C$

A = 11 cm/century ; K = -2 ; S = 18.6



$Y = AX + B \times \sin[(X + K)/S \times 2 x\pi] + C$

period: 1933 - 1984 : A = 20 cm/century

period: 1865 - 1930 : A = 3 cm/century

K = -2 ; S = 18.6

Fig. 3. Time series of mean sea level and of tidal range of tide gauge station Harlingen, Wadden Sea

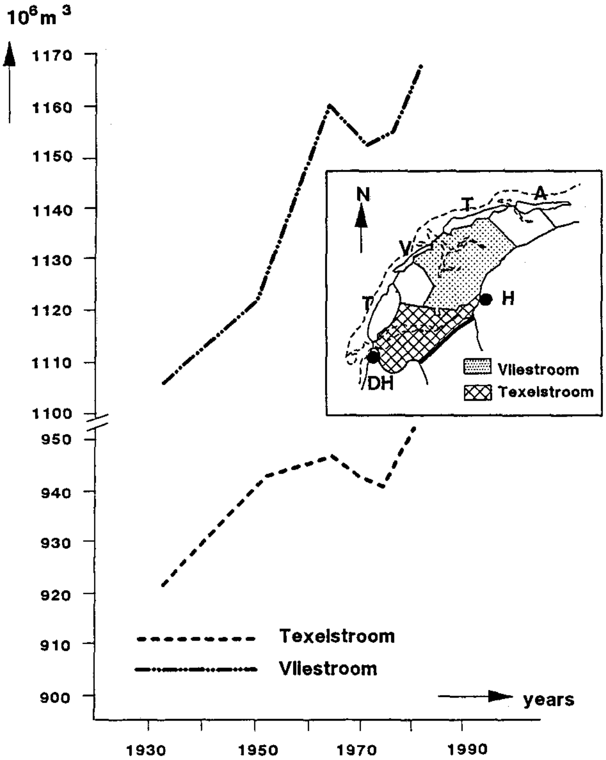


Fig. 4. Tidal volume of Texelstroom and Vliestroom tidal basin in million $m^3$

Before 1932, the increase of the tidal ranges at Harlingen and Den Helder amounted to 3 cm/century. In 1932, a sudden increase of about 50 cm at Harlingen and 15 cm at Den Helder coincided with the completion of the Enclosure Dike, closing off the Zuyderzee. This can be explained by the increase of tidal wave energy in the western part of the Dutch Wadden Sea, which previously dissipated in the Zuyderzee. Since 1933, the tidal range has increased remarkably by 20 cm/century at Harlingen and by 11 cm/century at Den Helder. A similar increase in the tidal range was observed after the closures in the southwest part of the Netherlands (van den Berg, 1986).

The tidal volumes of the Texelstroom and Vliestroom tidal basins, based on revised data (Glim et al., 1987, 1988), have increased during the last 50 years (Fig. 4) by 3 %, respectively 6 %.

The cross-sectional area of the tidal inlets of the Texelstroom (two different profiles in Fig. 5) and Eierlandse Gat (Fig. 6) has increased by about 25 %, respectively 35 %.

The cross-section of the Vliestroom tidal inlet has increased by about 30 % during the period between 1910–1975 (Klok & Schalkers, 1980).

Postma (1983) mentioned the existence of simple morphometric relations, derived from hydrographic data. The tidal volumes directly determined correspond with the ones derived indirectly by means of the cross-sectional surfaces (Gerritsen & de Jong, 1985) of the Texelstroom and Vliestroom tidal inlets over the past 50 years.

