Summary 1987-2000
Monitoring impact of subsidence on Ameland-East: evaluation after 13 years of gas production

Colofon

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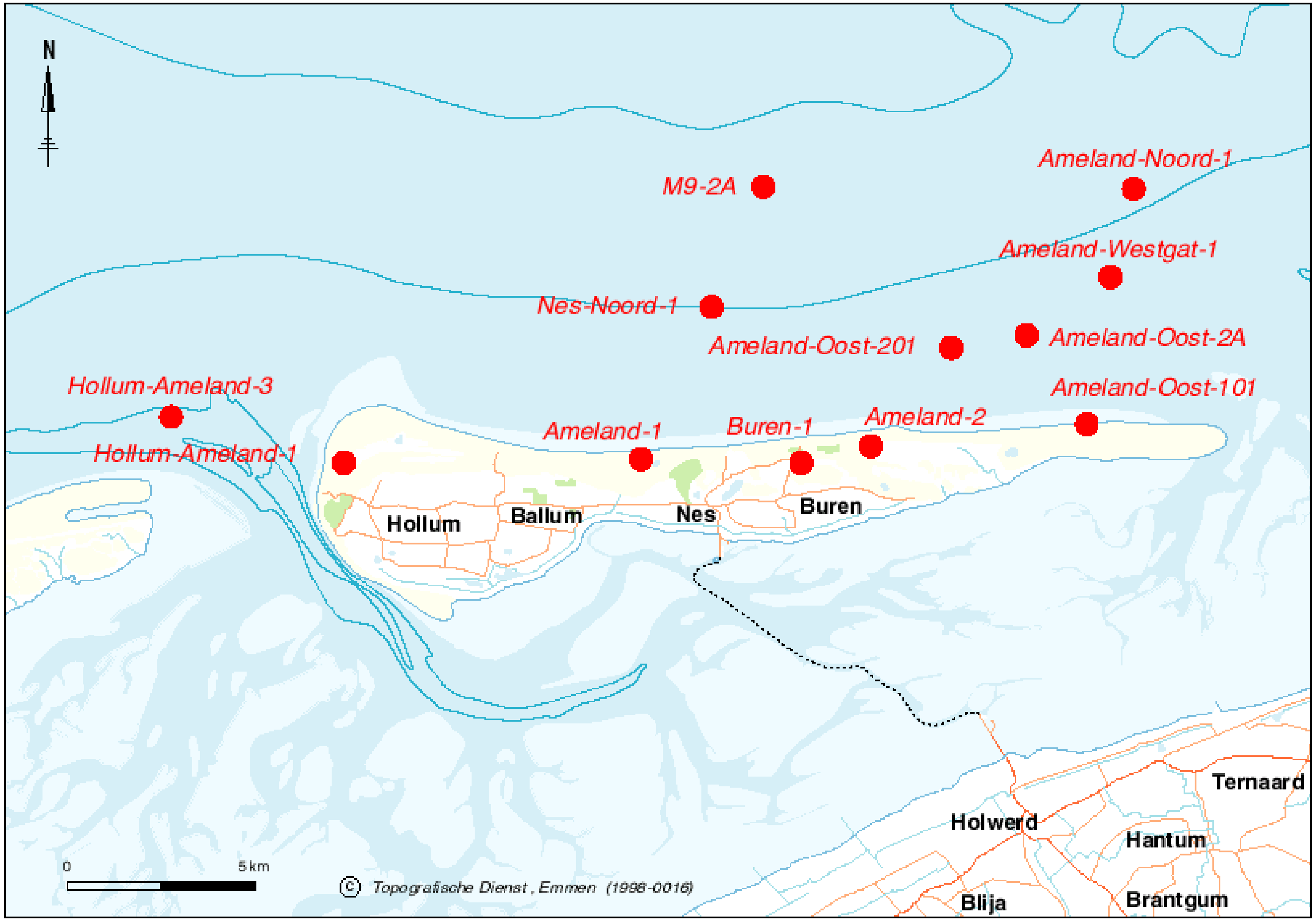
Introduction

The discovery of the Ameland gas field

After the discovery of the Groningen gas field in 1959 and the decision to develop an infrastructure for the production of this gas, the search for new gas fields rapidly spread to the whole of the north of the Netherlands. Gas was discovered on the Barrier Island of Ameland. Five exploratory wells were drilled at locations spread all over the island and an equally large area in the coastal area to the north of the island. Gas was found at the most westerly point of the island, just to the north of Hollum and at De Hon, the most easterly point. The gas field lying below the eastern nature conservation area and the adjoining North Sea coastal zone proved to be third largest in The Netherlands. The quantity was estimated to be 60 billion cubic metres of gas. A Royal Decree in 1969 granted the North Friesland concession, of which Ameland is a part. A plan for the development of this field was submitted in 1972. Production however did not start until 1986.



Locations of wells that were drilled around the island of Ameland before the year 1980.

Prior to 1972 only a rough estimate had been made of the subsidence to be expected as a result of producing gas from the Ameland Field, on the basis of a comparison with Groningen. Attention was focused very much on the immediate impact on the environment. This is why an environmental impact assessment with regard to the ecological adaptation of the location and the possible effect of the drilling was made. As a result of the increased public resistance to drilling activities and the litigation that had been started in the meantime, it was not until 1982 that the development of the East Ameland location could be started. The installation and the drilling of the first wells took place in accordance with the directions taken from the environmental impact assessment and the advice of the planning working committee (PWC).

Subsidence

Concern about a possible loss of ecological capital remained after 1982. This was because subsidence in the Groningen gas field had attracted attention and generated fears that the subsidence in Ameland would be on a comparable scale. In 1985 the predictive model developed for Groningen was therefore applied to the Ameland gas field. The predicted maximum surface depression above the centre of the field was then predicted to be 26+/-5 cm. This would produce a dish with a volume of approximately 28 million cubic metres.

The island pr oduction facility (Ameland-East) in 1983 directly after construction.

The island production facility (Ameland-East) in 1997 and had 6 wells drilled and in production.

This prediction prompted an investigation into the possible effects of this subsidence. Instructions to prepare an environmental impact assessment relating to the possible effects of subsidence on East Ameland were given to two organisations—the Hydraulic Laboratory (WL l Delft Hydraulics) and the Research Institute for Nature management (Alterra – Green World Research). The assessment was written up under the supervision of an independent committee. Needless to say the predictions were assumed to have a degree of uncertainty because there was no practical know-how in this field.

Monitoring

It Fryske Gea, the custodian of the nature reserve, then wrote to NAM asking it to reduce this uncertainty by conducting an evaluating investigation. This investigation evolved into the long-term monitoring programme that is being reported on in this document. At the same time the community's need for information was also being met. Concern has arisen about the possible effects of higher sea levels and a study of subsidence could lead to a better understanding of the way in which salt marshes and beaches with low-lying valleys would respond to such sea level rises

An independent committee supervised this investigation. The composition of the committee was based on a combination of expertise and representation of bodies with a vested interest in the Wadden. The investigation started in 1987, a year after gas production began and was conducted by the same organisations that had prepared the environmental impact assessment.

Summary and conclusions

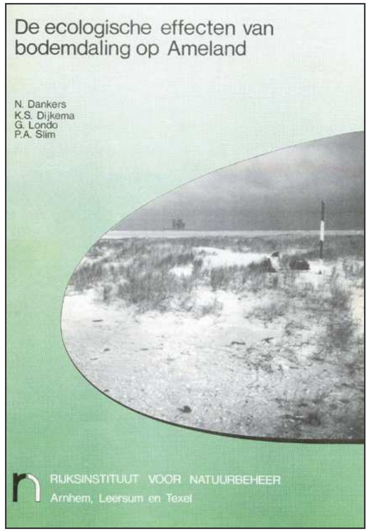
Since the autumn of 1988 the following data have been collected under the monitoring programme:

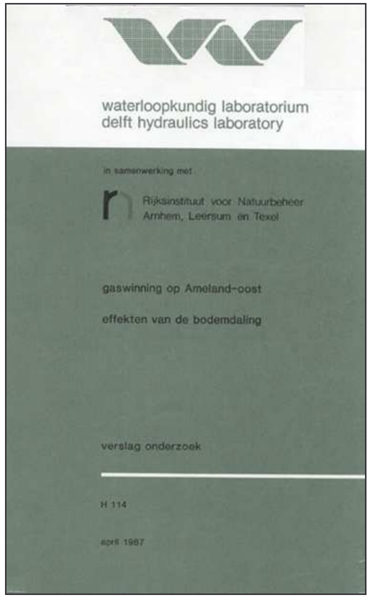
- accurate level measurements in order to determine the actual subsidence;
- data that are important in relation to the vegetation of the salt marshes and dunes;
- data that show changes in the topography and water depths;
- information that reveals or can explain changes in the bird population and vegetation;
- data that can be used to establish whether the subsidence can lead to economic damage to the Nieuwlandsrijd salt marsh, the Buurdergrie polder or the extraction of water in the Buurderduinen

This report presents an evaluation of the status and findings after thirteen years of gas production on East Ameland.

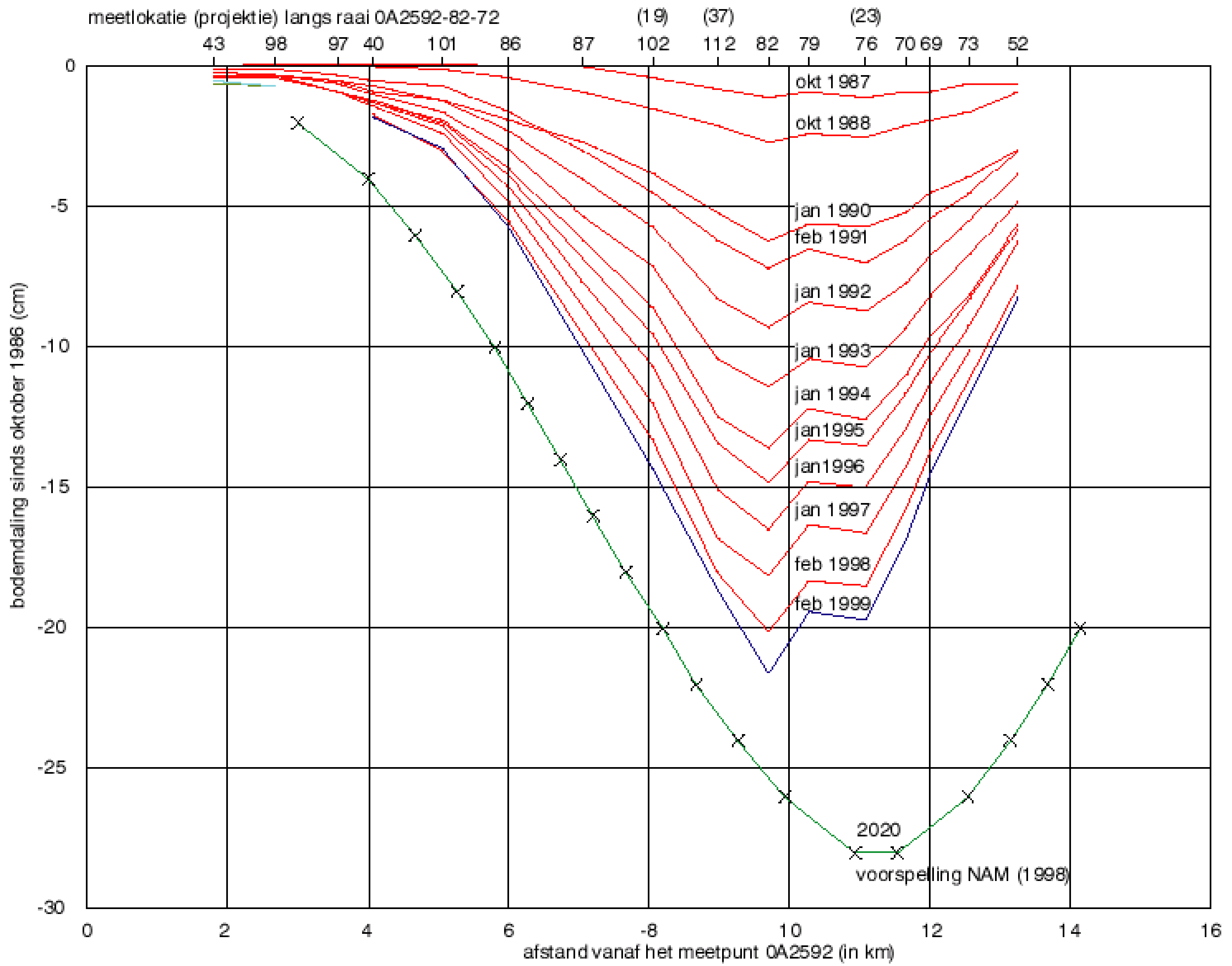
A - Subsidence

An initial forecast made in 1985 of the expected subsidence resulting from gas production on East Ameland gave an ultimate drop of 26 cm in the centre. This forecast was adjusted in 1991 on the basis of more recent information about the reservoir characteristics. The ultimate drop in the centre was estimated at that time to be approximately 18 cm.





The two Environmental Impact Assessment Reports that were issued in 1987.



Profiles of measured subsidence (red) and the final prediction for 2020 (green). The subsidence is shown in cm, going from west to east in km, starting at a fixed and stable control station in Nes.

