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Tidal-channel migration between 1997-2014 in relation to the local build-up of the subsurface, The Netherlands

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State
draft
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Contents

1 Introduction

1.1 Background

Areas with active tidal channels are currently the most naturally dynamic areas in The Netherlands. The position of these channels is frequently monitored, because 1) they are heavily used for navigation and accurate maps are needed, 2) some of them lie close to infrastructure, e.g., coastal defence works, and hence need to be monitored to constantly assess the stability of the infrastructure and 3) to understand the Dutch coastal system, including erosion/sedimentation patterns and the exchange of sediment between the different tidal basins and the adjacent North Sea coastal zone.

There is also an interest in predicting tidal-channel and tidal-inlet evolution in order to plan protection measures. This is commonly done using hydromorphological models like Delft3D. A current problem with these models is that they do not take the geological variation that exists in the subsurface in account and hence also not the differential erodibility that exists between different types of deposits. An example is that to all sediments a standard grain size of 200 µm is assigned, basically meaning that the subsurface is always schematised as consisting of medium sand. This limits the reliability of the outcome of the models, sometimes leading to clearly wrong predictions, especially if predictions are made for longer time periods and most likely also especially in areas where erosion-resistant deposits are present. Recently an overview was given of the presence, thickness and depth of such deposits in the subsurface along the Dutch shorelines (Hijma, 2017a). That report identified two main knowledge hiatuses:

1 There is insufficient information on the regional build-up of the offshore subsurface;
2 There is insufficient information on the erodibility of the different types of deposits.

This first hiatus will not be filled quickly, since there currently is no organized regional mapping program of the offshore subsurface. Still, improvements can be made by making better use of existing data, especially geophysical data (Erkens et al., 2014), and by better organizing all the information produced by different projects for e.g. wind farms, sand mining or scientific research. Most value comes from the bigger projects, like the one recently carried out for identifying suitable offshore locations for sand mining (Blauw et al., 2017).The latter locations lie seaward of the Dutch coastal foundation, that currently has a seaward border along the -20 m NAP contour line, and hence seaward of the area with tidal channels, but the gathering of knowledge about the regional geological build-up has also added value for our understanding of the build-up of the coastal foundation and the connected tidal basins (Hijma, 2017b). In addition, a priority list should be made of tidal-inlet/tidal-channel systems for which there is not sufficient subsurface information. Prioritisation will most likely be based on a combination of coastal-zone management issues and our current understanding of the subsurface build-up. It makes sense to study areas that at least have the potential for erosion-resistant layers being present.

With respect to the second hiatus, this is also not easy to improve. There is currently hardly any quantitative information on the erodibility of the different deposits. According to Hijma (2017a) a proper literature review is needed, not only to gather relevant studies, but also to determine a useful method for direct measurements of erodibility. Another recommendation is to analyse the long-term migration rates of tidal channels in relation to the build-up of the subsurface. This information can potentially be used to assign long-term erodibility parameters to the different subsurface deposits and hence their influence on coastal evolution can be better understood. Under laboratory conditions this would be hard to achieve, because of the difficulty of simulating offshore field conditions, including the mimicking of the different deposits. The study presented here follows from this last recommendation. The goals of this study were to develop a useful method to calculate the average migration rate of tidal channels and to make a first assessment of the relation between the migration rate of tidal channels and the subsurface deposits in which the channels are embedded. This first assessment was done by comparing bathymetric surveys from 1997-2002 and 2009-2014 and linking it to the overview of erosion-resistant deposits in Hijma (2017a).

The report starts with describing the method that was used to calculate migration rates, followed by the results and a discussion of the mentioned relation between migration rates and geology. It should be noted that the study was intended as a first step in quantifying the erodibility of different types of deposits based on bathymetric surveys and had corresponding time and budget associated to it. The discussion and analysis are therefore not exhaustive and not embedded within (inter)national literature. This and the analysis of average migration rates over other time periods could be part of a next phase in this line of research whereby the influence of geology on long-term coastal evolution is assessed and quantified.

2 Method to calculate average migration rates

The bathymetric datasets that were used are based on the annual ‘Vaklodingen’ of Rijkswaterstaat. Each year different parts of the shoreface and the tidal basins are surveyed and interpolated to a raster with 20x20 m resolution. To create a complete bathymetric map it is necessary to mosaic several rasters to one raster whereby it is common practice that the most recent data trumps older data, meaning that the resulting map displays the most recent data from the used raster series. For this study we compared mosaicked maps from the periods 1997-2002 with 2009-2014. The data from these periods is of good quality and a period of about 12 years is sufficient to see migration of the tidal channels.

From these two mosaicked maps contour lines for -6 m and -15 m NAP were extracted (Figure 2.1). These two contour lines were chosen to be able to analyse the migration of both the smaller and the bigger tidal channels. The migration distance was obtained by creating points in ArcGIS on the contour lines of the period 2009-2014. This was only done for contour lines that shifted due to erosion, not for contour-line shifts due to sedimentation. The distinction between migration through erosion versus sedimentation was done visually and based on the visible migration pattern. In a next step the distance between the points and the contour line of the period 1997-2002 was calculated with ArcGIS. In a final step the average migration rate for each point was calculated by dividing the distance by the number of years between the two compared bathymetric surveys. Since mosaicked rasters from two periods were compared, this means that the number of years can vary. The average number of years between the rasters is 11.7 year, while the minimum is 8 and the maximum is 15 year.

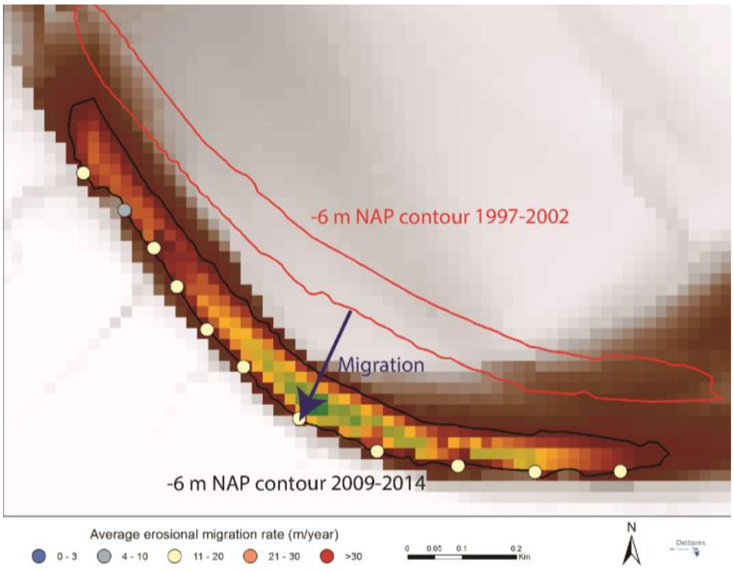


Figure 2.1 Example of the method used. Two contour lines are displayed: one from the period 1997-2002 (red) and one from the period 2009-2014 (black). On the 2009-2014 contour line points are created and the distance between the points and the 1997-2002 contour line is calculated (220 ± 9.9 m in this case). The average migration rate is then calculated by dividing the distance by the elapsed time (12 ± 0.5 years in this case), resulting in an average migration rate of 18 ± 0.8 m/year.

The uncertainty around the calculated migration rates is mostly depended on the vertical accuracy of the bathymetric measurements (estimated to be ± 0.25 m, 2σ) and the slope of the channel wall. To estimate the uncertainty, 8 channel walls were graphically plotted by extracting bathymetric data from ArcGIS. In these profiles each centre of a raster cell is a datapoint on the profile line. By adding or subtracting 0.25 m from the value of each raster cell, the 95% range in slope angles is determined. From this the 95% range in horizontal position of the contour line can be calculated. For the 8 channel walls the possible range in horizontal position of the contour line, relative to the mean position, was ± 2 and ± 12 m with an average of ± 7 m. This latter range was used for estimating the uncertainty around the measured distance between contour line.

As an example let's assume that the measured distance between two contour lines is 30 m. When normally distributed, the standard deviation around the measured distance will be ± 9.9 m (square root of 7^2+7^2). To calculate the average migration rate 30 ± 9.9 m has to be divided by the number of years passed between the bathymetric surveys, 12 years in this case. The migration rate is then calculated by dividing 30 ± 9.9 by 12 ± 0.5 resulting in an average migration rate of 2.5 ± 0.8 m/yr. The standard deviation of ± 0.8 m/yr is independent of the measured distance and the number of years. To avoid misguided conclusions about the spatial pattern in average migration rates only migration rates higher than 0.8 m/yr are labelled significant in this study and displayed in the maps.

3 Results: migration rates

This chapter provides an overview of the migration rates for different regions along the coast, without looking at the influence of the geological situation. Figures with the same geographical extent will be shown in Chapter 4, but then including the mapped distribution of the erosion-resistant deposits (Hijma, 2017a). The numbers in bold refer to locations on the maps. For some areas topographic maps are included to facilitate reference.