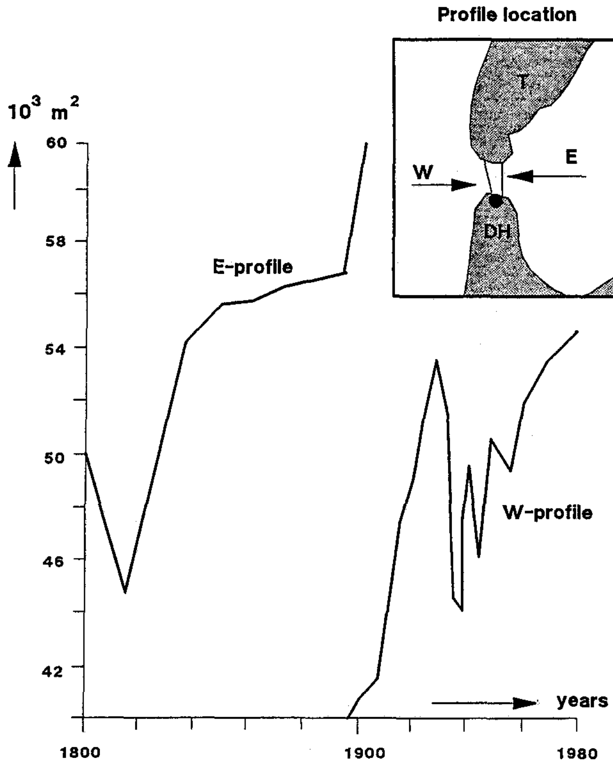


Fig. 5. Surface area ($A_c$) in $10^3$ m$^2$ of a cross-section of the tidal inlet Texelstroom

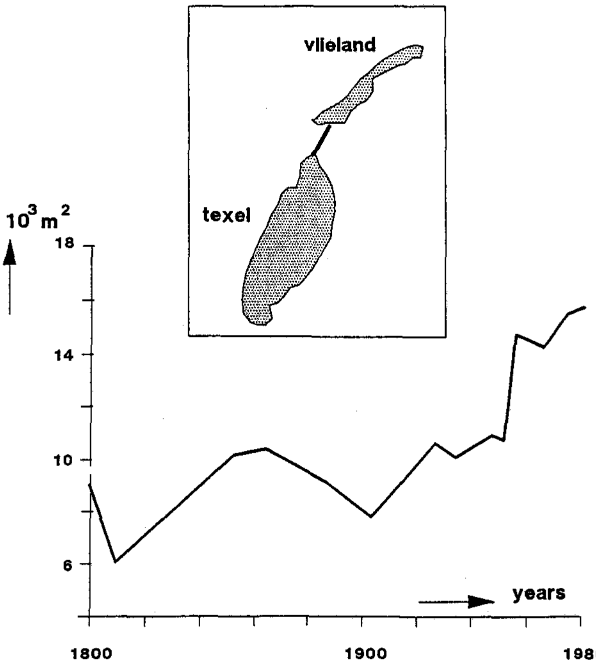


Fig. 6. Surface area ($A_c$) in $10^3$ m$^2$ of a cross-section of the tidal inlet Eierlandse Gat

During the first 20 years after the construction of the Enclosure Dike (1932), the intertidal surface area ($A_{b.i.}$) of the Texelstroom decreased and that of the Vliestroom remained the same. During the past 30 years, the intertidal surface area of the Texelstroom increased from 12 % to 15 %, that of the Vliestroom from 32 to 37 % of the total tidal basin surface area (Fig. 7).

A third tidal basin, the Borndiep between Terschelling and Ameland (Rijzewijk, 1986), was examined in another way. The surface area of the zone shallower than 5 m – DOL has gradually decreased by 4 % during the last two centuries, with an indication of an accelerated decrease since 1940 (Fig. 8).

The average height of the intertidal zones of the Texelstroom and Vliestroom tidal basins was calculated with respect to the mean low water level. Figure 9 shows that the average height of the Texelstroom intertidal zone has been decreasing gradually at a rate of 0.39 cm/year ($r = 0.94$), while the average height of the Vliestroom intertidal zone has been decreasing by 0.03 cm/year with a non-significant value of $r = -0.23$. The latter value implies a non-change.

Figure 9 also shows the rising of the average half tide sea level (= high water level minus low water level) at a rate of 0.14 cm/year ($r = 0.99$).