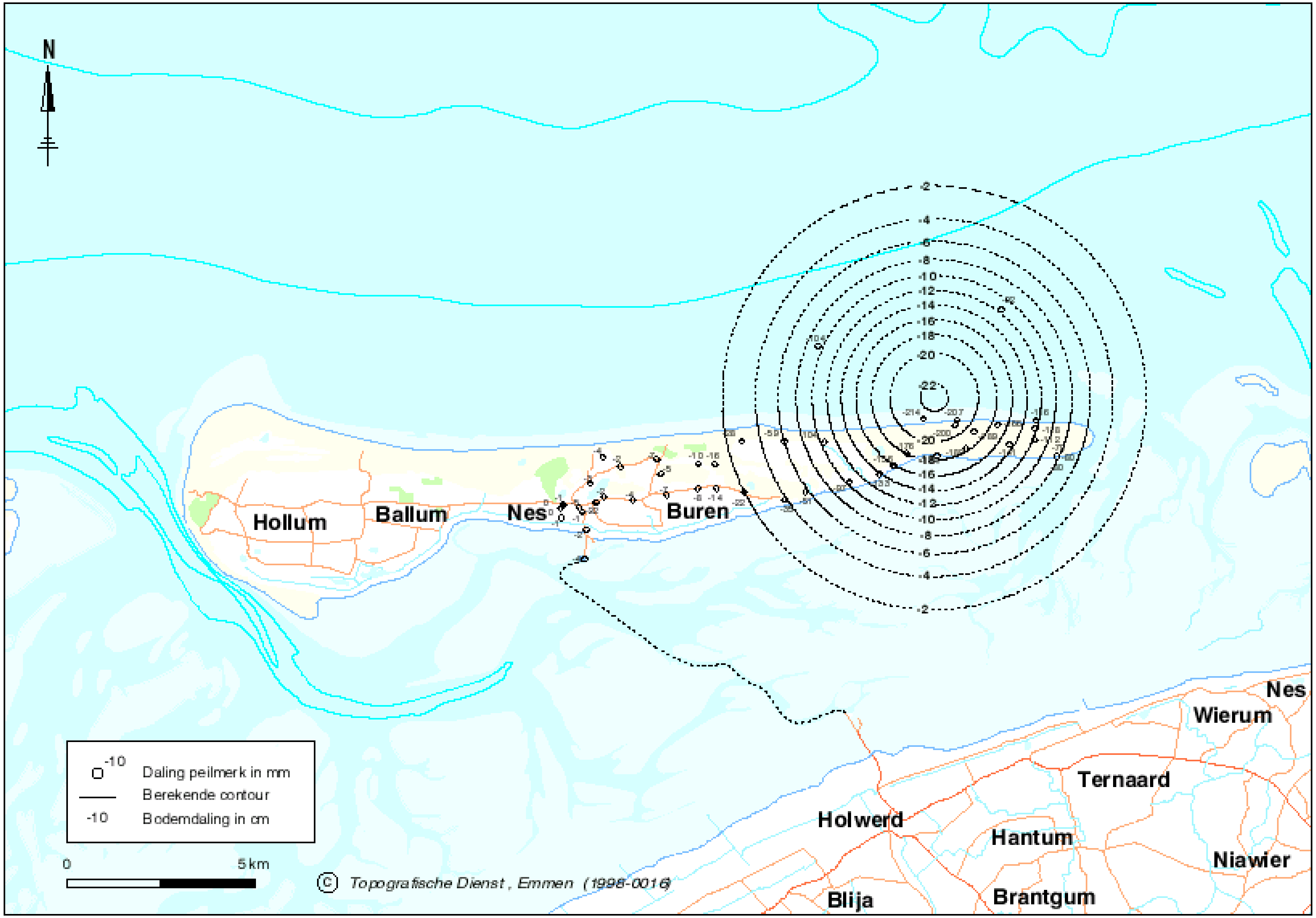
However, measurements showed that the rate at which subsidence was taking place in the vicinity of the NAM location was higher than forecast in 1991. In fact the subsidence rate corresponded almost exactly with the 1985 forecast. In the interim report in January 1995 an explanation for the observed differences that appeared to be plausible was found on the basis of general theoretical considerations and the known reduction of the gas pressure in the reservoir. Nevertheless the 1991 forecast of the ultimate subsidence was still considered to be the most reliable and the subsidence rate in the centre of the dish was expected to drop dramatically after 1994. Much to our surprise, this didn't happen, prompting NAM to research why the model had failed.

NAM and TNO (Netherlands Organisation for Applied Scientific Research) made new calculations of the expected subsidence using the latest knowledge, improved subsidence models and additional data. These calculations produced a new model that reproduced the observed subsidence more accurately and resulted in predictions that:

- the ultimate subsidence in the centre of the dish would be 28 cm and
- the subsidence bowl will be slightly deeper in the middle and slightly shallower at the edges than originally predicted in 1985. The total subsidence volume will ultimately be significantly less than predicted in 1985, as can be seen from the table below.

Prognoses	Maximum subsidence (cm)	Total subsidence (10^6 m^3)
1985	26 (21-31)	28
1991	18 (14-22)	18
1998	28 (22-34)	14-18

This brings the expected maximum drop in the centre of the dish close to the basis for the 1987 impact predictions. The actual subsidence in February 1999 at the deepest point was approximately 22 cm, i.e. 70% to 75% of the ultimate drop now expected. At that time the volume of the dish was 9 * 10^6 m^3. The subsidence closer to the edges still remains less than the 1985 prediction.



Map of the island of Ameland. Contours of the subsidence based on measurements of a network of sampling stations that are secured in deeper sand layers.

B - Abiotic factoren

Water levels

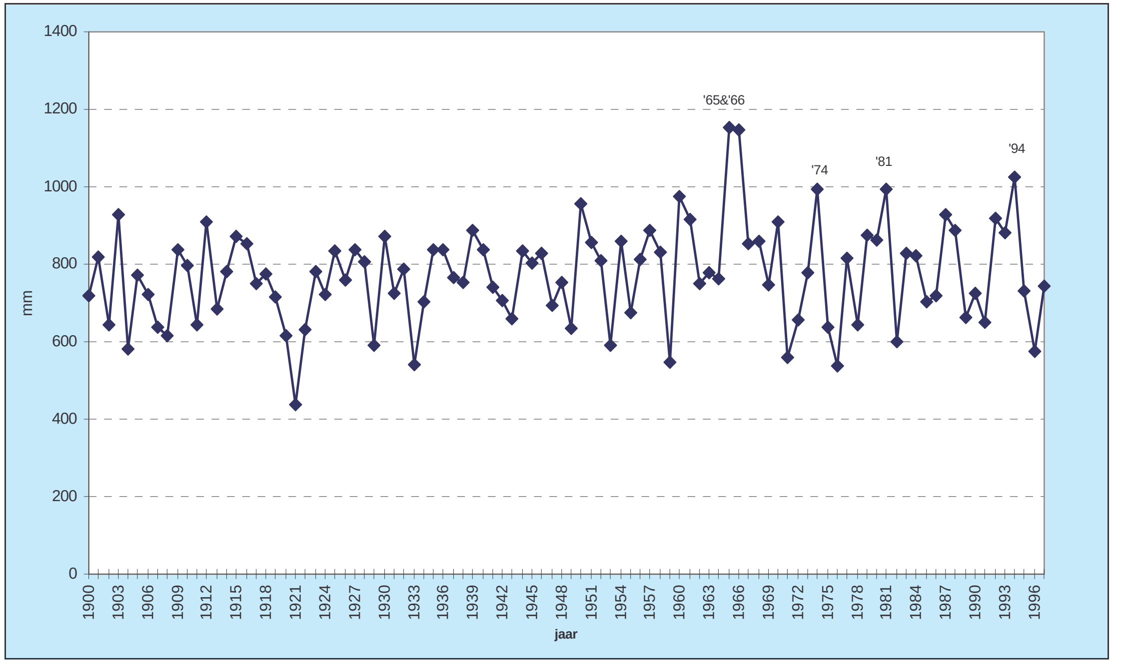
The water level data from the Nes tidal station, particularly the high tide data, are representative of the water levels on the Nieuwlandsrijd and De Hon salt marshes. The Den Helder station is considered to be the most representative for evaluating changes in the relative sea level rise. There are no indications that the sea level rise has increased more as a result of the widely discussed greenhouse effect. The sea has risen ‘on average’ by 2 cm since subsidence started in 1987.

A level of 2.5 m above NAP (the Amsterdam ordnance datum) is exceeded once or more virtually every year. A level in excess of 2.8 m above the Amsterdam ordnance datum (NAP + 2.8 m) is also occasionally observed. Very high storm tides (higher than NAP + 3 m) occurred only 11 times in the 1981-1998 period. These events took place in 1981, 1983, 1990, 1993, 1994 and 1995. In 1990 and 1994 in particular many highs and also the very highest storm tides were observed. Some highs were late in the winter season and close to spring (end of February and beginning of March).

Precipitation and evaporation

Precipitation and evaporation figures are important for the interpretation of changes in the vegetation. The precipitation data was collected for the Nes station and the (crop) evaporation figures from the closest station to Nes, . As a rule this was the Lauwersoog station.

Between 1984 and 1998 the 1992-1995 period was a succession of wet years with 1994 having extremely high rainfall (1018.3 mm). The wet years 1993 to 1995 also coincided with many very high storm tides.

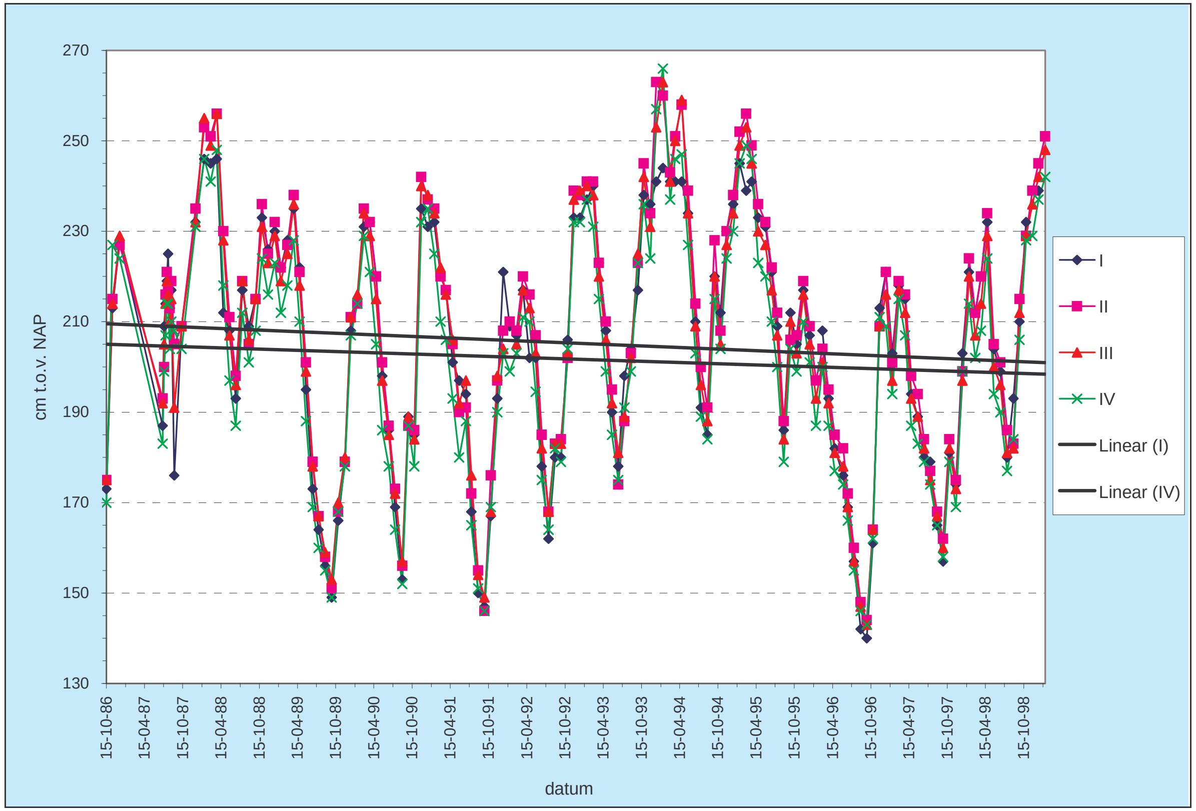


De Bilt precipitation data since 1900 (after J.C.A.M. Bervaes, Alterra). The high rainfall in 1994 was particularly important for the monitoring programme, since it also resulted in a high groundwater level (also see next figure).

Groundwater levels

By now a great deal of information and understanding have been acquired about the behaviour of the groundwater level on East Ameland. The annual fluctuations in the different piezometers are comparable and are quite large. Depending on the annual rainfall and fluctuation in the average sea level, the fluctuation varies between about 0.5 m and around 1 m.

The groundwater level is fairly constant across the eastern part of Ameland, with gentle gradients from higher areas to lower-lying areas. The rise and fall of the groundwater level through the year occurs to more or less the same degree everywhere (parallel displacement). No clear effect of the subsidence on the groundwater level compared with NAP can be discerned. In other words the groundwater level is increasing compared with ground level in areas where there is subsidence caused by gas production. This effect is permanent in areas without compensation through accretion, as in polders and dunes.

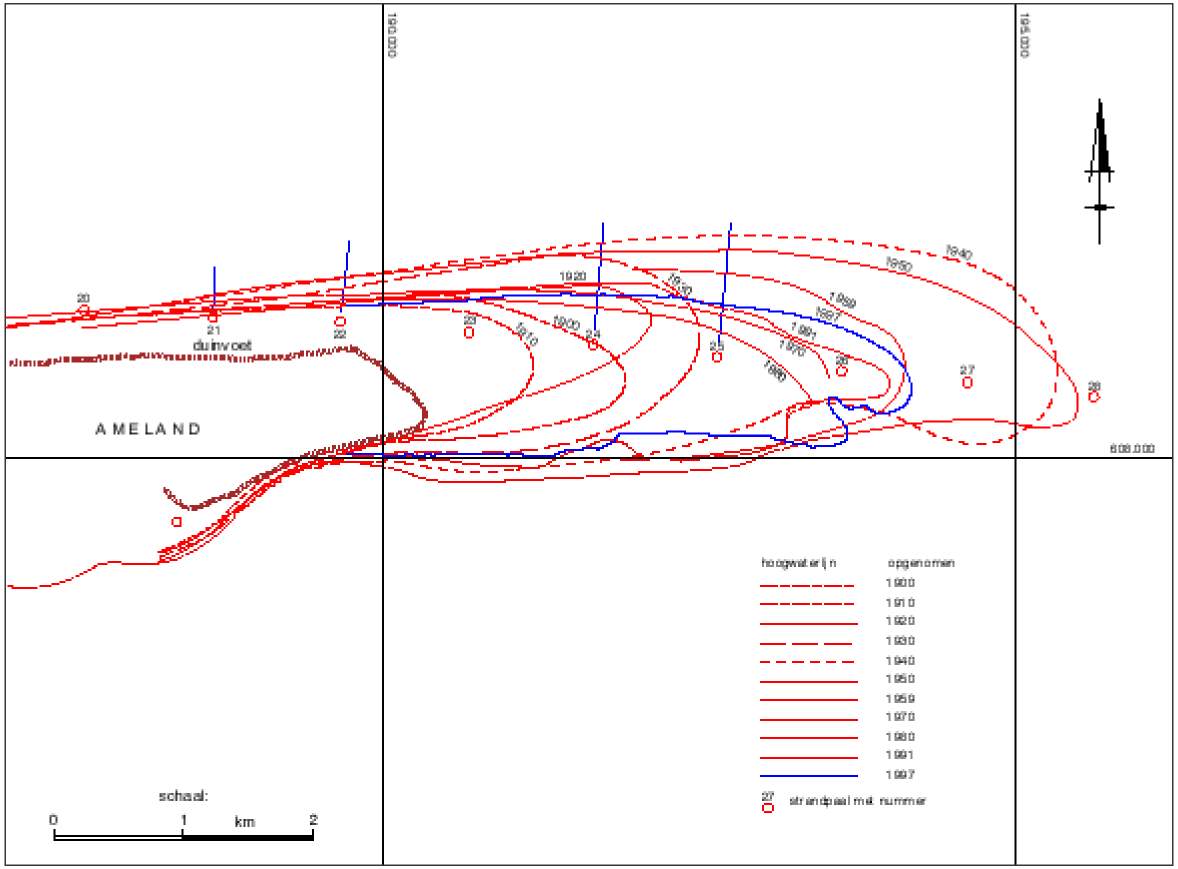


Groundwater data from measuring stations in the Kooiduinen (1986-1999). The large fluctuations in groundwater level (0.5 – 1.0 m) are characteristic for the dune ecosystem. Due to the well drained, sandy soils, these fluctuations are observed in parallel in all measuring stations.