3.1 Eems-Dollard-Groninger Wad

The Dollard-area is quite shallow and no -15 m NAP contour lines are present (Figure 3.1). The main channel system of the Dollard (Mond van de Dollard-Groote Gat) widened at the -6 m level, at some places considerably with rates of 21-30 m/yr (1). This widening trend at the -6 m level is visible all the way north up to the Eemshaven-area, since at both sides of the Eems erosion has occurred (**2, 3**). The highest rates are found on the eastern side, just north of the bend in the Eems, where the -6 m contour line has migrated 300-400 m at several places (**3**). At present it is unclear whether this is related to human activities (dredging) or not.

In the area where the Eems bends north the estuary is deep and reaches below -15 m. In general the deepest parts have shifted towards the east with relatively low rates of 2-5 m/yr (**4**). Also in front of the Eemshaven the estuary is deep, most likely due to dredging. The deepest parts have widened on both sides with rates as high as 20 m/yr, but on average about 5 m/yr (**5**). Seaward of the Eemshaven area (Figure 3.2), the east side of the main channel (Westereems) shows erosion at several places with the highest rates in the ebb-tidal delta area (**6**). The west side shows little erosion, except directly north of Rottumeroog where strong erosion occurred, on average with rates of 25 m/yr, but with maximum rates of 40 m/yr (**7**). In many places the -15 m contour line expanded on both sides of the deepest parts of the Westereems, meaning that the deepest parts have increased considerably in area (**8**).

The tidal channels west and east of Rottumerplaat (Figure 3.3) have migrated over large distances (Figure 3.2). In between Rottumerplaat and Rottumeroog the channel shifted east with rates of 6-20 m/yr (**9**), but especially the channels Eilanderbalg and Spruit in between Rottumerplaat and Schiermonnikoog have been very active with rates higher than 30 m/yr being the norm (**10**). At the southern end of the large system (Zuid Oost Lauwers) migration rates drop sharply (**11**). Most of the channels are shallower than -15 m, but in the small part of the Zuid Oost Lauwers that is deeper than -15 m NAP migration rates are high (**12**).

3.2 Friesche Zeegat

In the ebb-tidal delta area of the largest channel system, Westgat-Zoutkamperlaag (Figure 3.3), the main flow shifted to the northwest, resulting in a large expansion of the area below -6 m (**13**) and with average erosion rates above 30 m/yr (Figure 3.5). South of the Engelmansplaat this channel system migrated towards the west with rates of mostly 4-10 m/yr (**14**). At its landward end erosion rates drop to an average of 3 m/yr (**15**). The area of the Westgat-Zoutkamperlaag that is deeper than -15 m is small and located in the middle of its largest bend (**16**). This area shifted westward with rates of 4-20 m/yr.

The channel system directly south of Schiermonnikoog, het Gat van Schiermonnikoog, migrated with rates of 11-20 m/yr in its western part (**17**) and with lower rates, 1-10 m/yr, in its eastern part (**18**). In the Pinkegat area, directly east of Ameland, the highest rates lie close to 20 m/yr, but average rates are in the order of 6-12 m/yr (**19**).

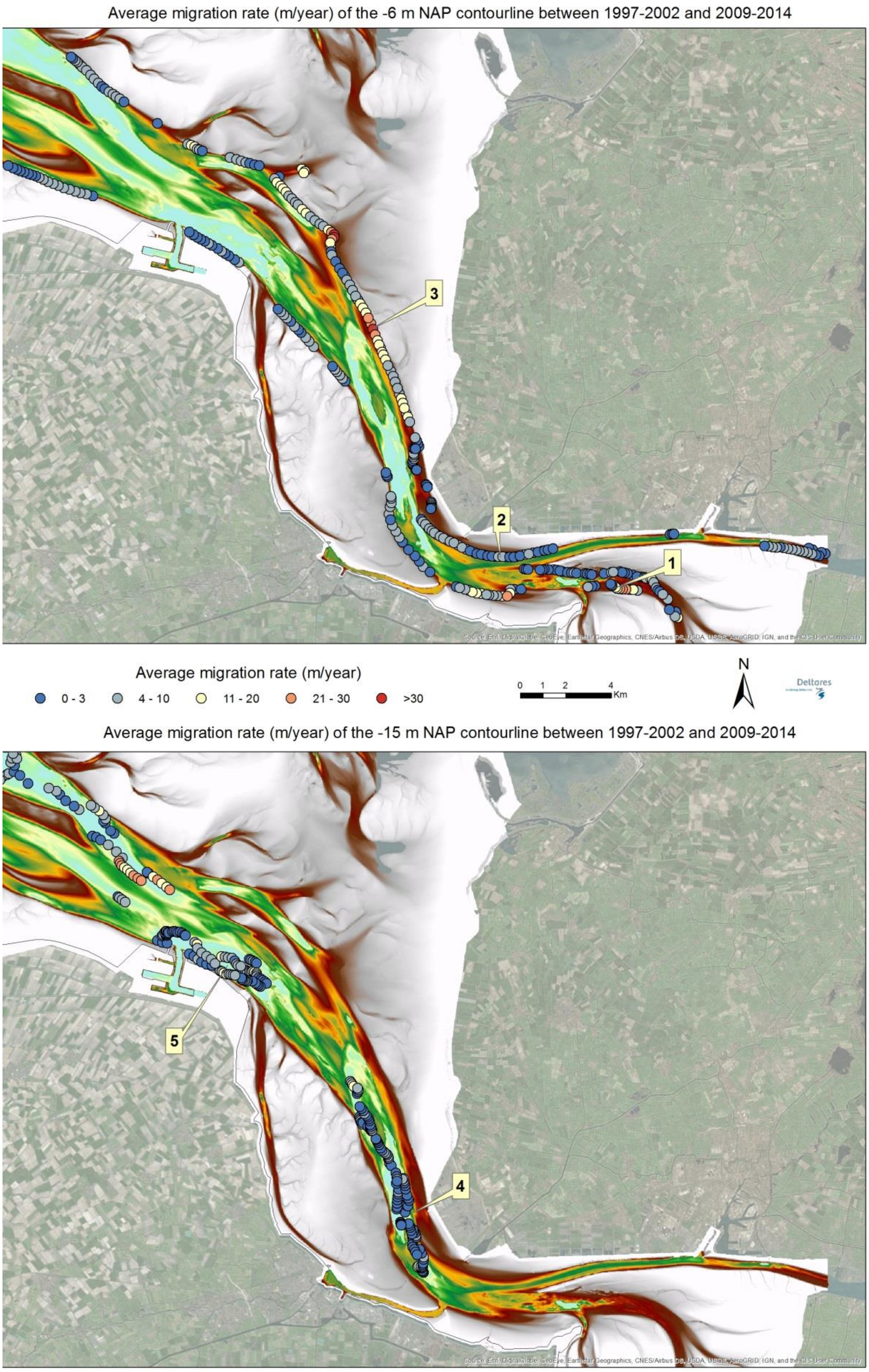


Figure 3.1 Average migration rates for the southern Eems-Dollard region between 1997-2002 and 2009-2014.