## CONCLUSIONS AND DISCUSSION

At the water level stations Den Helder and Harlingen, a general mean sea level rise of 15 cm/century was observed during the last century. No signs of an acceleration in the

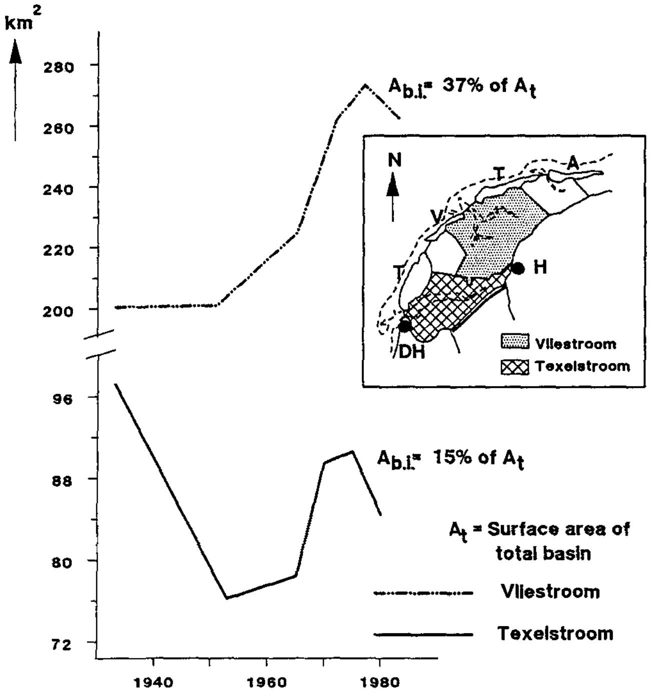


Fig. 7. Surface area of intertidal zone ($A_{b.i.}$) of Texelstroom and Vliestroom in km$^2$

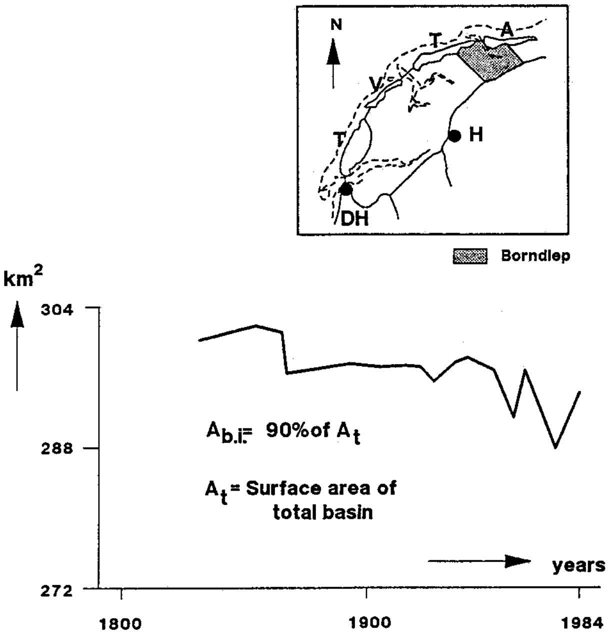


Fig. 8. Surface area ($A_{b.i.}$) of the zone above 5 m-DOL; tidal basin of Borndiep: Terschelling-Ameland