C - Morphology

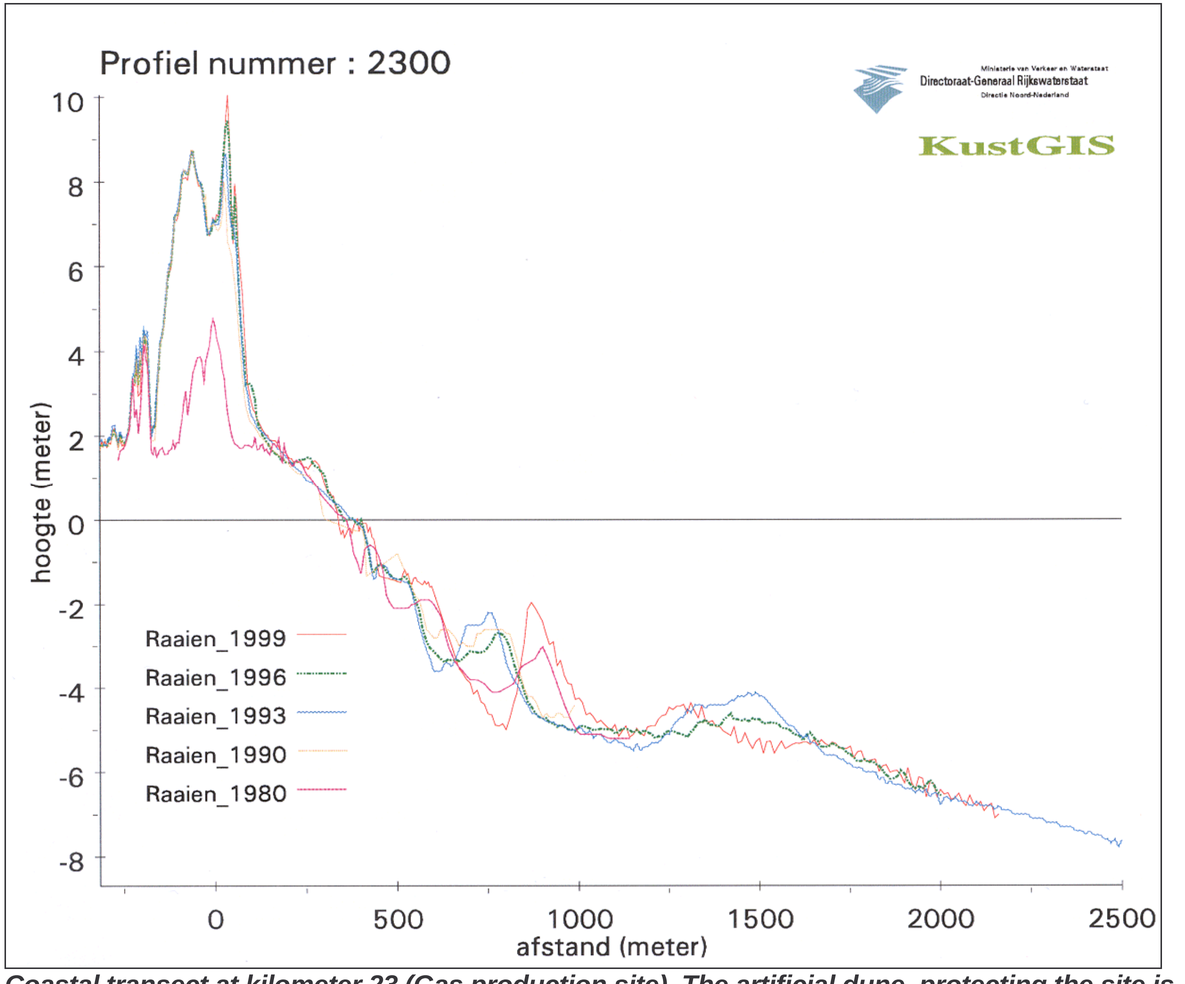
North Sea coast

The approach taken by Rijkswaterstaat (Directorate-General for Public Works and Water Management - RWS) since 1990 is to maintain the coastline by means of beach nourishment with sand. Over the last 10 years large quantities of sand (5.3 million m³) have been used to maintain the coast of Ameland 23km to the west of the NAM location . There is a fairly natural dynamic to the east of the NAM location.



Development of the eastern cape of Ameland (1900-1997). The size of the cape is highly variable and depends on eastbound migration of the channels.

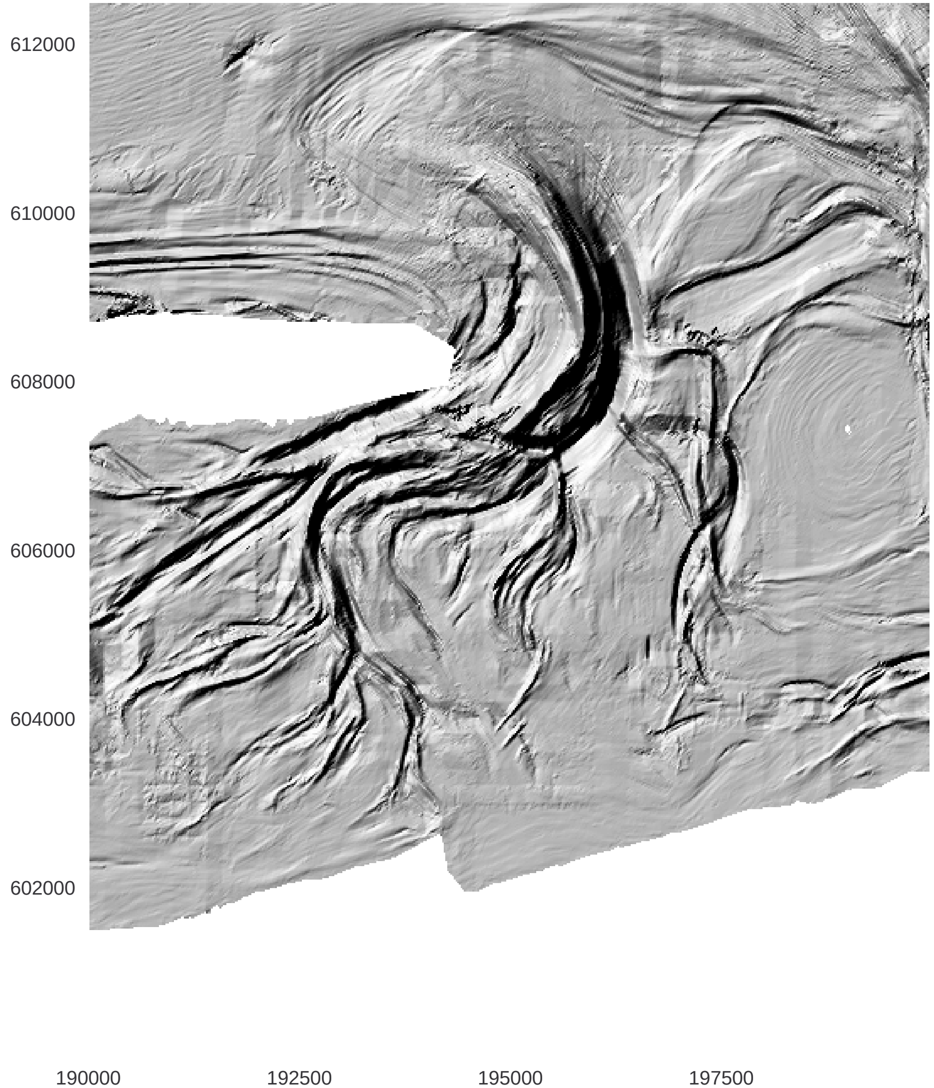
Coastal changes, for example the position of the average high-water line, were analysed prior to the monitoring using hydrodynamic models developed by Delft Hydraulics. These models are widely applied, also on a national scale to predict coastal erosion and plan the required artificial nourishment. The predictions by the model and the monitoring data clearly show the strong, natural dynamics in the morphological behaviour of the North Sea coast of Ameland. Because of this and also partly because the beach nourishment as calculated differed from the actual beach nourishment in the last 13 years (larger volumes and at other years), it proved impossible to discern the effect of the subsidence caused by gas production on the behaviour of the coast. Meanwhile, three-quarters of the subsidence has already occurred. The general trend is that the coast to the east of the NAM location is growing towards the sea quickly, whereas the coast to the west is showing a natural withdrawal, which is being systematicly compensated by artificial nourishment with sand.



Coastal transect at kilometer 23 (Gas production site). The artificial dune, protecting the site is situated at 0 meter and was created in 1980.

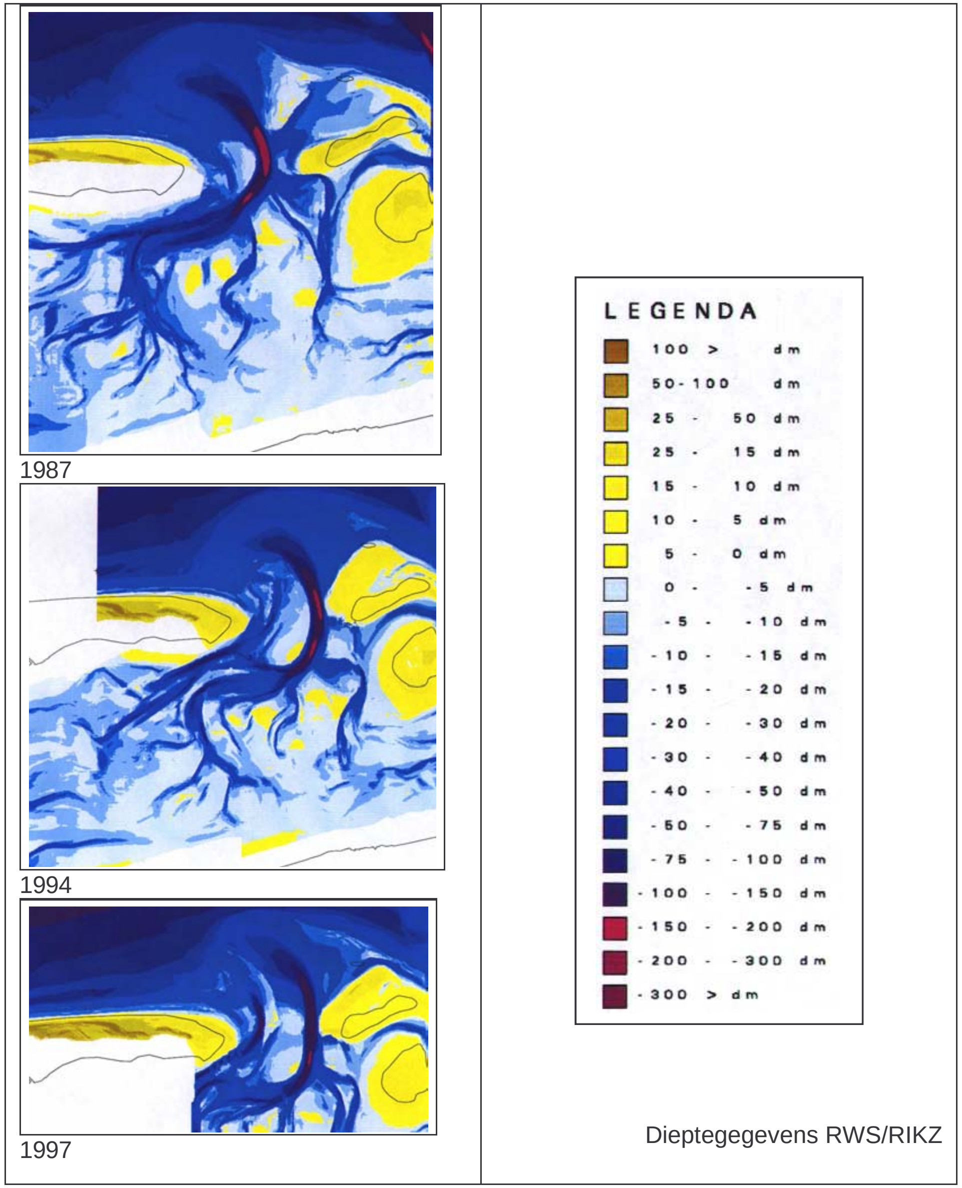
Friesche Zeegat and De Hon

The eastcape of the island is called De Hon and the main channels are named Holwerderbalg and Pinkegat. Between 1980 and 1986 the length of De Hon increased towards the east as a result of natural channel migration from De Holwerderbalg and the Pinkegat caused by erosion of outside bends and sedimentation in inner bends. Accretion stagnated between 1986 and 1991 because of the creation of a new channel between De Holwerderbalg and De Hon. There has been steady growth again since 1991 as a result of natural channel migration from the new channel, De Holwerderbalg and the Pinkegat.



The dynamic nature of the tidal inlet the Friesche Zeegat and the tidal flats based on depth measurements between 1987 and 1994. In grey are areas with no change in depth and in black areas with migrating channels. The subsidence bowl remains invisible as a footprint due to the ongoing sedimentation.