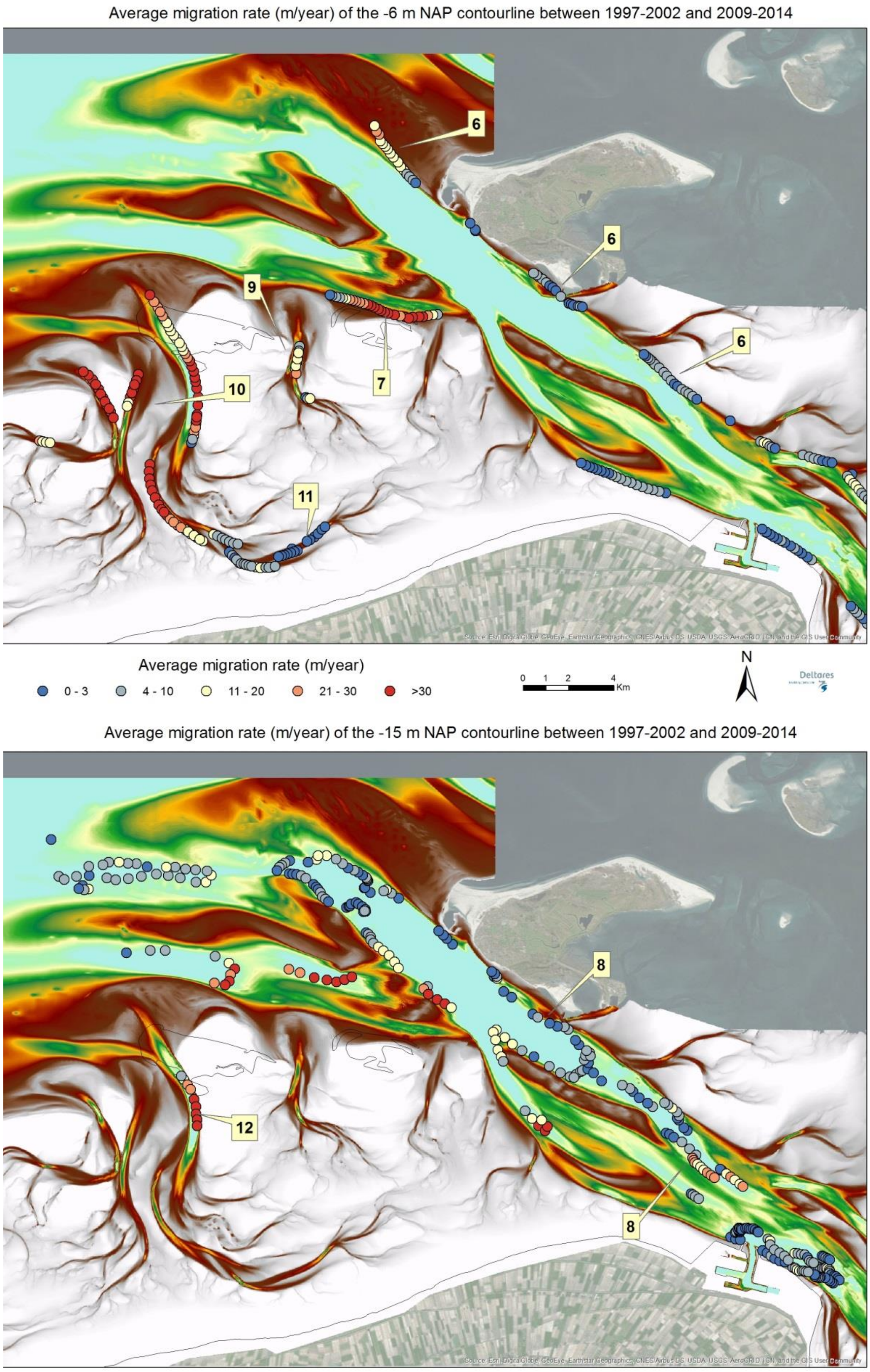


Figure 3.2 Average migration rates for the mouth of the Eems estuary and the Groninger Wad between 1997-2002 and 2009-2014.

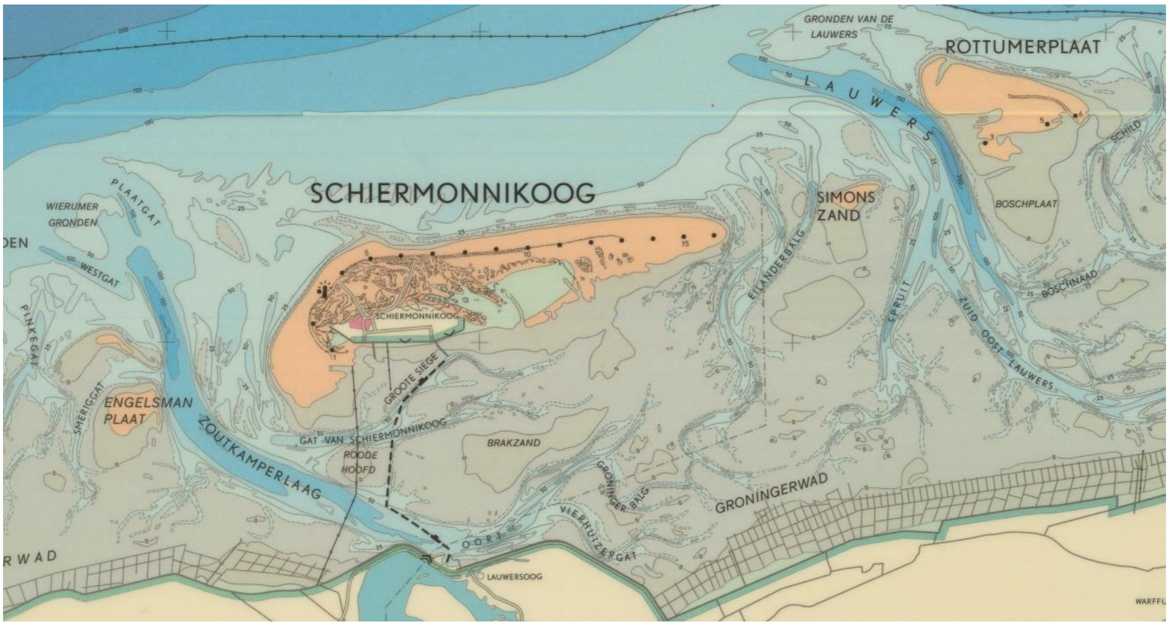


Figure 3.3 Map of the Friesche Zeegat and the Groninger Wad.

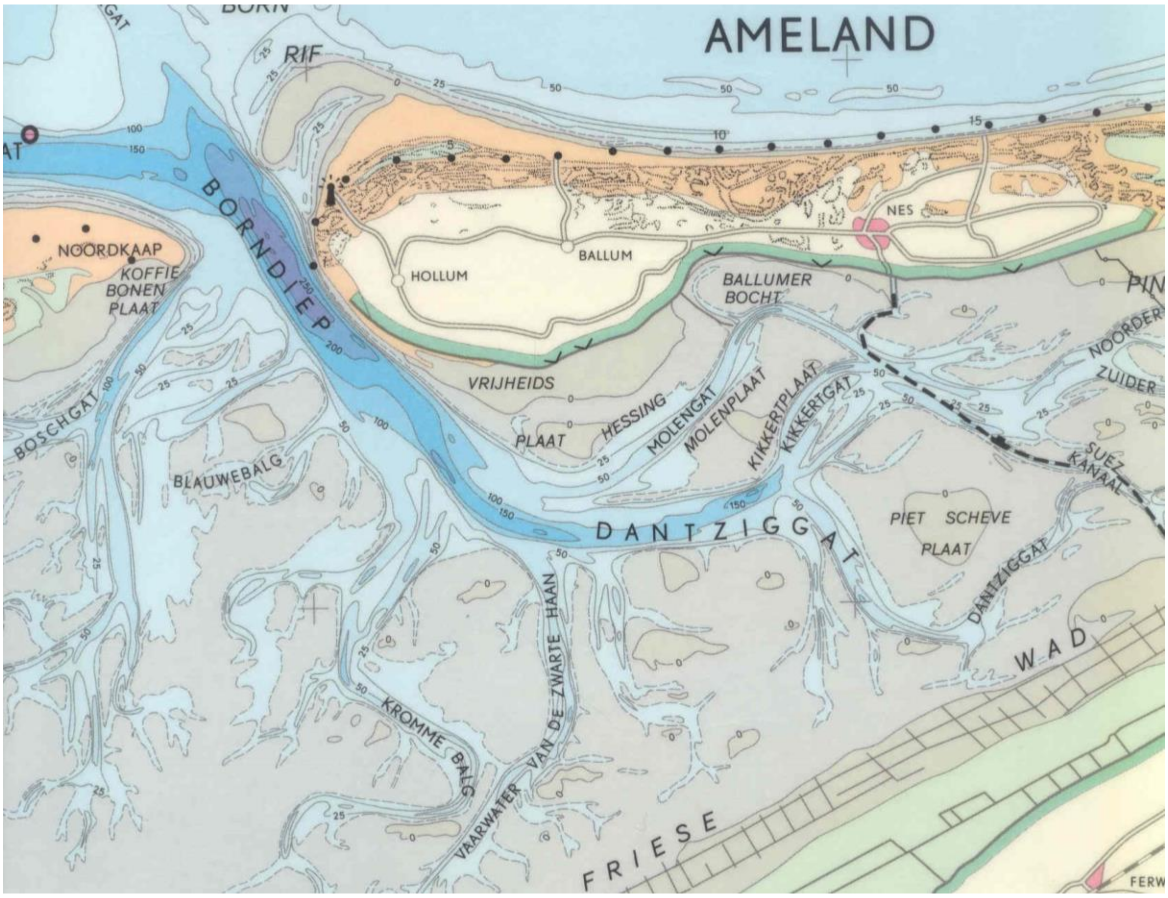


Figure 3.4 Map of the Borndiep inlet.