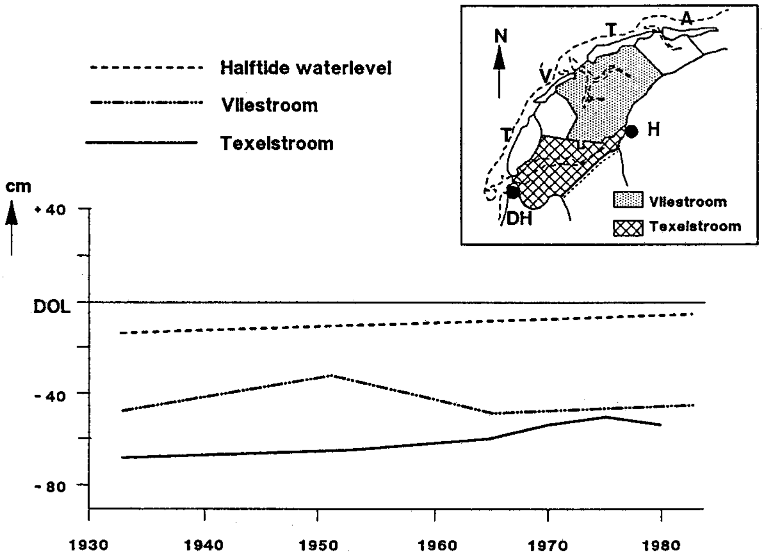


Fig. 9. Average height of the intertidal areas of Texelstroom and Vliestroom tidal basin and halftide waterlevel, 1933–1980/83

mean sea level rise have been recorded during the last decades. The measured accelerated increase in the tidal range during the last half century may be caused by the morphological adaption of the western tidal basins since the construction of the Enclosure

Dike (1932). However, a general increase in the tidal range has also been observed, particularly after 1950, along the German North Sea Coast (Führböter, 1986).

The sea level rise during the last 150 years coincides with the increase in the cross-sectional area of the two tidal inlets (Texelstroom and Vliestroom) during the last two centuries, and with the observed increase of the tidal volumes during the last 50 years. However, it is too early to draw a convincing causal relationship due to human interference.

The decrease in the intertidal surface area of the Texelstroom tidal basin during the first 20 years after the construction of the Enclosure Dike can partly be explained by sediment transport from the intertidal area to the "sediment hungry" dead-end tidal channels in the vicinity of the Enclosure Dike (Fig. 10). This internal reworking process might also be responsible for the lack of growth of the surface area of the Vliestroom intertidal zone during this period.

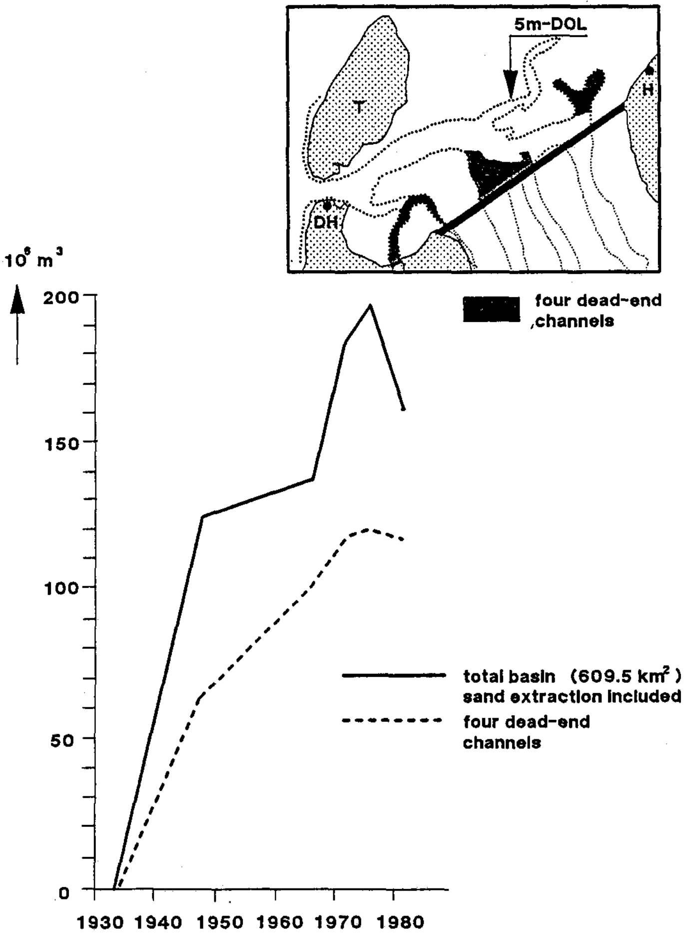


Fig. 10. Cumulative sedimention of the four dead-end tidal channels (<5-m-DOL) – Texelstroom tidal basin – since the construction of the Enclosure Dike 1932

During the last decades, the average intertidal surface area of the Texelstroom and the average height have increased. The non-change in the average height of the intertidal area of the Vliestroom during the last decennia coincides with an increase of the intertidal surface area.