It is not possible to determine to what extent this process, particularly in De Holwerderbalg and in the secondary channel in the tidal passage, has been accelerated by the subsidence caused by gas production on Ameland. The 1987 impact prediction report referred to the possibility that the additional demand for sand in the tidal basin of the Pinkegat is partially compensated by delayed growth of De Hon. The 1987 environmental impact assessment, which was based on the 1985 subsidence prediction, made a rough estimate that the overall reduction in the total growth to the east would be 500 m and the reduction in this accretion would be a maximum of 10 m/year. The developments that have been taken place do not rule out this possibility. However, the (temporary) stagnation of the growth of De Hon towards the east can as well be explained by the natural developments in the Holwerderbalg channel that has proceeded to turn in an anti-clockwise direction towards Ameland.



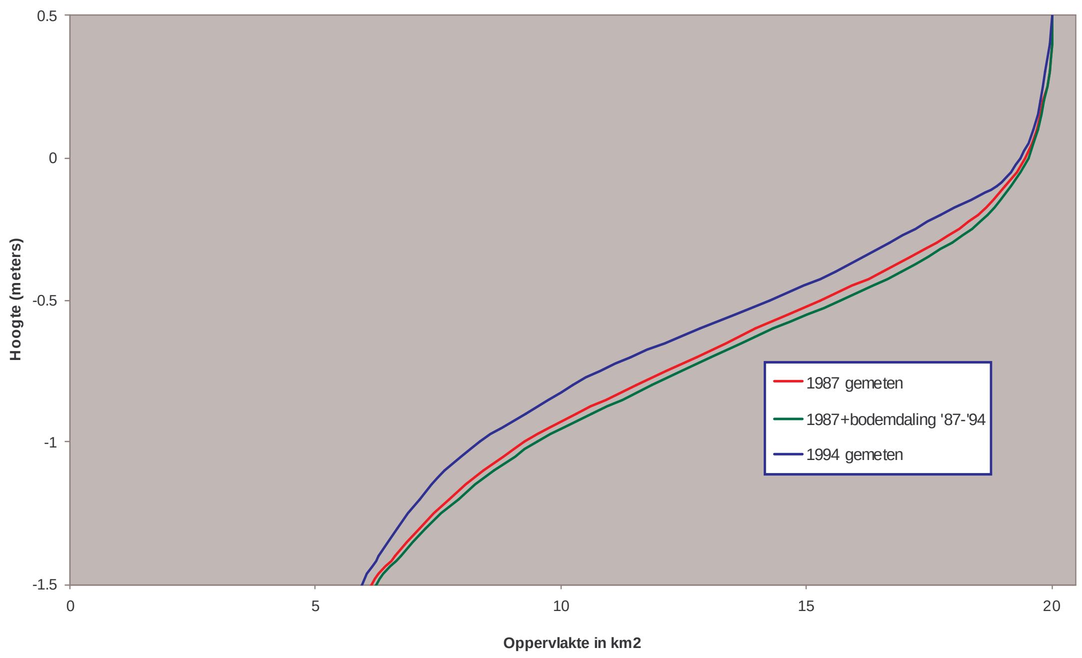
Recent developments in the position of the channels in the tidal inlet and the tidal flats south of Ameland. The eastbound migration of the main channel results in the development of a new channel in the west.

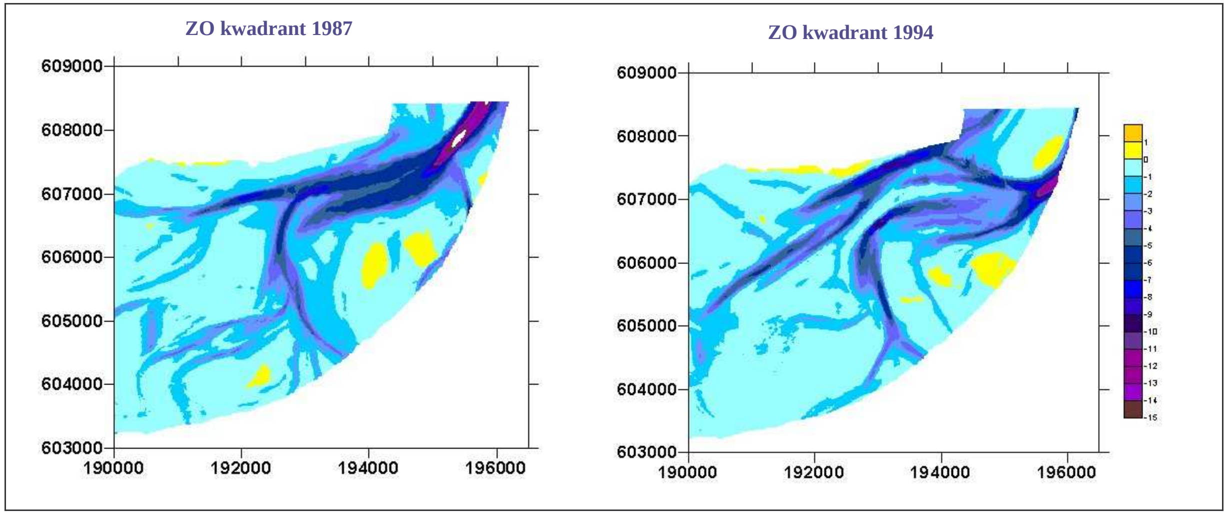
Wadden Sea

The strong dynamics in the system (tides, currents, storms) also makes it impossible to discern, both now and in the future, local relatively small changes caused by subsidence in the Wadden Sea.

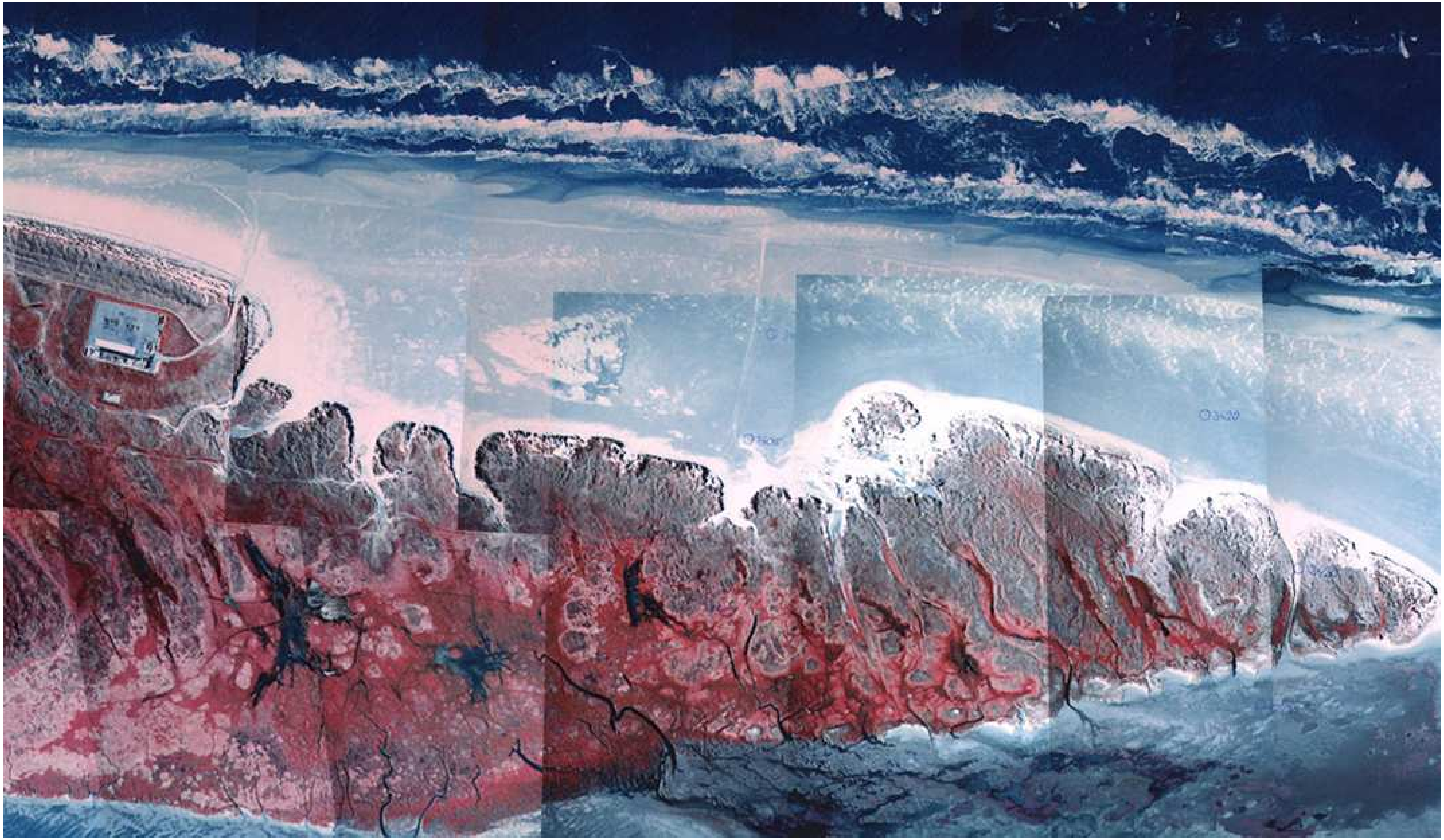
Similarly, if the average level changes or volume change of the tidal basin are examined, these changes are not demonstrable because they are within the inaccuracy of the measurements. It was only on the shallows just under De Hon that a drop in the level of the mud flats of the same order of magnitude as the subsidence was observed from level measurements in 1988 and 1998. Here too, however, it is possible that compensation occurs through accretion but that this effect is in turn counteracted by the natural channel changes (Holwerderbalg) on the mud flats.

The latter theory seems to be confirmed by, among other things, the drop in the level of the mud flats just off the coast at the Oerderduinen/Het Oerd, which is approximately three times as great as the subsidence there caused by gas production. This appears to be caused by the development of a shallow channel just off the coast in that area.





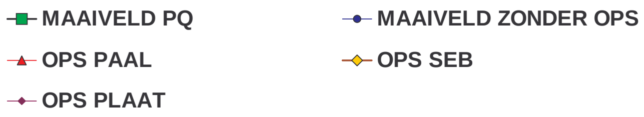
The south-eastern quadrant of the area of the Ameland subsidence bowl is depicted. In the top figure, the surface area of tidal flats is shown in km^2 surface under a certain depth contour ranging from –1.5 m (channel) till +0.5 m. The blue (1994) and red line (1987) are based on depth measurements (see the 2 figures below). The green line represents a calculated surface area, based the measurements in 1987 and (subtracted) the subsidence of fixed measurement points in 1994. Clearly, the surface of tidal flats did not decrease, but increased due to a combination of ongoing sedimentation and migration of channels.

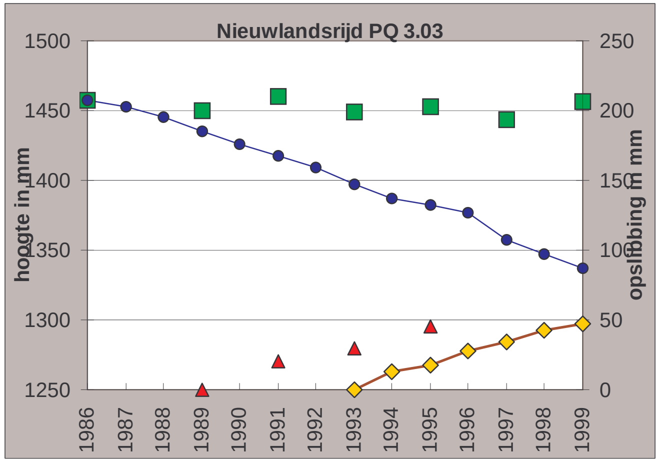


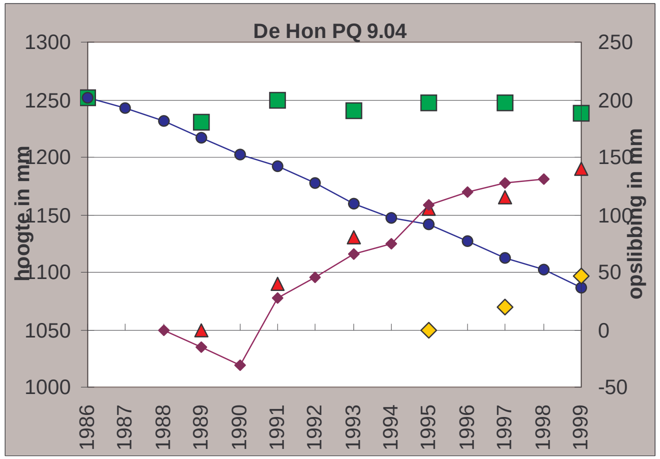
A birds eye view of the eastern part of Ameland based on aerial photographs taken in 1997. Such photographs are taken every 5 years by the Meetkundige Dienst (RWS). This and the other compilations can be found on the CD that is included in this report.

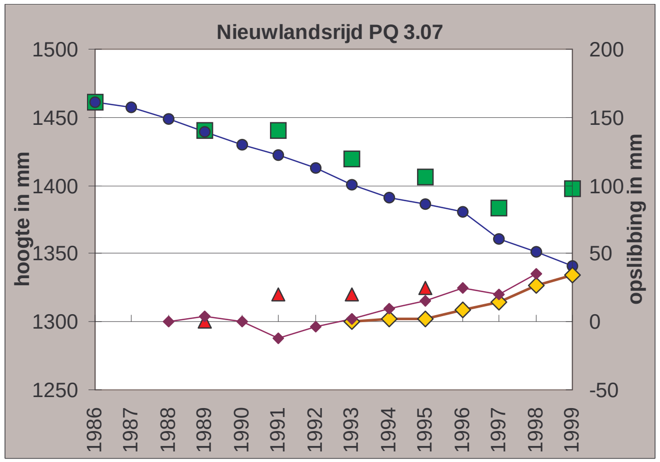
Salt marshes

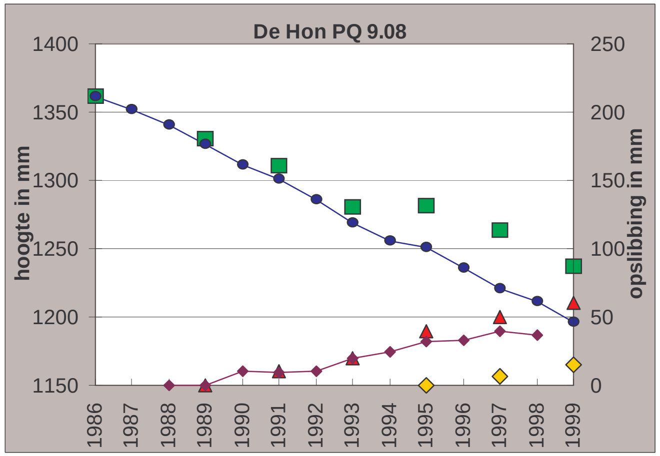
The accurate level measurements on East Ameland give a clear picture of the subsidence caused by gas production. There is local compensation in the level of the salt marshes as a result of sedimentation.