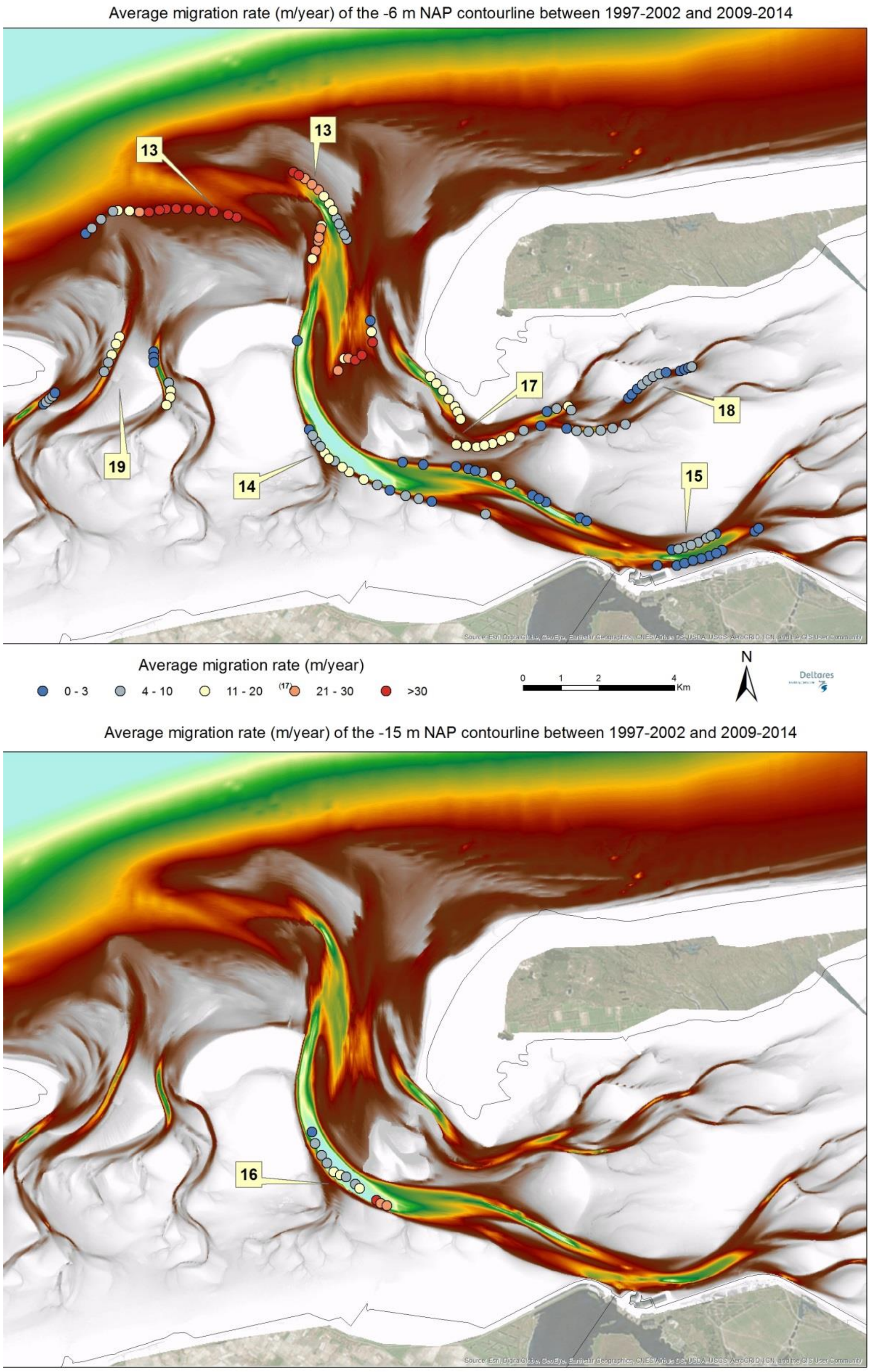


Figure 3.5 Average migration rates for the Friesche Zeegat between 1997-2002 and 2009-2014.

3.3 Borndiep inlet

The main channel in this inlet is the Borndiep that branches off in several directions (Figure 3.4, Figure 3.6). At the tip of Ameland the -6 m area has expanded on both sides with about 1-5 m/yr (**20**). Similar migration rates, but mostly on the western side, can be seen for the -15 m contour line (**21**).South of Ameland the Borndiep has widened considerably, especially on its eastern side, with average rates of 15 m/yr (**22**). Because migration due to sedimentation is not analysed it is not visible in the figure, but the area deeper than -15 m decreased considerably in surface area south of Ameland (**23**). High migration rates are calculated for the most southern end of the area below -15 m (**24**).

The direct extension of the Borndiep, the Dantziggat, shows relatively high average migration of 12 m/yr (**25**), while the small channel directly south Ameland, the Molengat, was rather stable (**26**). The other small channels in the eastern part show high migration rates, in the order of 3-13 m/yr, possibly influenced by maintenance of the navigation route between Holwerd and Ameland (**27**). The southwestern branch of the Borndiep shifted towards the west with rates of 3-15 m/yr (**28**). Finally, the channel southeast of Terschelling, the Blauwe Balg, shifted considerably toward the east with rates up to 45 m/yr, but with average rates around 25-30 m/yr (**29**).

3.4 Vlie inlet and Eierlandse Gat

The Vlie inlet (Figure 3.7, Figure 3.8) is dominated by the Vliestroom (**30, 32**) that branches towards the east (Westmeep, **31**). Large parts of the Vliestroom are deeper than -15 m. Directly south of the tip of Terschelling the channel migrated northward with rates of 2-10 m/yr (**33**), while to the south the channel migrated mainly westward but with similar rates (**34**). The northernmost bend in the Noordmeep migrated north with rates as high as 20 m/yr, but commonly with rates between 1-8 m/yr (**35**). The deep part in the Boomkensdiep migrated over 500 m towards the south (**36**), while the deep part of the Schuitengat remained rather stable (**37**). The western part of the Zuiderstortemelk, north of Vlieland, moved towards the south (**38**), while the eastern part shifted a little northward (**39**).

When all shifts of the -6 m contour line are averaged, this results in a rate of 4-5 m/yr, with a largest rate of 26 m/yr. Compared to the channel systems described in paragraphs 3.1-3.3 channel migration rates do not decrease visibly towards their landward ends. In contrast, several of them, e.g. the Oostmeep (**40**) and the navigation channel to Harlingen (**41**), show high migration rates in their eastern part. The navigation channel is obviously maintained, so the observed migration is likely strongly influenced by human activities. Most systems show erosion on one side, signifying migration, but some show erosion on both sides, signifying widening. This latter is e.g. true for the Noorderbalgen (**42**), the Vliestroom and parts of the navigation channels towards Harlingen. The most dynamic areas consist of the area north of the Richel (**43**), the area directly south of the point where the navigation channel meets the Vliestroom (**44**), the north side of the Noordmeep (**45**) and the eastern end of the Oostmeep (**40**).

The Eierlandse or Engelsman Gat, the inlet between Texel and Vlieland is rather small and contains no parts deeper than -15 m. Near the tip of Vlieland migration rates are relatively high with an average of 13-15 m/yr (**46**). Further eastward, erosion rates drop to an average of 3 m/yr (**47**). In many places erosion occurred on both sides, meaning that at those locations the channels have widened.