The Borndiep area shallower than 5 m – DOL has decreased during the last two centuries.

This remarkable difference in behaviour might be explained by the differences in geometry of each tidal basin (channel/flats).

Besides sea level rise, many other factors play a role in the morphological developments of tidal flats. Some factors are natural, like the presence of current resistent boulder clay in tidal inlets, others are man-induced:

- The construction of the Enclosure Dike suddenly increased the tidal range (Fig. 3) and tidal volume of the Texelstroom tidal basin (Fig. 4). The Amsteldiep Dike (1925) and the Enclosure Dike (1932) cut off four tidal channels. This caused strong sedimentation in these dead-end channels during 1933–1966 in the zones deeper than 5 m and 2.5 m – DOL (Fig. 10), amounting to 70 % respectively 90 % of the accumulation in the total Texelstroom tidal basin.
- Sand extraction is mainly confined to the Texelstroom and Vliestroom tidal basins, and was started in the middle of the 1960s. It is limited to the tidal channel zones deeper than 5 m – DOL and has, therefore, no major or direct effect on the intertidal zones and tidal volumes.
- Gas exploitation near Ameland is causing sinking (DHL/RIN, 1987) of the tidal flats. This may lead to extra sedimentation of about 0.3 million m$^3$/year in the Borndiep tidal basin during the next three decades.
- Other artificial factors are:
  - the presence of the revetment construction of Den Helder for many centuries;
  - the construction of sand drift dike uniting islands and
  - continuous reclamation.

These man-induced factors together with relatively limited analysis of the depth sounding data do not allow serious predictions about the future morphological developments of the tidal flats.

Future analysis of the relatively undisturbed tidal basin of Borndiep might reveal extrapolation trends, in combination with studies on hydraulic regime.

## FUTURE MORPHOLOGICAL MONITORING

To predict seriously the effect of the increase of sea level rise on the development of tidal flats, further analysis of historical data is needed. Continuous morphological monitoring is needed to establish trends.

Depth sounding surveys and data processing are time consuming activities. At the moment, applications of Remote Sensing techniques for morphological monitoring are being executed. The Rijkswaterstaat is putting effort into processing LANDSAT TM images in such a way that digital depth maps of coastal areas are derived. A first result is the digital depth map of the area of north eastern Vlieland from LANDSAT TM image 26/6/1986, 2 hours after high slack tide (Fig. 11; van Hengel & Spitzer, 1988). The maximum