Nieuwlandsrijd (grazed by cattle)

PQ 3.03 is situated close to the Wadden Sea. Sedimentation is equal to the subsidence (120 mm in 13 years). The surface is therefore in equilibrium. The vegetation pattern develops in a natural way and both regression and succession are observed.

PQ 3.07 is situated at a larger distance from the Wadden Sea. The subsidence is also about 12 cm. Sedimentation is less than in PQ 3.03 due to the increased distance from the sea. The ground level at this point has fallen some 50 % of the actual subsidence. The sedimentation balance is negative and the level is 5 cm below the original level in 1987. The vegetation is stable.

De Hon (non grazed by cattle)

PQ 9.04 is situated close to the Wadden Sea. Sedimentation fully compensates for subsidence (165 mm in 13 years). The surface is therefore in equilibrium. The vegetation pattern is stable with a high diversity.

PQ 9.08 is situated quite somedistance from the Wadden Sea. The subsidence also is also about 17 cm. Sedimentation is less than in PQ 9.04 due to the increased distance from the sea and at this point the ground level has fallen some 50% of the subsidence.. The sedimentation balance is negative and the level is 10 cm below the original level in 1987. The vegetation shows regression.

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In February 1999 the subsidence caused by gas production on Nieuwlandsrijd was approximately 13 cm on the eastern side of the salt marsh decreasing to 3 cm on the western side. These are 60% and 35% respectively of the original 1985 subsidence prediction. The drop in ground level is usually less as a result of compensation by accretion. A revetment (artificial enforcement) fixes the Nieuwlandsrijd salt marsh strip and because of this the salt marsh is protected from erosion.

The subsidence caused by gas production in the natural salt marsh on De Hon in February 1999 varied from about 22 cm at the NAM location in the west to some 9 cm at the most easterly point. These are 75% and 45% respectively of the original 1985 subsidence prediction. Here too the drop in ground level is usually smaller than the subsidence caused by gas production as a result of accretion. The average high water line on the mud flats side has moved approximately 100 metres to the north since 1988 as a partial consequence of the effect of subsidence but mostly by erosion of the shallows by natural channel migration of De Holwerderbalg. The salt marsh strip has been eroded in some parts and has grown in others.

The accretion in the salt marshes depends on the salt marsh level and, probably, the distance to the Wadden Sea or a salt marsh creek. As a rule the subsidence in the low-lying salt marshes (lower than NAP +1.25 m) is more than compensated for by accretion. On the higher salt marsh, the compensation gradually decreases with the increasing level and the greater distance from the Wadden Sea to zero at a level of 2 m above NAP relatively close to the coast or 1.7 m above NAP at a greater distance from the sea. No accretion occurs above these levels. In other words generally speaking the salt marsh becomes somewhat flatter.

A low-lying area, south-east of the NAM location on De Hon contains some places that drain poorly. This low level is the result of seawater that during storm tides takes water to or removes it from the low valleys to the west and south-west of the NAM location. This low level is exacerbated by the relatively rapid subsidence in the area.

Dune areas

The dunes alongside the beach and the new dunes on De Hon are very dynamic and the effects of subsidence here are completely overshadowed by the natural dynamic.

The investigation of the vegetation in the dunes was carried out primarily in the older, inactive dunes with dense growth. There is virtually no sand movement here, so the subsidence caused by gas production corresponds virtually completely with the drop in ground level. In principle, therefore, the subsidence will result in a more permanent lowering of the dune landscape.

The edge of the grazed salt marsh (Nieuwlandsrijd). The most eastern side is unprotected and erosion has caused a steep edge to develop.

Storm tide channels
Based on the available data and the topography seen from three locations on De Hon, it can be concluded that there is no real danger of the sea breaking through as a result of subsidence. In only once place was a development (not an alarming one) observed as a result of flow over De Hon during a severe storm.

Polders
Ground level in the pastures in the Buurdergrie polder will be lowered permanently by the subsidence caused by gas production. In February 1999 the subsidence there ranged from 0.7 cm in the west to 4 cm at the furthest eastern point.

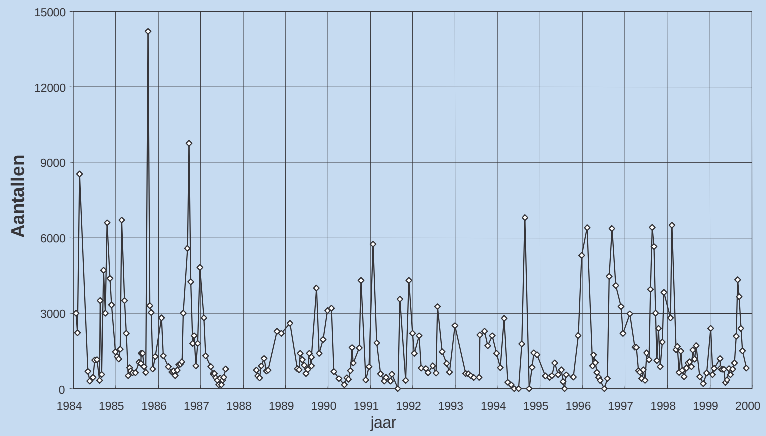
D - Ecology

Birds
The possible effects of subsidence on East Ameland on migratory birds were investigated through comparison with trends in other areas where there is no subsidence. The comparison covered the period from 1 January 1984 to the autumn of 1999. The Boschplaat on the island Terschelling was selected as the reference area because the situation of the Boschplaat is roughly comparable to that of East Ameland. Studies were also made of general population trends in the Wadden Sea, numbers in the rest of the island Ameland and the numbers on the island Engelsmanplaat.

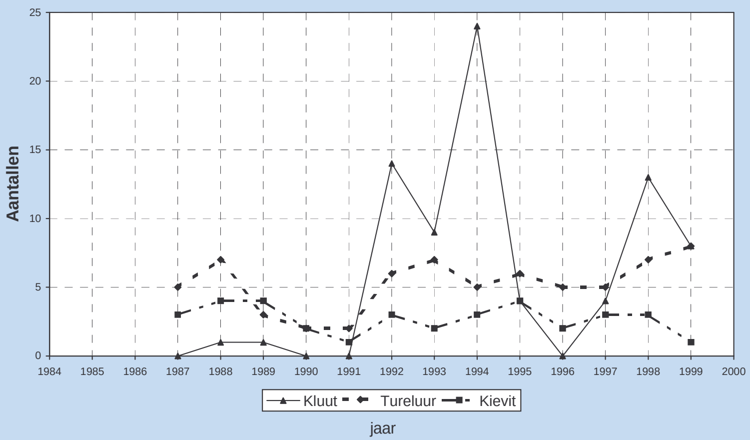
A storm tide channel is situated east of the land-based gas production siteon Ameland. Onthe horizon a production platform situated in the coastal zone is seen. The gas from the land-based site is purified on the platform and together with the gas from this offshore platform delivered to a west – east offshore gas-transport pipeline.

The trends in numbers in East Ameland largely corresponded with the trends observed elsewhere and were practically identical to those on the Boschplaat. This was the case with total bird numbers and also individual species. So far there has not been any indication whatsoever that changes in the number of migratory birds or the relative numbers of different species have occurred as a result of subsidence. The effects of the disappearance of the mussel beds around 1990 and the low numbers of shellfish in the years thereafter are clearly a result of the increased numbers of some bird species.

The only study of summer birds related to their number was in the salt marshes on De Hon. This is the area with the greatest subsidence and where nesting sites could have become unsuitable as a result of changes in the vegetation and/or a drop in ground level. However, the numbers turned out to be more or less stable. This consistent with the fact that the changes in the vegetation have so far been very modest.



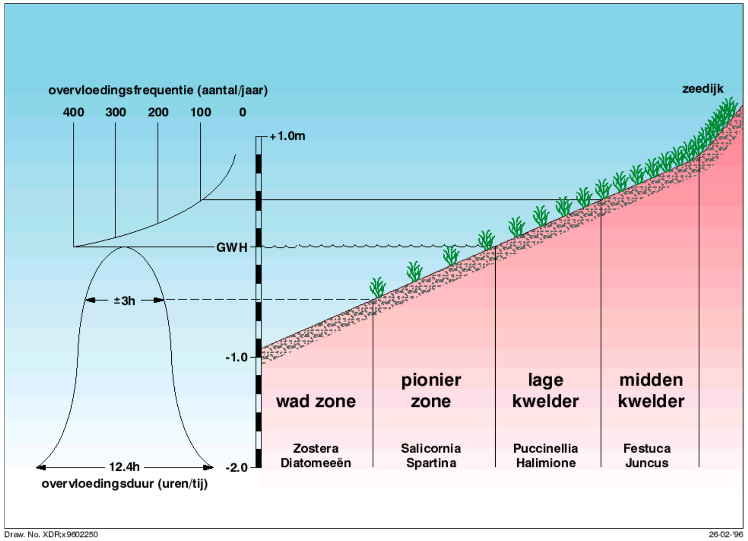
Annual variations (1984-2000) of the Oystercatcher on De Hon.



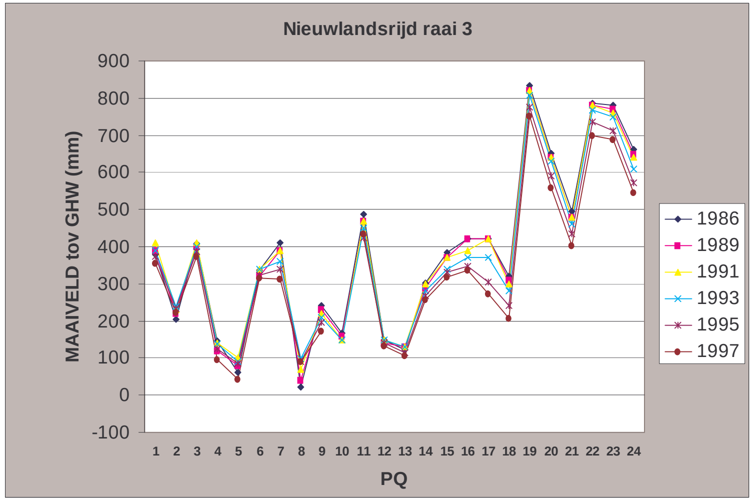
Annual variations (1984-2000) of 3 species of nesting birds, Avocet, Redshank and Lapwing on De Hon.

Salt marsh vegetation

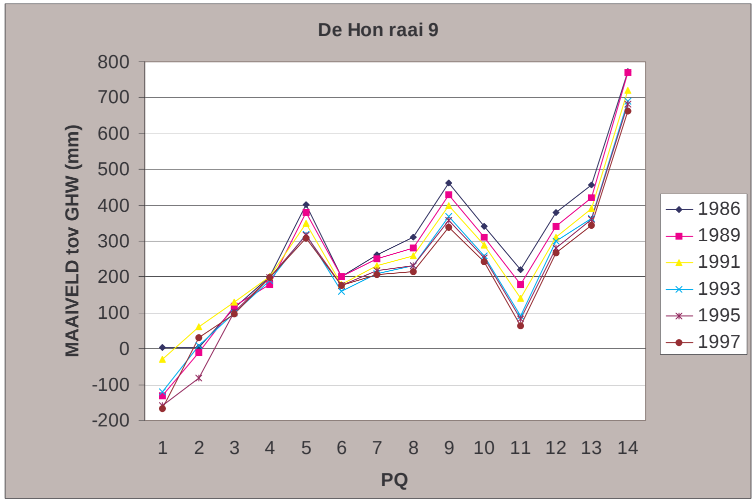
The elevation, and drainage of the soil and the salt content of the moisture in the soil are the factors that determine the type of vegetation in a salt marsh. The drainage depends on the morphological condition of the creek system and the distance to a creek. The number of floods is related to the elevation and the annual average level of the mean high water level.



Zoning of salt marshes is related to flooding (duration and frequency). The different zones are characterised by ground level and the related vegetation type.

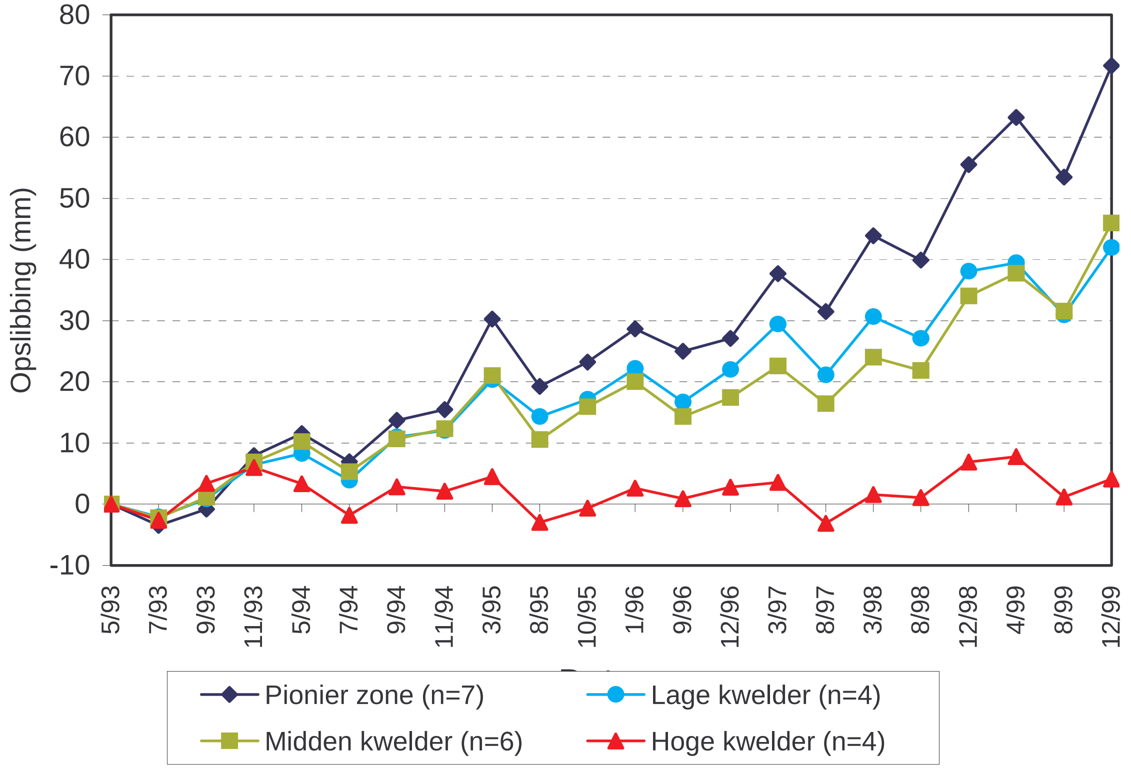


The development of the ground level in the transects 3 and 9 in the period 1986 to 1999. The subsidence of 15 cm (transect 9) at the edge of the marsh fully is fullycompensated by annual sedimentation. At some distance from the sea and creeks, less silt is available and compensation is partial.