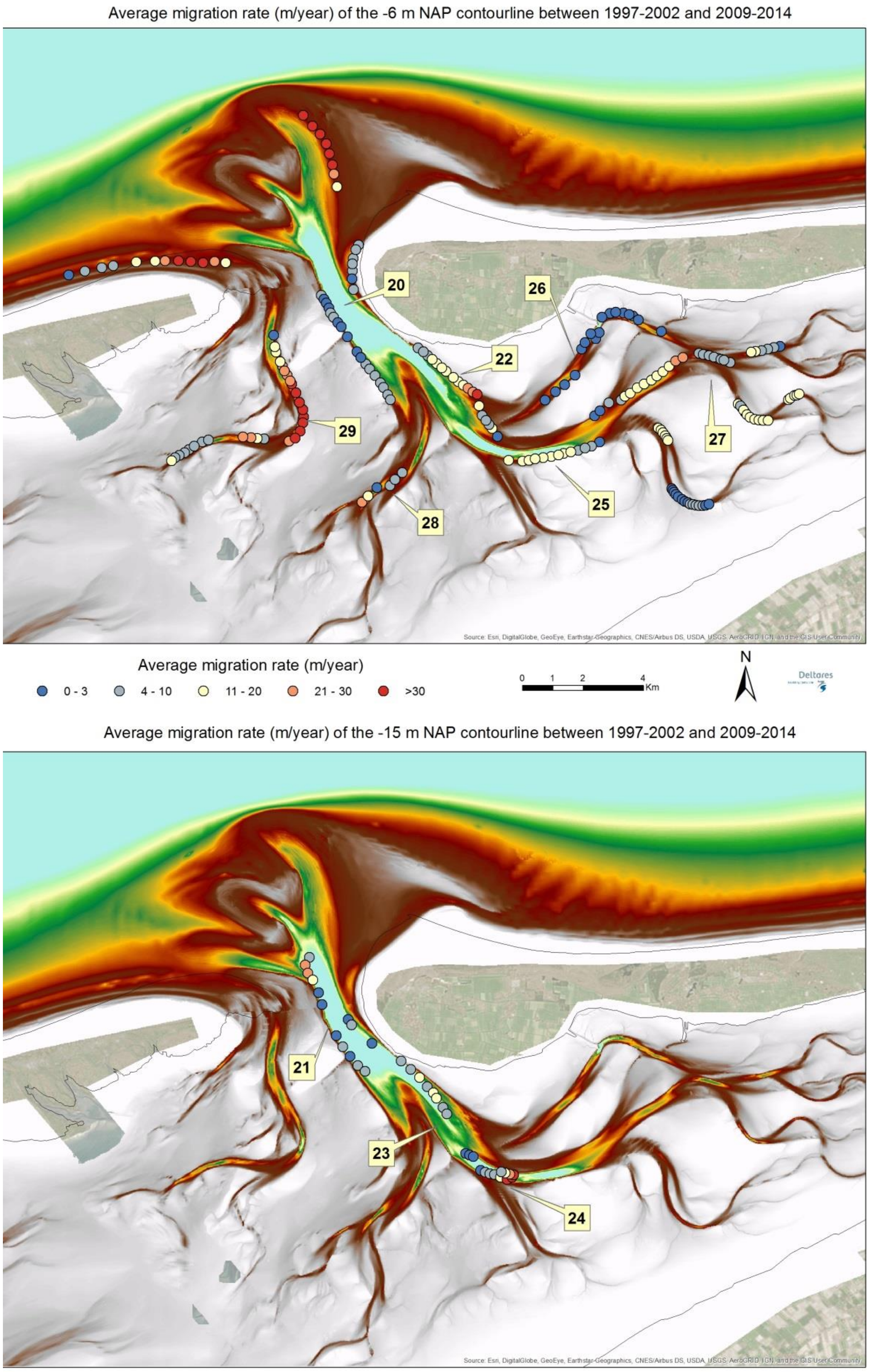


Figure 3.6 Average migration rates for the Borndiep inlet between 1997-2002 and 2009-2014.

Figure 3.7 Map of the Vlie inlet and Eierlandsche Gat

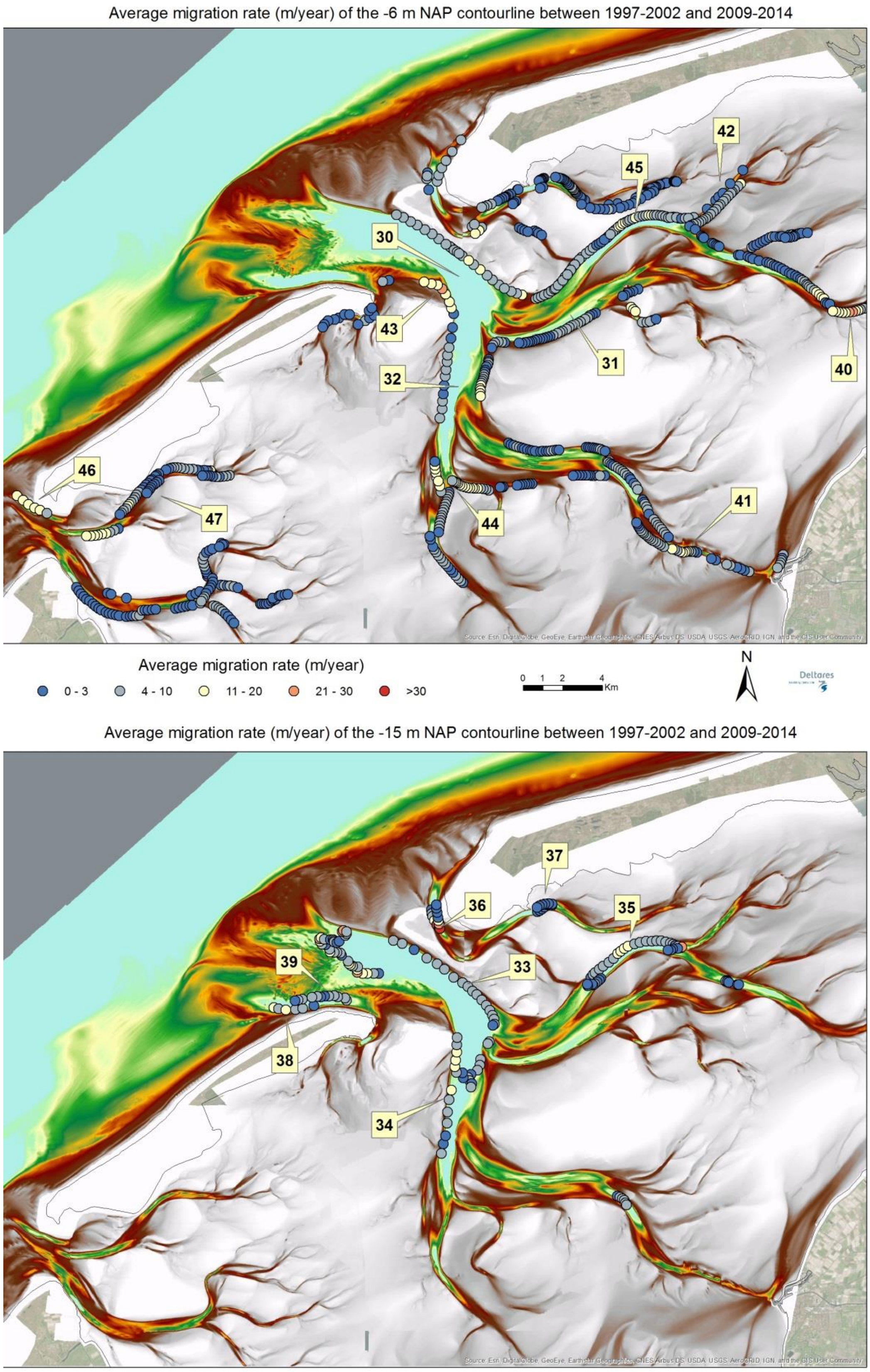


Figure 3.8 Average migration rates for the Vlie-Eierlandsche Gat between 1997-2002 and 2009-2014.

3.5 Texel inlet

The Marsdiep-Texelstroom system (**48)** is very large and for a large part deeper than -15 m (Figure 3.9, Figure 3.10). From its western end until the point where the channel starts to bend eastward the -15 m contour line shifted on both sides of the channel. Migration rates are commonly only a few m/yr, partly due revetments in areas where the channel edge lies close to the main land, e.g. around the tip of North-Holland and along Texel. The smaller pockets with deep water near the start of the Doove Balg (**49)** and also in the Malzwin (**50)**, migrated in an easterly direction. Offshore the Nieuwe Schulpengat shifted landward with average rates of 8 m/yr, but in its southern part rates are as high as 16 m/yr (**51**).

Concerning the -6 m contour line it is clear that migration rates commonly are 1-5 m/yr. More active areas are found along the northernmost part of the Texelstroom (**52**), near the landward end of the Omdraai-Oude Vlie (**53**), in the Vogelzand-Burgzand area (**54**) and in the Doove Balg (**55**). Relatively high rates of migration are also found southwest of Kornwerderzand (**56**).