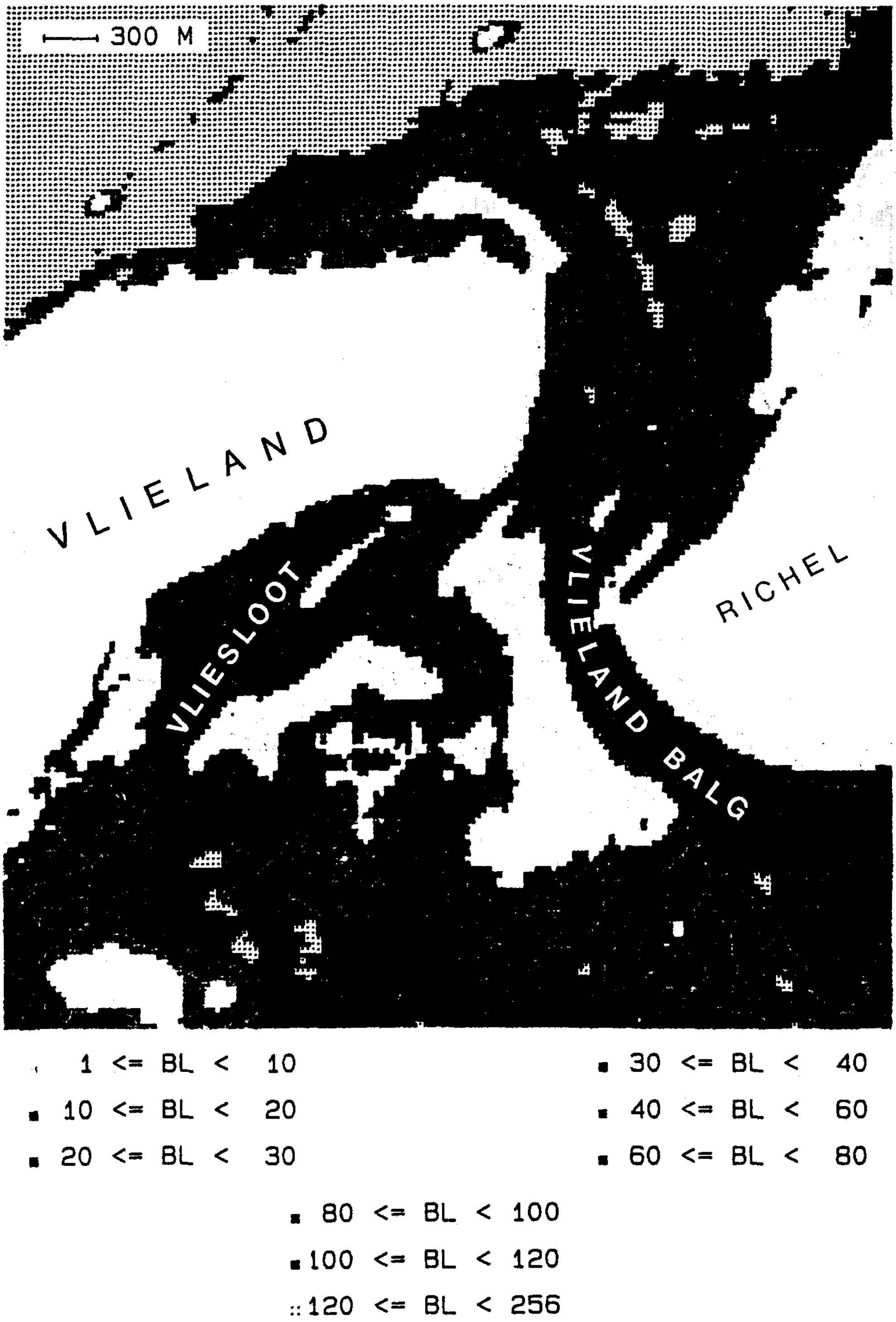


Fig. 11. Plot of bottom levels (DM NAP) (from van Hengel & Spitzer, 1988)

depth processed is about 12 m – DOL. A comparison with depth sounding maps shows an estimated relative error of 10–15 % of the sounded depth (van Hengel & Spitzer, 1988).

Special attention should be paid to shallow, potentially turbid areas. Analysis of multi-temporal imagery can increase the reliability of the computed maps (van Hengel, 1988).

The advantage of applying Remote Sensing is obvious: one image occupies an extended area and, besides morphological monitoring, estimations of biomass of macrophytobenthos are feasible as well (Meulstee et al., 1986, 1988).

Another way of obtaining information on the vertical movements of tidal flats is an airborne surveillance technique, combining Laser with GPS (Global Positioning System). Some experiments were carried out with both Laser and GPS. International Laser experiments were executed on board of a survey vessel in order to measure the depth. During airborne surveillance, accurate positioning is essential. Rijkswaterstaat is testing the GPS as an efficient tool in photogrammetry (van der Vegt et al., 1988). The very first results of test flights demonstrate a 10 cm accuracy for the GPS positions within each test strip.

These experimental results are hopeful, and will contribute to the development of a synoptical survey method which can be used for monitoring the (morphological) developments of the Wadden Sea.

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