Accretion is in equilibrium with subsidence in the lowest zones of the salt marsh and the parts closest to the Wadden Sea or the creeks because these are the places where accretion is the greatest. Ground level in the central and high salt marshes and the salt marshes that are distant from the mud flats has dropped as a result of subsidence. The limit value of 5 cm that has been defined for a negative accretion balance is exceeded here. A negative accretion balance represents a potential risk of change in the vegetation to that of the lower salt marsh zone. There is no risk of the salt marsh becoming smaller because the zone with too little accretion is not on the mud flats side. The original ground level will be restored after termination of gas production as a result of what will then be a positive accretion balance.

The fact that accretion is lagging behind subsidence in a part of the salt marshes has had essentially no implications for the salt marsh vegetation. Only one of the 50 test areas displayed a clear regression of the vegetation during the entire 1986-1997 period. The causes of the virtual absence of effects on the vegetation are that (1) the subsidence was generally insufficient to reach the critical lower limit of the salt marsh zones and (2) the annual average high water level dropped between 1988 and 1993. Even when ground level dropped below the critical lower limit (generally in the 1986-1993 period) there was essentially no effect on the vegetation. Nor was there any later on when the annual average high water levels increased again.



Results of the annual measurements using the "sedimentation-erosion bar method" (transect 3). In the lower zone (pink line) sedimentation is highest (12 mm/yr), close to the dunes (red line), sedimentation only occurs during severe storms.

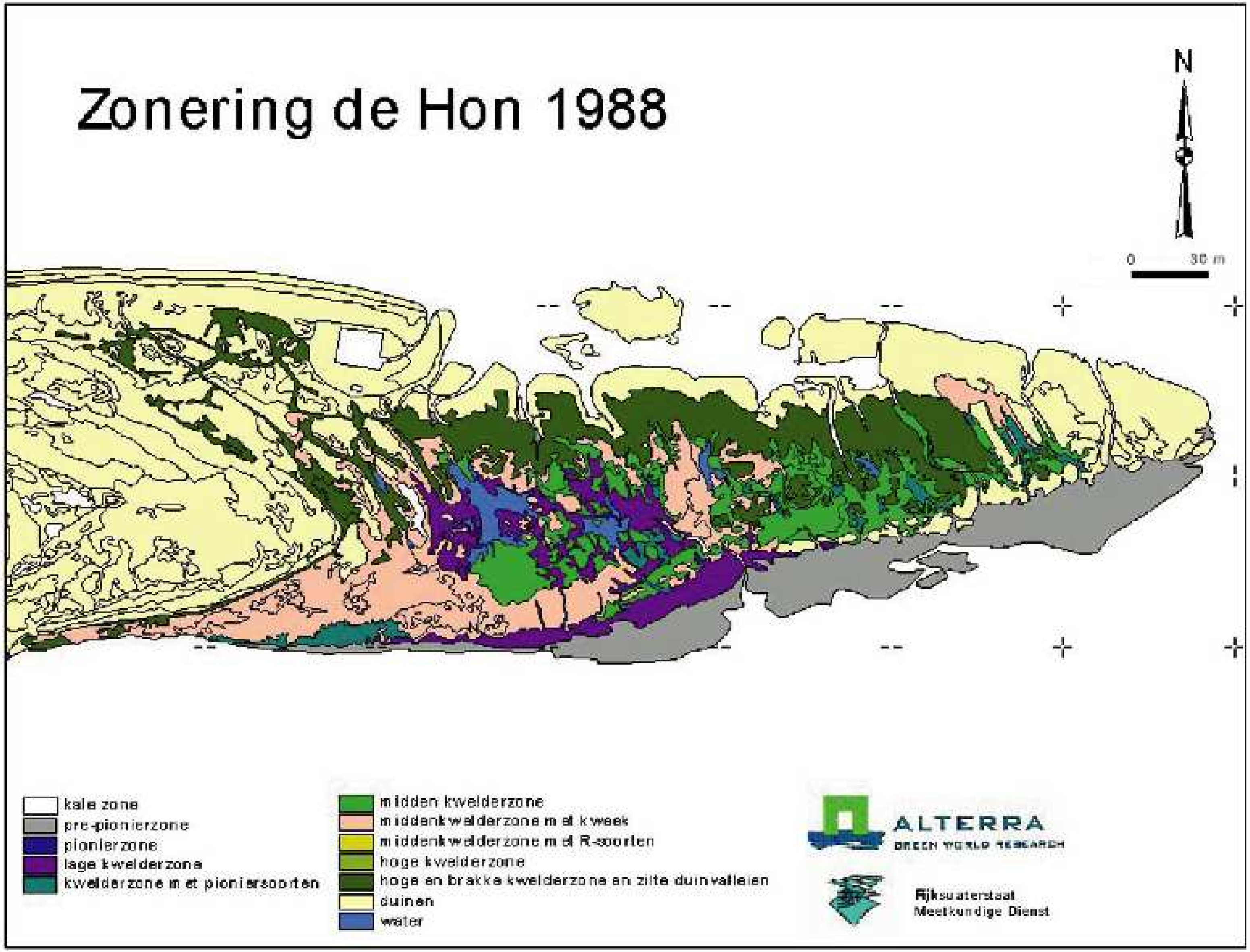
The results of the salt marsh monitoring on Ameland therefore give rise to the question as to whether the current theory about the significant role-played by the ground level in the salt marsh zoning is credible. The degree of drainage appears to play an equally important part, and within certain limits perhaps an even bigger one! A clear indication of this is given by changes in some permanent test areas in the middle of De Hon, caused by saturation after a creek was blocked.

The vegetation of adjoining permanent test areas at the same elevation, with the same subsidence and close to a creek with no problems did not change.

The next few years of the monitoring programme will show whether or not setting the limit value for a negative accretion balance at 5 cm has been far too cautious. The response, if any, of the salt marsh vegetation to ground level changes will depend on the combination of further subsidence, accretion and the future annual average high water levels.

The maps of the vegetation zones dating from 1988, 1993 and 1997 also show that no major changes have taken place in the salt marshes. Most changes take place on Nieuwlandsrijd, for example more Common Saltmarsh grass in the east. Incidentally there is no clear direction and cause. Subsidence has similarly not played a large part in changes in the vegetation on De Hon. The changes in some permanent test areas are very local in nature. It is possible that more succession (= change from lower to higher salt marsh zones) would have occurred if there had been no subsidence in the East Ameland salt marshes. It appears, therefore, that subsidence retards the ageing of salt marshes on Ameland. This is a side effect of gas production.

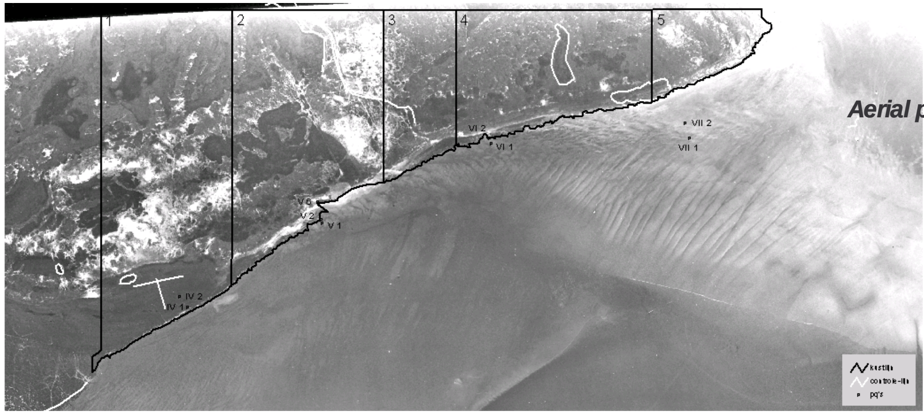
The creek that was blocked in 1985 can still be recognised from the difference in vegetation (central part of the photograph taken in 1998).



Vegetational zoning map (1988) based on the analysis of aerial (false colour) photographs. These maps are available for 1988, 1993 and 1998

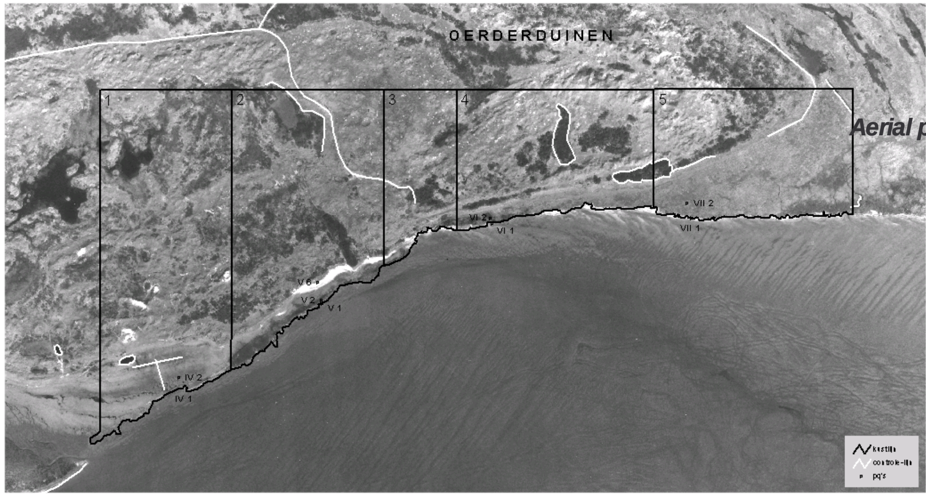
Oerderduinen salt marsh strip

The vegetation of the coastal strip south of Het Oerd and the Oerderduinen is characterised by a great diversity of species. The combination of species is unique because of the salinity gradients. Coastal erosion is threatening the vegetation of this narrow coastal strip. Accretion and erosion of the coast has been quantified over the last fifty years by means of aerial photograph interpretation of the coastline. The coast south of the Oerderduinen grew until about 1979. Erosion began well before the start of gas production in 1986.



Aerial photograph made in 1949

Tussen 1979 en 1986 vond afslag plaats. De afslag begon dus al vóór de aanvang van de gaswinning in 1986. Door de analyse van historisch fotomateriaal dat vanaf 1949 beschikbaar was, kon een beeld gevormd worden van de geschiedenis van de kwelderrand.



Aerial photograph made in 1996

	Edge of the marsh		Difference between years (in m^2)									
	Section	Length (in m)	'49-'59		'59-'69		'69-'79		'79-'86		'86-'96	
Net	1	400	-1807	-	232	0	2951	+	119	0	-4821	-
	2	475	-2039	-	5170	+	6889	+	-238	0	-124	0
	3	200	-2151	-	1617	+	5552	+	-4994	-	-1564	-
	4	500	22.083	+	5163	+	7637	+	-11.303	-	-8795	-
	5	500	77.549	+	34.498	+	32.018	+	-11.087	-	-18.555	-
Total	6	2075	93.635	+	36.459	+	53.858	+	-27.713	-	-30.861	-

Net regression and increase

- = regression
+ = increase
0 = neutral

Erosion can be as rapid as over three metres a year. Generally speaking no acceleration of erosion was found after 1986, except for a few isolated parts of the coast. The consequences for the vegetation were established by comparing descriptions of the vegetation made in 1986 with 1999. The vegetation on the mud flats side was eroded between 1986 and 1999, and saline plant species were found more frequently in the adjoining area. The erosion of the coast appears to be consistent with the natural dynamics of the coast. During the first ten years of gas production accelerated coastal erosion was only recorded locally.

Dune vegetation

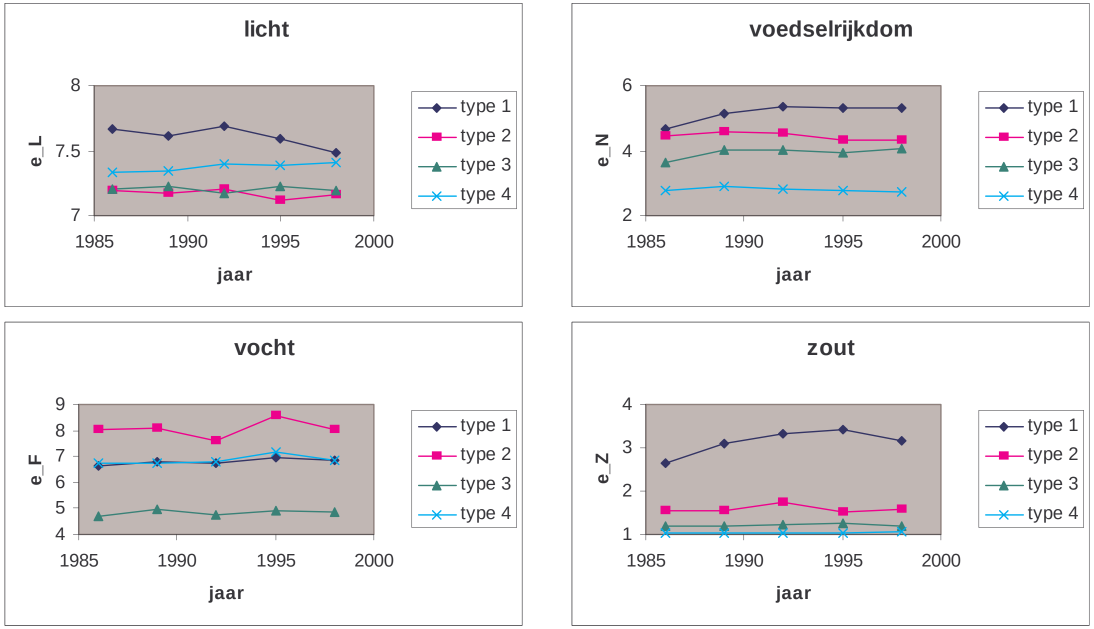
The changes in the dune vegetation have been studied since the start of gas production using 56-66 permanent test areas. The vegetation in these test areas (permanent plots) was recorded in 1986, 1989, 1992, 1995 and 1998. The permanent test areas are located along five lines running from salt marsh to dune. The lowest-lying permanent test areas are salt marshes and are occasionally flooded with seawater. The highest are in the dry dunes.