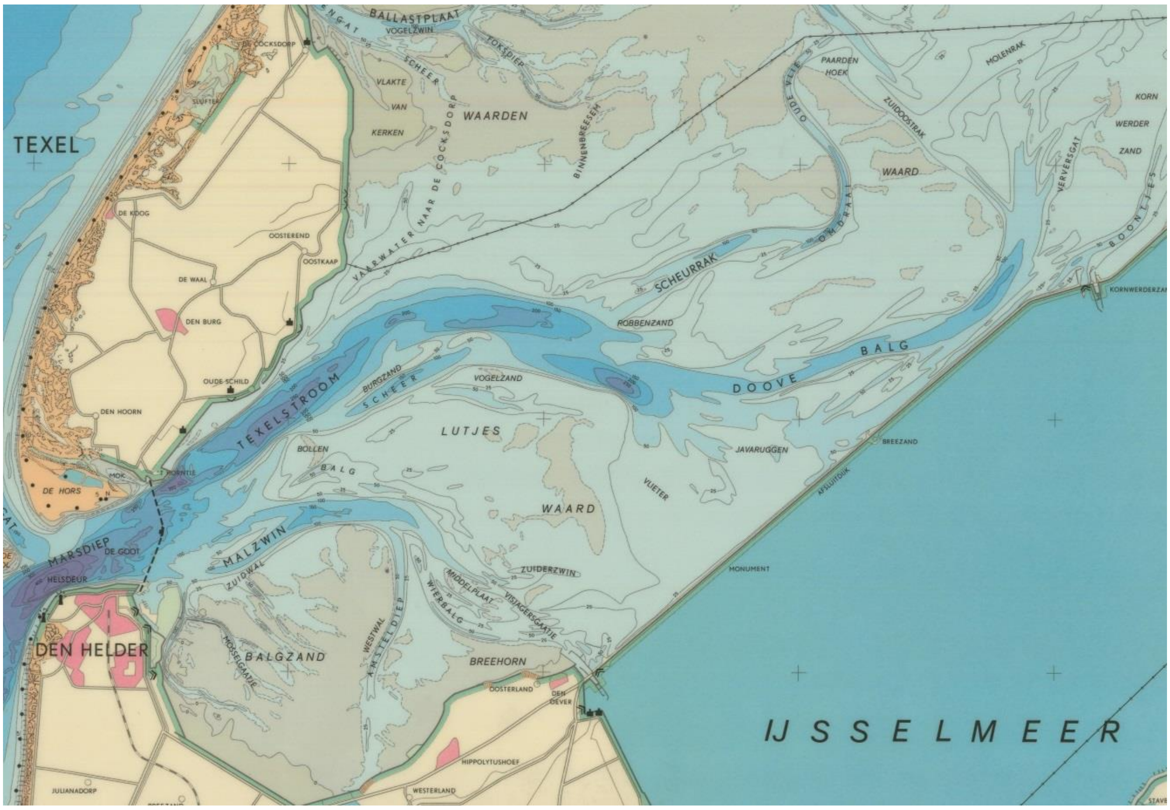


Figure 3.9 Map of the Texel inlet

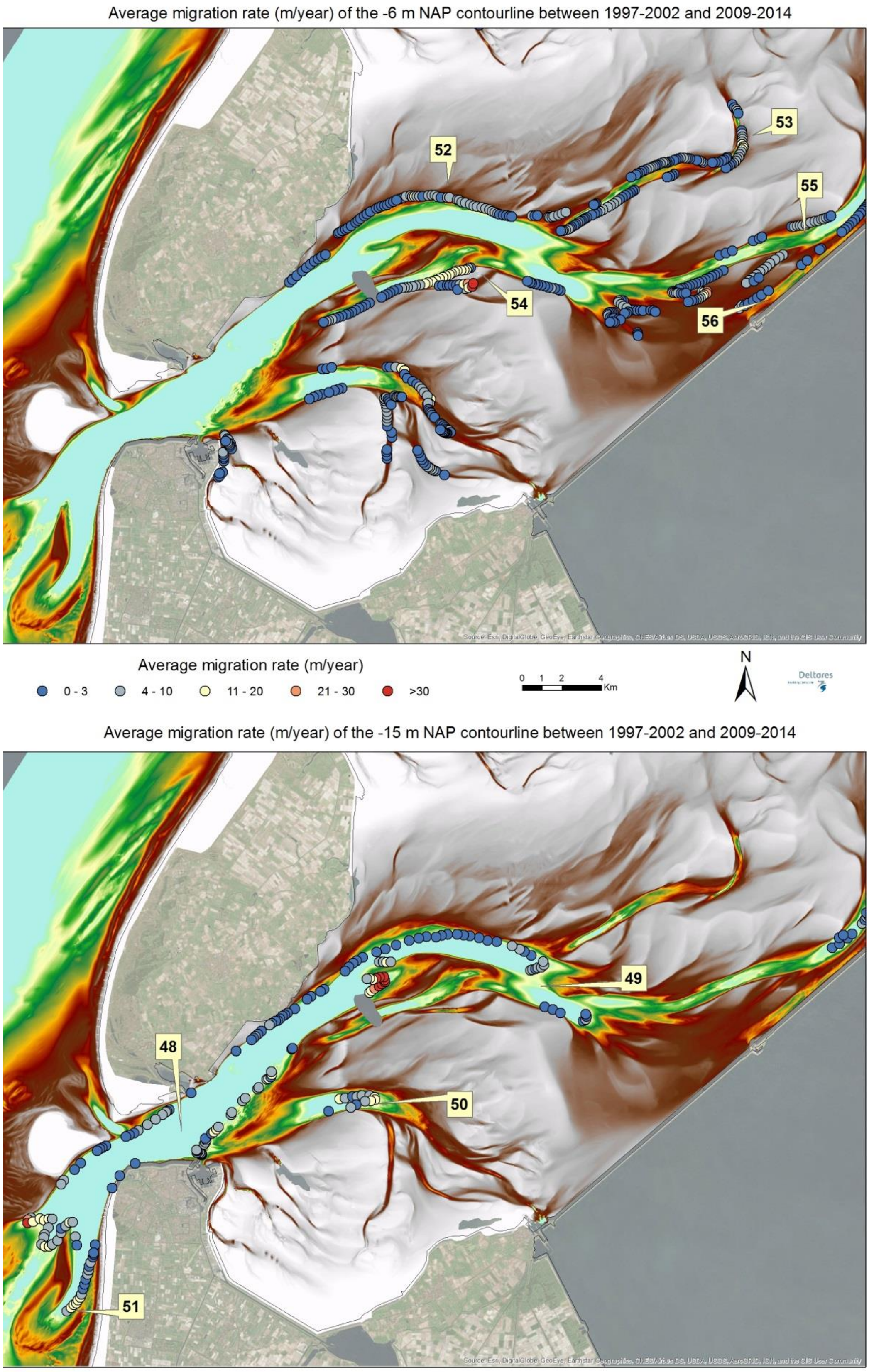


Figure 3.10 Average migration rates for the Texel inlet between 1997-2002 and 2009-2014.

3.6 Oosterschelde-Grevelingen

There are hardly any erosional patterns visible along the -15 m contour line (Figure 3.11), except for some offshore pockets that have shifted (**57**). The shifts in the -6 m contour line show that the offshore shoals are eroding rapidly at several places. While several shoals are eroding on one side only, like north of the Brouwershavensche Gat (**58**) and the shoals Hompels (**59**) and Noordland (**60**), the Banjaard (**61**) is eroding on all sides with average rates of 25 m/yr and with maximum rates of ~60 m/yr. The Krabbengat (**62**) along the tip of Schouwen has widened slightly. The channels in the closed-off Grevelingen did not migrate due to the absence of tidal currents, but also in the Oosterschelde estuary the channels, especially their deeper parts, show little migration.

3.7 Westerschelde

The mouth of the Westerschelde contains an important, deep and heavily managed navigation channel towards the estuary entrance and the harbour of Antwerp (Figure 3.12). Several parts are maintained by dredging and hence observed migration patterns are certainly not only the result of natural processes.

The Wielingen channel (**63**), along the south side of the Vlakte van de Raan (**67**), shows a relatively stable -15 m contour line although at several places erosion rates reach 5-10 m/yr. The channel along the tip of Walcheren, the Oostgat (**64**), has been stable, except for an expansion of the deeper part of the channel towards the north. The stability is predominantly the result of a sand nourishment of almost 10 Mm^3. The -6 m contour line indicates relatively strong migration rates of the shallower shoals in the outer delta area. West of the Oostgat, the Bankje van Zouteland (**65**) and the Deurloo (**66**) mostly migrated towards the east with rates of 5-15 m/yr, but at some place with more than 20 m/yr. The highest part of the Vlakte of the Raan was strongly eroded on several sides (**67**).

The channels in the Westerschelde estuary (Figure 3.9) show significant shifts of both the -15 m and the -6 m contour line, except for areas where the channel lies very close to the shoreline and migration is prevented by revetments. The highest rates for the -15 m contour line can be found in the Everingen-Middelplaat region (3-26 m/yr, **68**), along the Platen van Hulst (5-28 m/yr, **69**) and the east side of the Zuidergat (4-24 m/yr, **70**). Also the -6 m contour line shifted considerably in the Everingen-Middelplaat region (4-30 m/yr), but also along the east side of the Pas van Borssele (10-15 m/yr, **71**), the Platen van Ossenisse (8-20 /yr, **72**) and the southeast side of the Plaat van Walsoorden (8-20 m/yr, **73**) migration rates were high.