The processing of the data focuses on the question of the extent to which the observed changes in the vegetation can be attributed to subsidence. The ‘five factor model’ has been used as the basis for establishing the effect of subsidence. In this model the vegetation is considered to be a result of 5 environment variables: groundwater level, nutrient supply, acidity, salt and management. Sophisticated statistical techniques have been used to identify and analyse the relationship between observations, species and abiotic conditions. An indication factor for ‘nature conservation value’ was also used.

Four types of vegetation have been defined:

1) salt dune valleys;
2) wet dune valleys;
3) dry dunes;
4) damp dune heath.

Temporal trends in the average ecological indication values of the vegetation are barely distinguishable. A change of type in a test area over time has been found to occur only sporadically.



The trend in the statistically calculated ecological index value is shown for the period 1985-2000. This so-called “Ellenberg value” was calculated for the impact of (a) light , (b) moisture , (c) nutritional state and (d) salinity .

Type 1 shows a downward trend in the light indication value. This could reflect succession whereby the salt marsh vegetation has become gradually more dense. The extremely wet year of 1995 can be clearly recognised from the moisture indication in the wet types, and the high tides at the beginning of the nineteen-nineties are clear to see in the salt indication for type 1.

Generally speaking the changes in the vegetation have been very minor. The changes in each type of vegetation are also very small compared with the differences between the types. It also appears that no significant changes have occurred in the ‘nature conservation value’. The most striking results are the marked presence of aquatic and marsh plants in 1995 and a fairly marked presence of salt-loving plants in 1992. Groundwater level and flooding frequency have been found to explain most of the variance in the vegetation. In principle subsidence could therefore result in important effects on the vegetation through changes in these parameters.

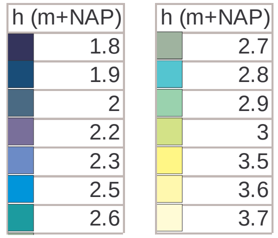
The effect of subsidence in the years after 1992 and in the permanent test areas with subsidence greater than 15 cm in 1998 was found to be of the same order of magnitude as the effect of the weather during the period of observation. The effect of subsidence on the ‘nature conservation value’ is also negligible.

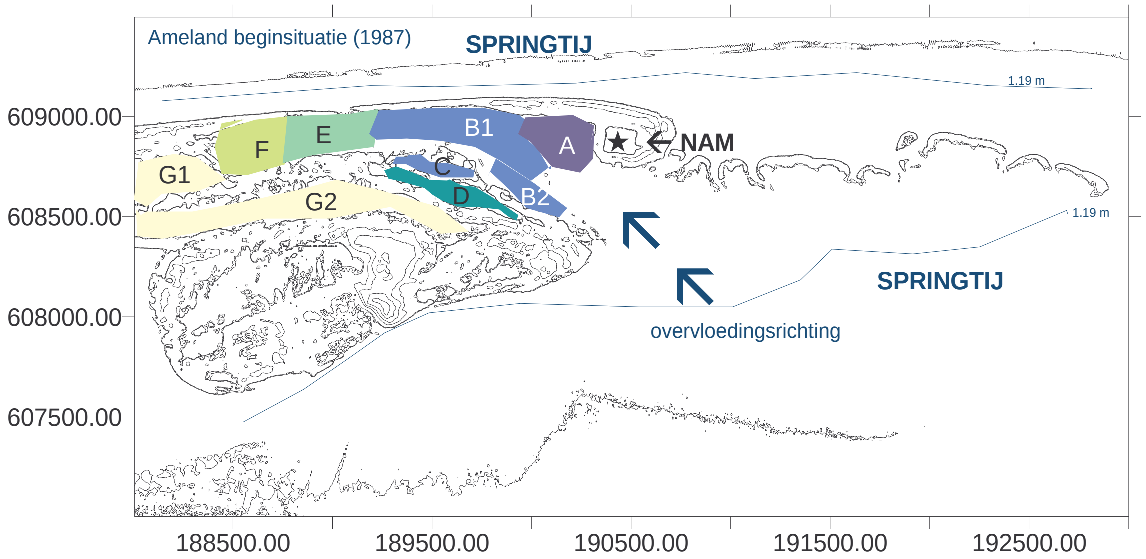
Death of scrubs

The standard monitoring programme has been focused primarily on the behaviour of the herbaceous, low vegetation in the salt marshes and the dune areas of East Ameland. In 1994 there were indications of the sudden death of hawthorn and elder in a few, entirely enclosed valleys in the Oerderduinen. During regular fieldwork in the dunes in 1995 fairly widespread death of Sea-buckthorn was observed in a few new dune valleys just to the west and south of the NAM location. The dead vegetation was outside the selected permanent test areas. In 1996 it was therefore decided to conduct an additional investigation into the cause of the dead scrub. The area of dead Sea-buckthorn extends to about 25 hectares on East Ameland. The area of dead hawthorn and elder is limited (approximately half a hectare).

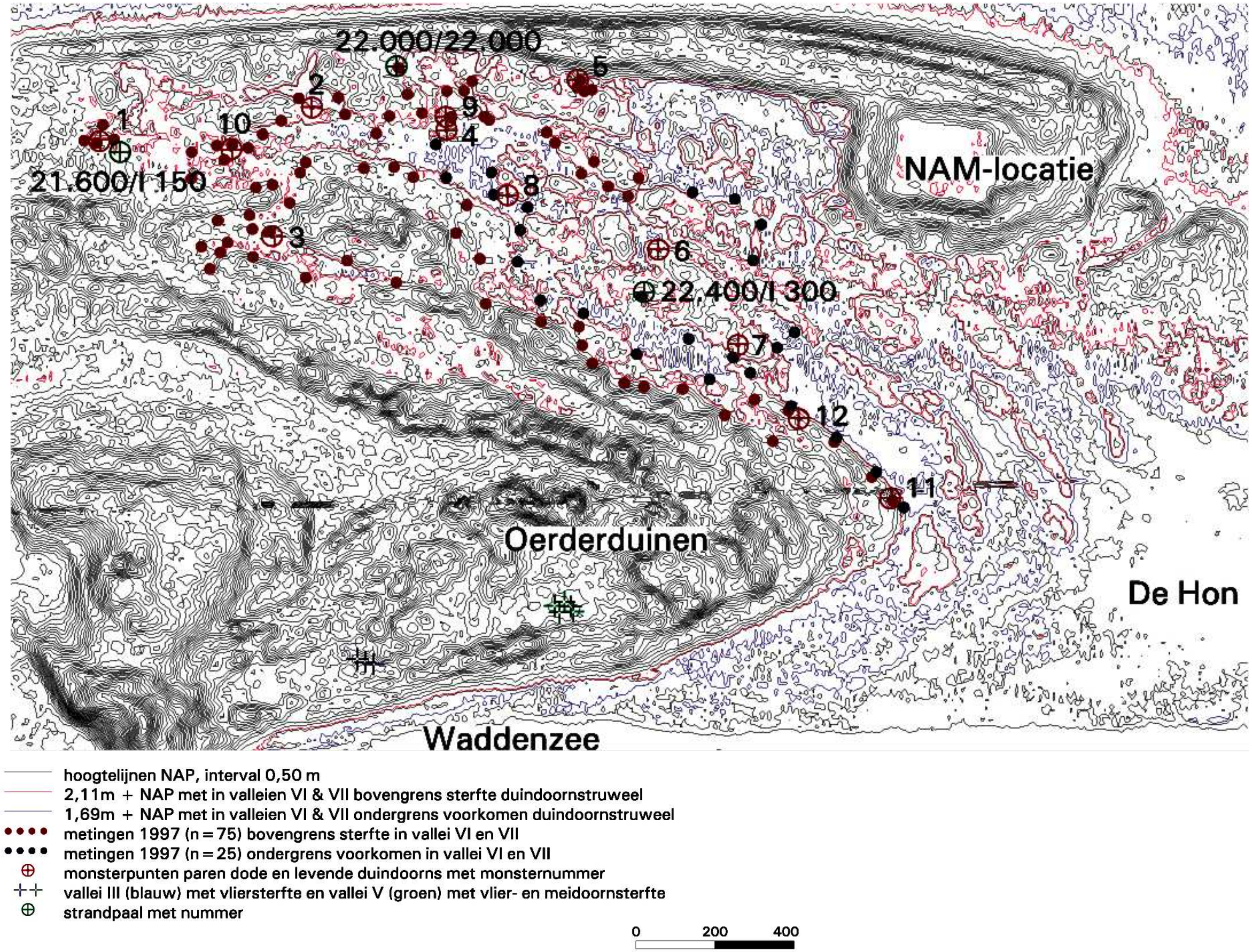
As many possible alternative causes of the dead scrub as possible (other than extreme weather conditions and subsidence) were inventoried and eliminated in a preliminary investigation carried out in 1996 and 1997. Dead Sea-buckthorn has also been observed in the eastern part of the neighbouring islands of Schiermonnikoog and Terschelling, albeit to a different degree. There is no subsidence in these last two areas.

The follow-up investigation in 1998 and 1999 focused on the occurrence of extreme events in the weather and the associated saturation and/or salinification as a possible cause of the death. Finally, the degree to which the subsidence had an influence on the death observed was also looked into.





On the west side of the gas production site, a number of low valleys can be observed. Indicated are the sea level at which they might be submerged. Valleys A to C are normally submerged a few times per year. This frequency will increase due to



Drowned Sea-buckthorn and Hawthorn have been located in the lower valley region and in some enclosed valleys in the dunes. Death of the Sea-buckthorns is attributed to extreme flooding by the sea in 1989/90 and 1991/92. Drowning of Hawthorn and Elder is attributed to extreme precipitation in 1993/94).

It is reasonable to conclude that the death of the Sea-buckthorn was caused by extremely high water levels (seawater from the Wadden Sea) in the period between 1989/90 and 1991/92. New growth was observed in the area after 1995. The effects of the ‘natural dynamic’ of the system (primarily as caused by the weather) and the additional effect of subsidence (caused by gas production) could be separated in relation to the death of Sea-buckthorn. The conclusion is that the impact of subsidence is minor compared with the impact of the ‘natural dynamic’ in this very dynamic area. Based on the area determined in 1986 and 1991, approximately 85% of the death can be attributed to the ‘natural dynamic’. The remainder can be attributed to subsidence

It is reasonable to assume that the hawthorn and elder died as a result of the extremely wet 1993/94 period (rainwater). During this time the level of the groundwater in the valleys concerned rose to far above ground level. The conclusion is that subsidence is subordinate to the disruption caused by the ‘natural dynamic’. Consequently in 1993/1994 subsidence contributed to no more than 1/3 of the total death of vegetation.

Flooding risk in dune valleys

The primary effect of subsidence and a rise in sea level will be an increased frequency of flooding of dune valleys close to the NAM location that are accessible to the sea. Over the years and depending on the threshold level in the valleys, the frequency of flooding is increasing. Valleys with low thresholds are seeing an increase from 4 to 13 times a year. The frequency in valleys with high thresholds is increasing from 2 to 3 times per hundred years. The contribution of a rise in sea level to this is modest.

Increase in the flooding frequency per year in the event of a future sea level rise of 25 cm per century and a situation without and with subsidence. The height of the thresholds is given in m + NAP. Subsidence is assumed to occur at a constant rate.

Valley	**Initial situation 1987**		**Final forecast without subsidence**	**Final forecast with 28 cm subsidence**	
	Threshold height	**Flooding frequency**	**Flooding frequency**	**Threshold height**	**Flooding frequency**
A	2,2	4	5	1,9	13
B1, 2	2,3	3	3	2	9
C	2,5	2	2	2,3	3
D	2,8	0,5	1	2,6	1
E	2,9	0,3	0,4	2,7	1
F	3	0,2	0,3	2,8	0,5
G1, 2	3,7	0,02	0,02	3,6	0,03

The flooding risk, defined as the chance times the size of the potentially affected area is increased by a factor 2.5 compared with 1987 through subsidence without a rise in sea level.

Seawater remains behind in the valleys after extremely high tides because of the presence of the thresholds in the dune valleys. A secondary effect of the increased flooding frequency for dune valleys accessible by the sea is that soil conditions that are important to the vegetation change. Anaerobic situations persist for extended periods in most flooded valleys, and this causes vegetation to die. There is saturation, an increase in the salt content of the soil, an increase in sediment in relation to the flooding frequency and delay in decalcification.

These factors hinder a normal vegetation succession. In fact there is a regression towards more salt-tolerant species, particularly in the low-lying parts of the valleys. However, many of these salt marsh species have a high value in terms of rarity, degree of decline and international importance.

Natural dynamic

The dynamic that is naturally present in the dune area of East Ameland is an integral part of the local ecosystem. This dynamic creates conditions for the particularly high ecological value. Extremes in the dynamic (inundation as a result of precipitation or high tides) can kill some vegetation on a fairly large scale.

E - Effects on economic use

Nieuwlandsrijd

In 1999 the flooding frequency of the Nieuwlandsrijd salt marsh increased during the grass season on average as a result of subsidence. Consequently there was a ‘production loss’ as a result of subsidence in the capacity of 70,000-hectare days compared to the original situation. This loss was estimated at around 2% in 1994 and about 3% in 1998.

These loss percentages are based on long-term average conditions. Given the substantial fluctuations than can occur from year to year in the frequency with which very high tides occur and in the rainfall figures, it is not out of the question that the differences in the annual yields from the salt marsh are larger than the loss caused by subsidence.

Dead Sea-buckthorn (died in 1991/92) standing in valley B1. The picture was taken about a week after a storm event took place (1998). The seawater is locked in the valleys and the flooding condition may last for several weeks.