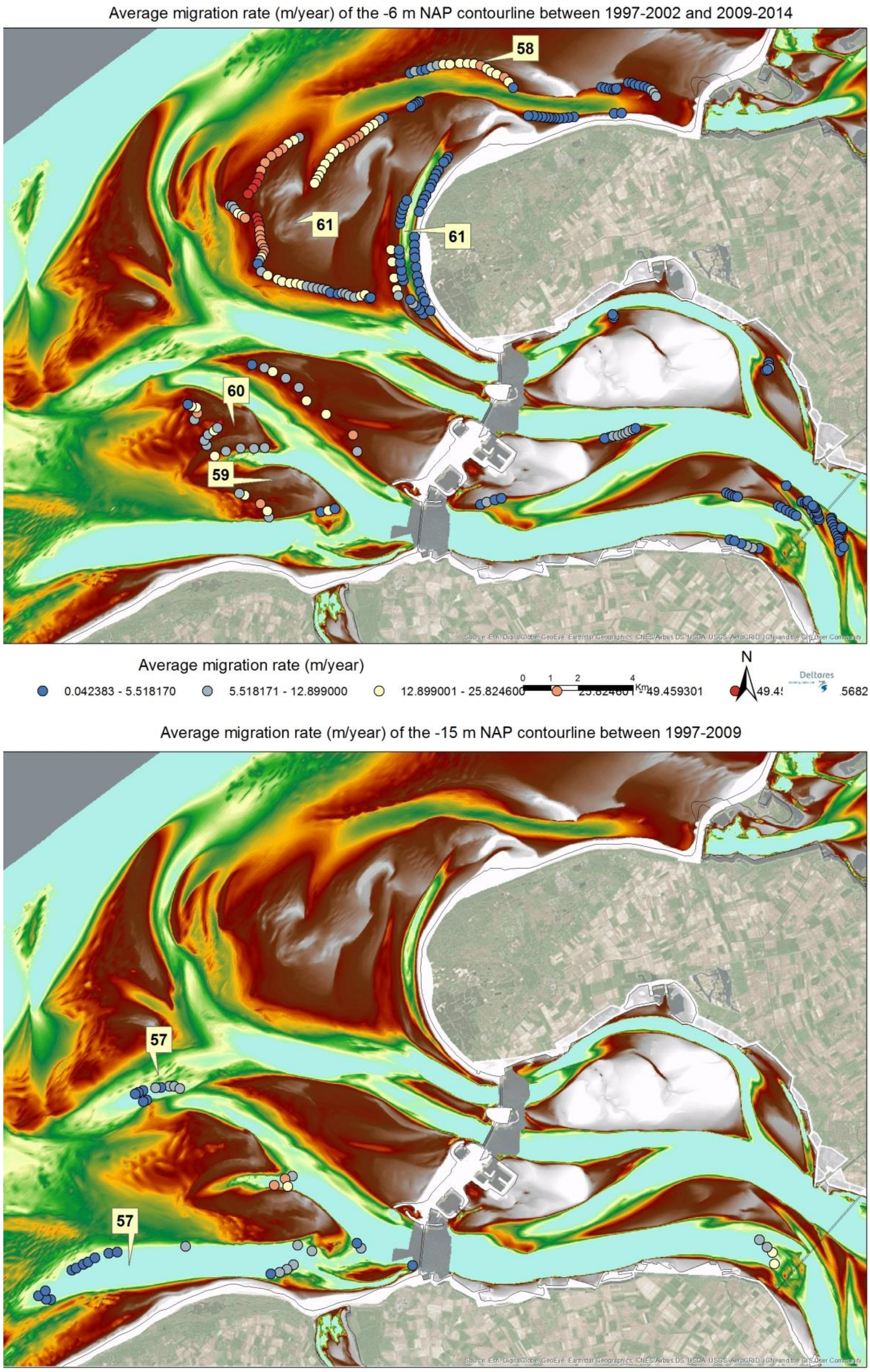


Figure 3.11 Average migration rates for the Oosterschelde-Grevelingen region between 1997-2002 and 2009-2014.

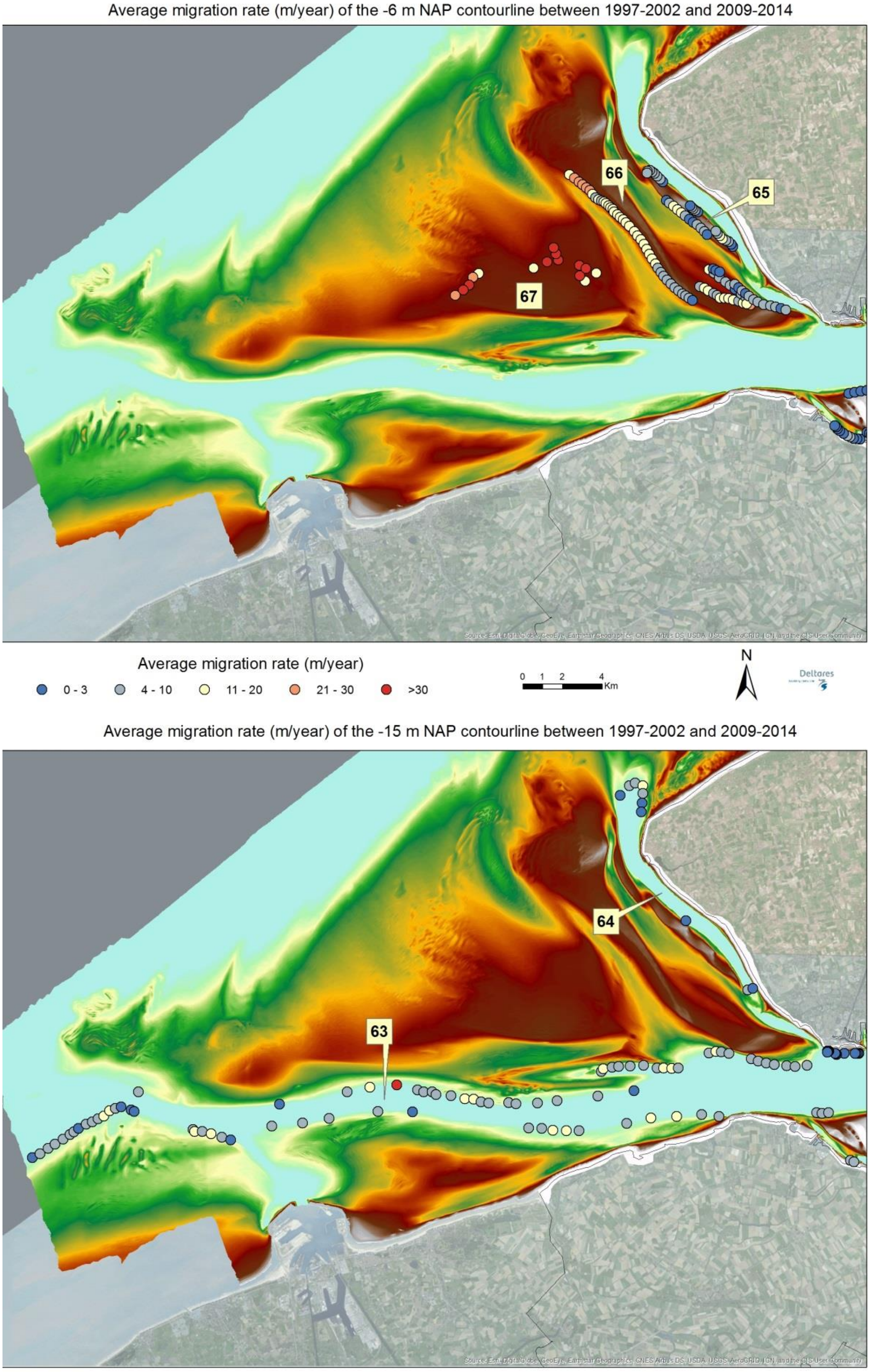


Figure 3.12 Average migration rates for the mouth of the Westerschelde between 1997-2002 and 2009-2014.