Buurdergrie Polder (Zwartwoude)

The effect of subsidence on the chance of inundation in Zwartwoude during westerly storms and on the grass yield has been studied extensively. As a basis this report describes the effects of 10 cm of subsidence. The actual subsidence in the Buurdergrie polder in February 1999 ranged from 0.7 to 0.8 cm near Buren to a maximum of 4 cm in the most easterly point of the polder. At that time the subsidence in the Zwartwoude area was between 2 and 3.5 cm. Consequently the effect of subsidence on the grass yield, even in low-lying parts of the area, is well below one percent (no noticeable influence). The chance of inundation similarly barely changes.

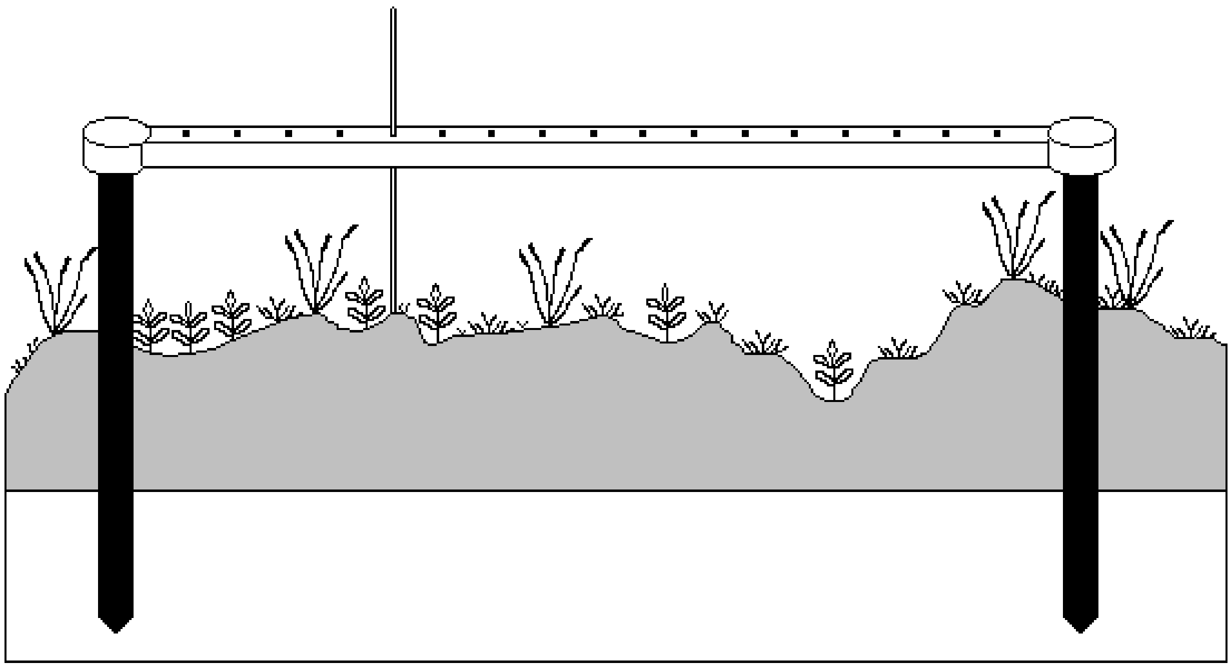
Water extraction in Buurderduinen

The available data reveal that in any event coastline movements of 40 to 50 m have no demonstrable effect on the chloride content of the water extracted from the Buurderduinen.

This, together with the government policy to maintain the coastline, leads to the conclusion that the Nuon Water company will not suffer any disadvantages as a result of subsidence caused by gas production. This subject has been deemed to be dealt with since the interim report in 1995 and further data collection in this regard has been discontinued.

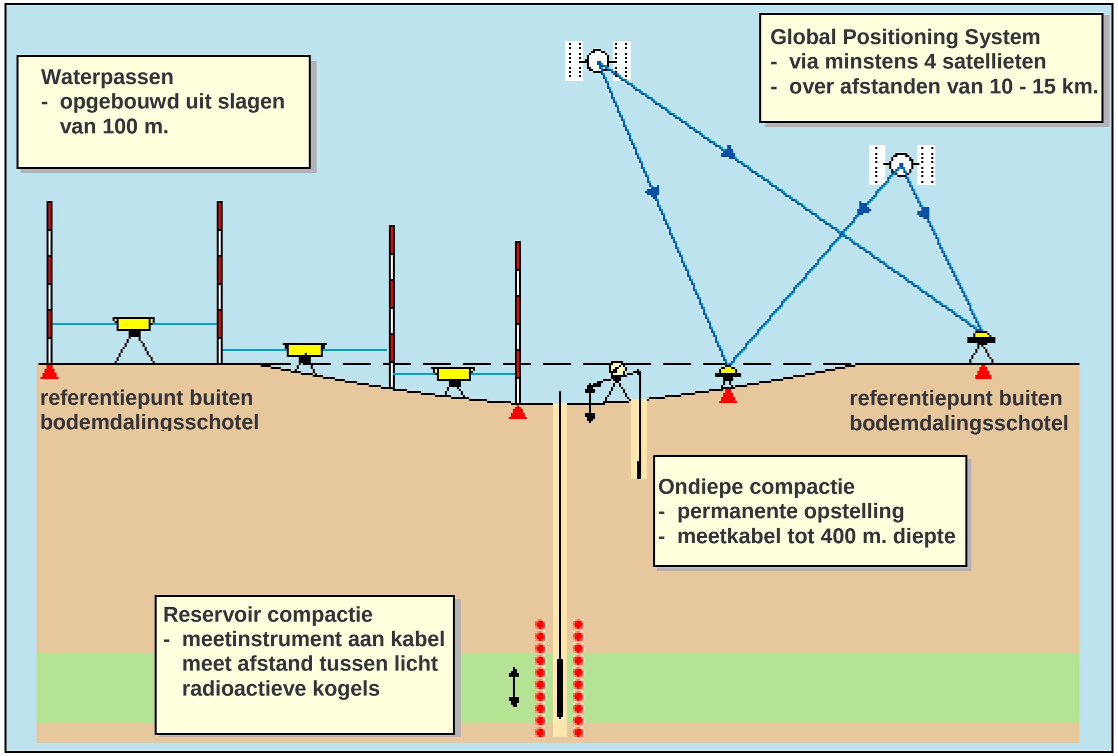
F - Monitoring

It is recommended that monitoring of the effects of subsidence should be continued because of the fact that subsidence on East Ameland is still ongoing and that a possible lag exists in the response of the vegetation.



The "Sedimentation – Erosion Bar method" (SEB) is used to measure annual sedimentation – erosion.

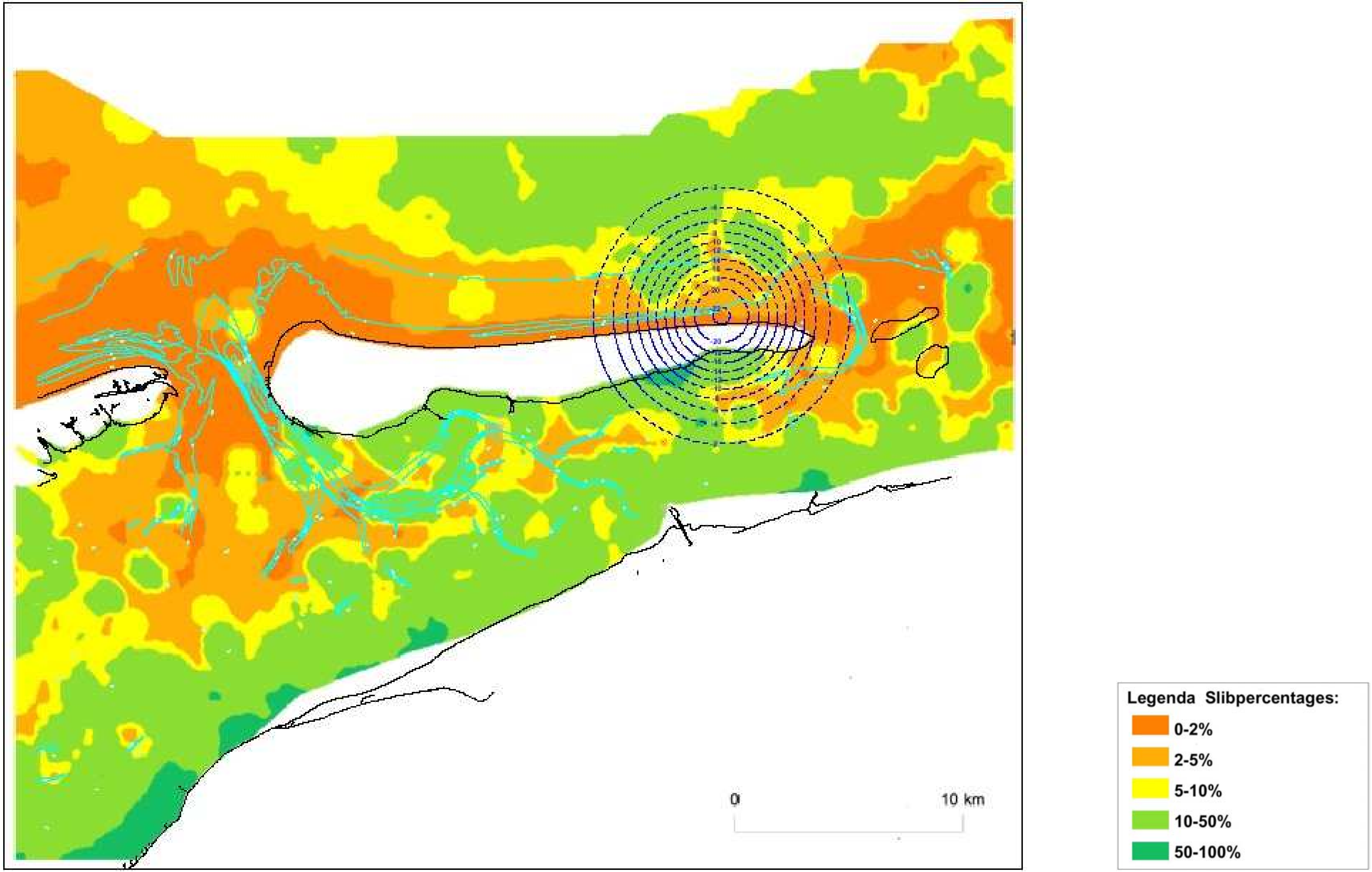
In order to assess subsidence rates, a variety of methods is being employed. The precision is in the order of mm.

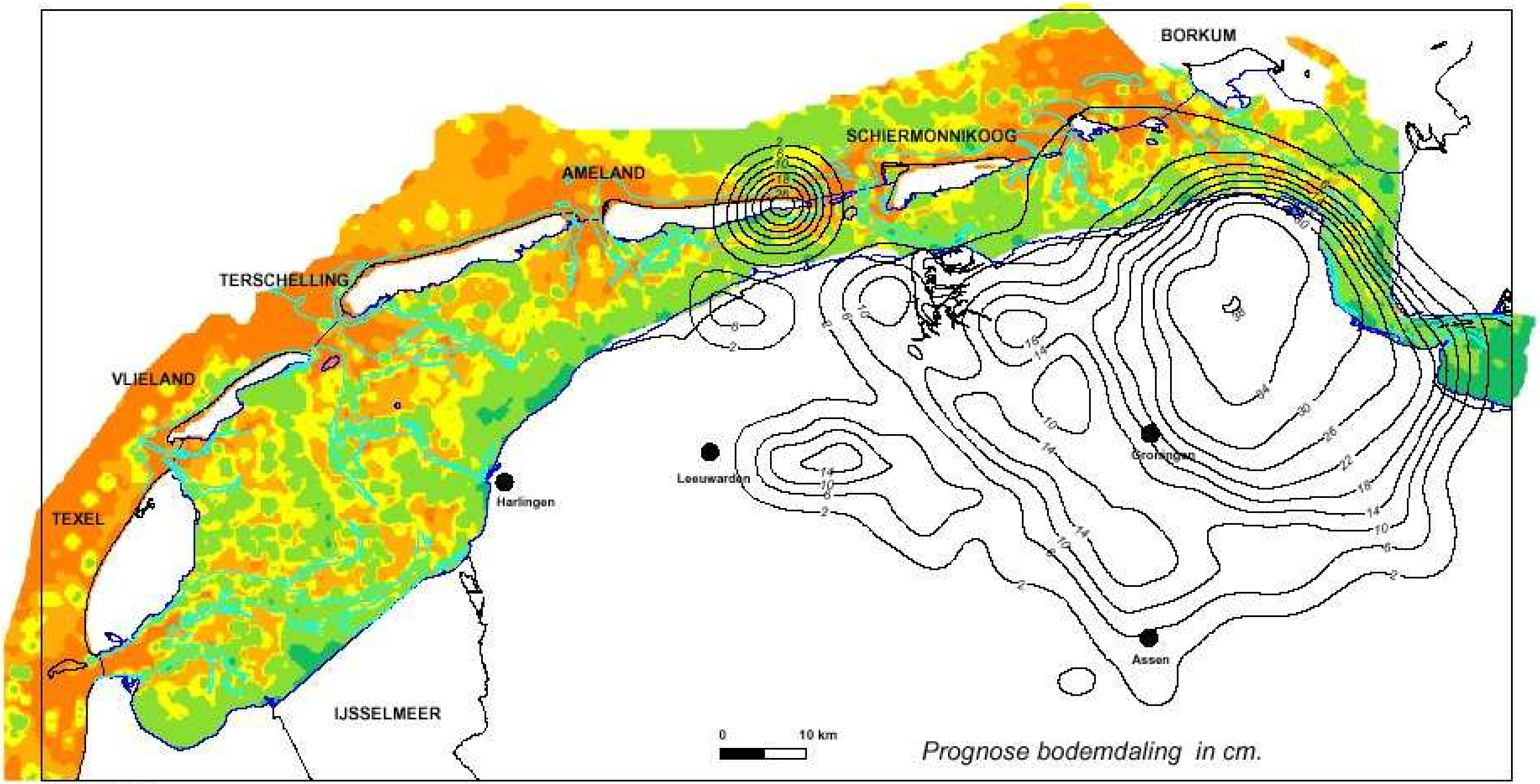


Methode	Nauwkeurigheid (2σ)
Optisch Hydrostatisch GPS	1,2 mm x √afstand in km 0,4 mm + 0.05 mm x afstand in km 2,0 mm + 2,00 mm x afstand in km

Subsidence and sediment composition

The 2 maps show the percentage of silt and the subsidence contours. There is no clear relation between the two variables.


0
10 km
Legenda Slibpercentages:
0-2%
2-5%
5-10%
10-50%
50-100%



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