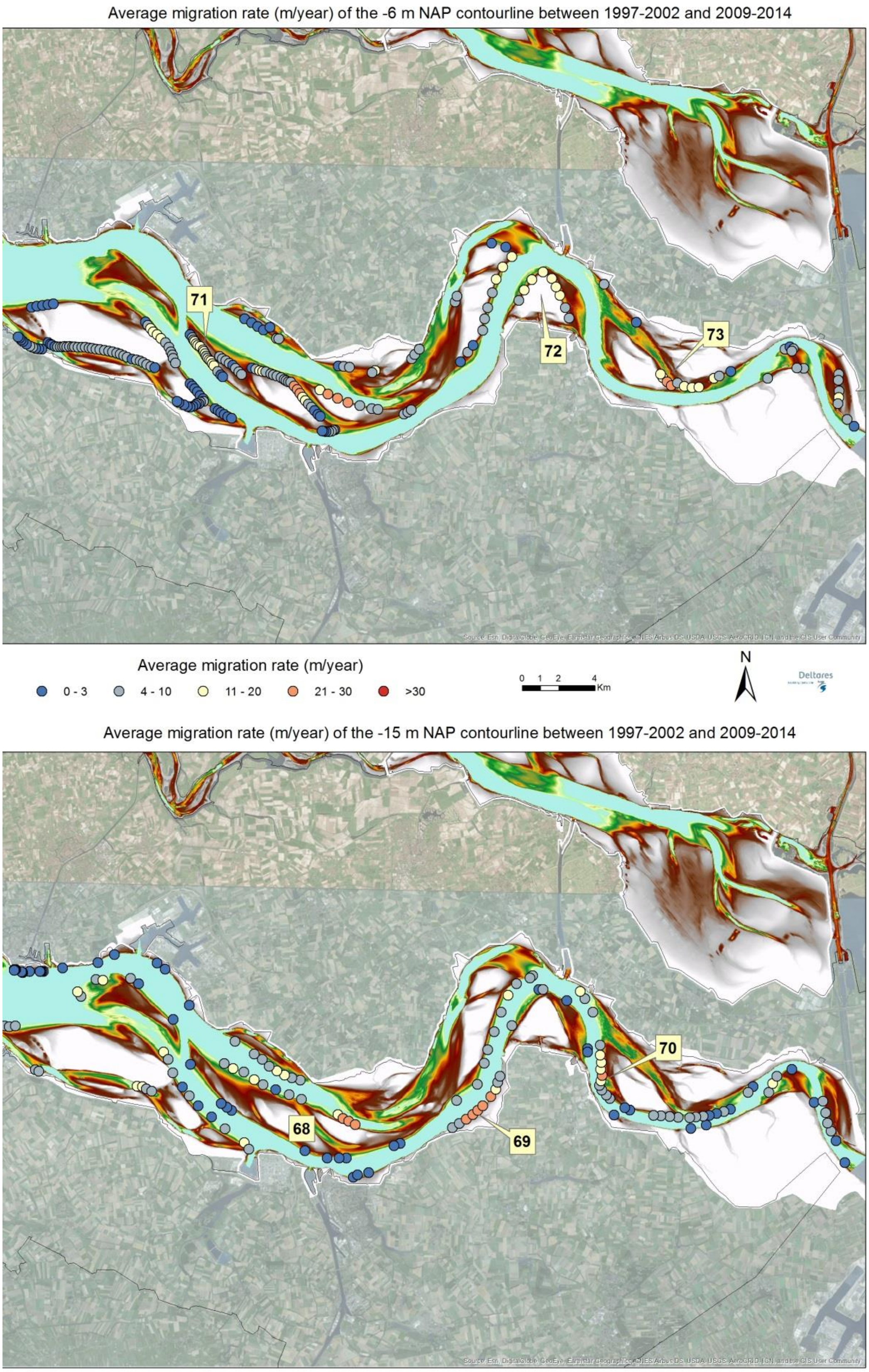


Figure 3.13 Average migration rates for the Westerschelde estuary between 1997-2002 and 2009-2014.

4 Discussion: migration rates and geology

The figures below show the calculated migration rates together with the area where erosion-resistant deposits are most likely present. The numbering of the areas with these deposits corresponds with the numbering in Hijma (2017a). Below the relation between these deposits and migration rates is explored for three regions: Eems-Dollard-Rottumerplaat, Wadden Sea and Zeeland, followed by an analysis of thalweg migration over longer periods of time.

4.1 Eems-Dollard-Groninger Wad

Is this region the erosion-resistant deposits consist of Holocene clay and peat layers, and Pleistocene till and Potclay (Figure 4.1; Figure 4.4). The Pleistocene deposits commonly lie deeper than -6 m NAP, only in geological area *29* there is a small chance that Potclay occurs shallower. This means that it are Holocene peat and clay layers that are relevant for the migration rate of the -6 m contour line. It should be realised that in most areas the data density is limited and in many cases it will not be possible to have direct borehole information for an area where there is an apparent change in the rate of erosion. This applies especially to the German side of the Eems estuary, e.g. east of Eemshaven, where clear differences in migration rates are found, but no subsurface information is available.

In general migration rates of the -6 m contour line are low. One anomaly is formed by a small section on the south side of the Groote Gat where migration rates are locally higher than 21 m/yr and rapid widening has occurred. Zooming in on that specific location shows that four boreholes from 1981 are available (Figure 4.2). In contrast to almost any other available borehole in the area, these four boreholes show that the subsurface consists of sand instead of thick clay and peat layers (Figure 4.3). It is therefore not unlikely that this contrast in subsurface build-up played an important role in defining the area of strongest erosion. This figure also shows the lack of data in the eastern part of the Dollard region. Since no boreholes are available east of these four boreholes, it cannot be concluded with certainty that the drop in migration rates towards the east is due to a return of thick clay and peat layers or due to a change in hydrodynamic conditions.

Another area that stands out with a distinctive change in the rate of erosion is the Zuid Oost Lauwers, directly northeast of geological area *25* (Figure 4.4). Very high rates are visible to the north of this area, but closer to the area the rates drop sharply. Since there is very little information about area *25* it is not yet possible to say if this caused by a change in subsurface build-up, but the information that is available does not indicate substantial layers of erosion-resistant deposits at the -6 m NAP level. So it is possible that the drop in erosion rates should mainly be attributed to a change in hydrodynamic conditions.

Compared to the -6 m contour line the -15 m contour line is rather stable in the Eems estuary. In geological area *29-31* it is possible that this is the result of the presence of Potclay at that level. In front of the Eemshaven, where no Potclay is present within relevant levels, the erosion rates are higher than in areas *29-31*. There is, however, a strong chance of the occurrence of thick Holocene clay layers in the Eemshaven area. The offshore extension of the Eems estuary crosses geological area *27*, an area where Potclay is expected to lie at the base of the channel. It is striking that south and west of this geological area erosion rates are much higher than in the area itself. Since there are hardly any data available, it is again too early to attribute this predominantly to the presence of Potclay in that area, but it is not unlikely that is the occurrence of Potclay plays a significant role in the observed patterns of erosion in this area.

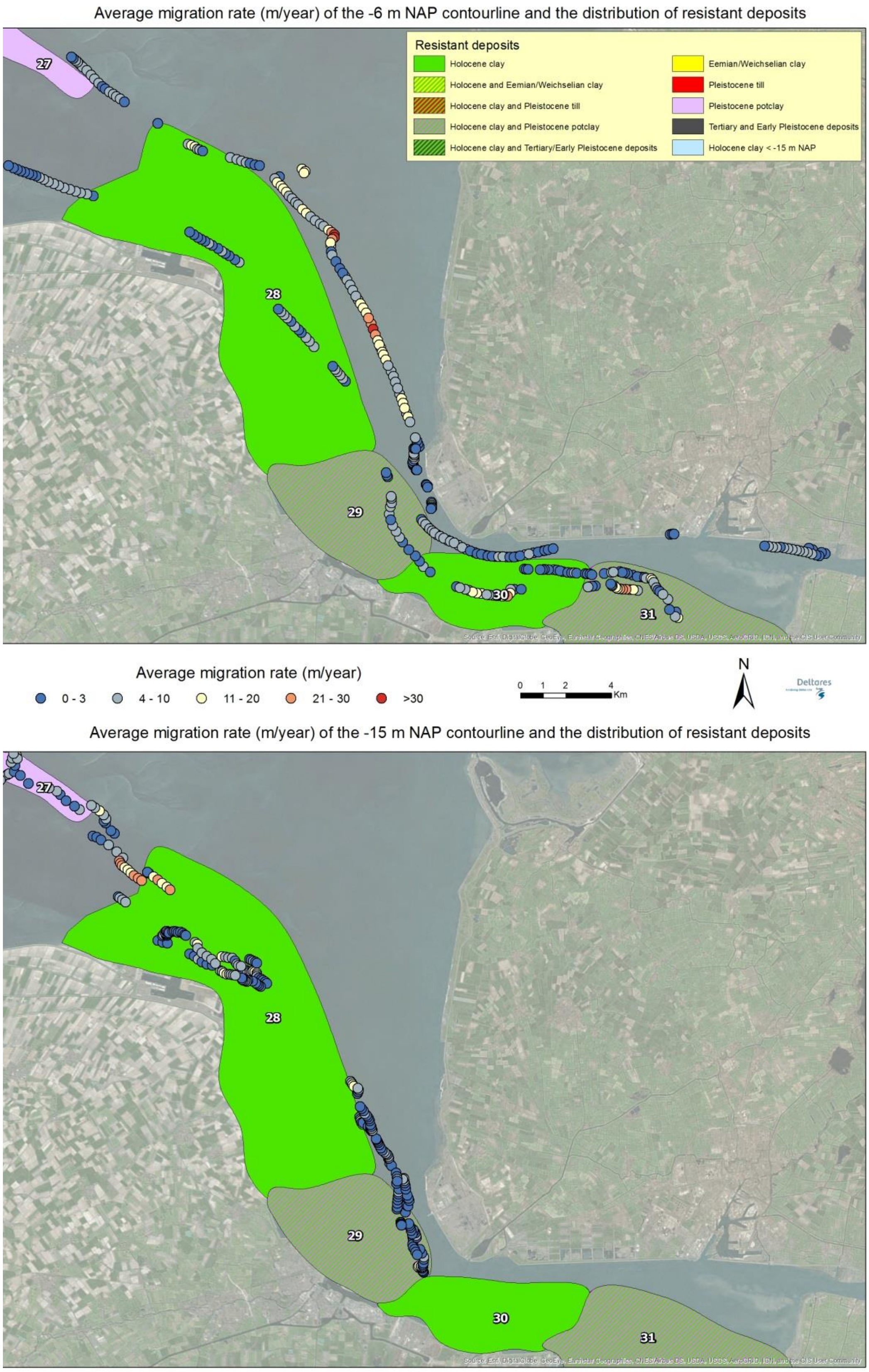


Figure 4.1 Average migration rates for the southern Eems-Dollard region and the distribution of resistant deposits.

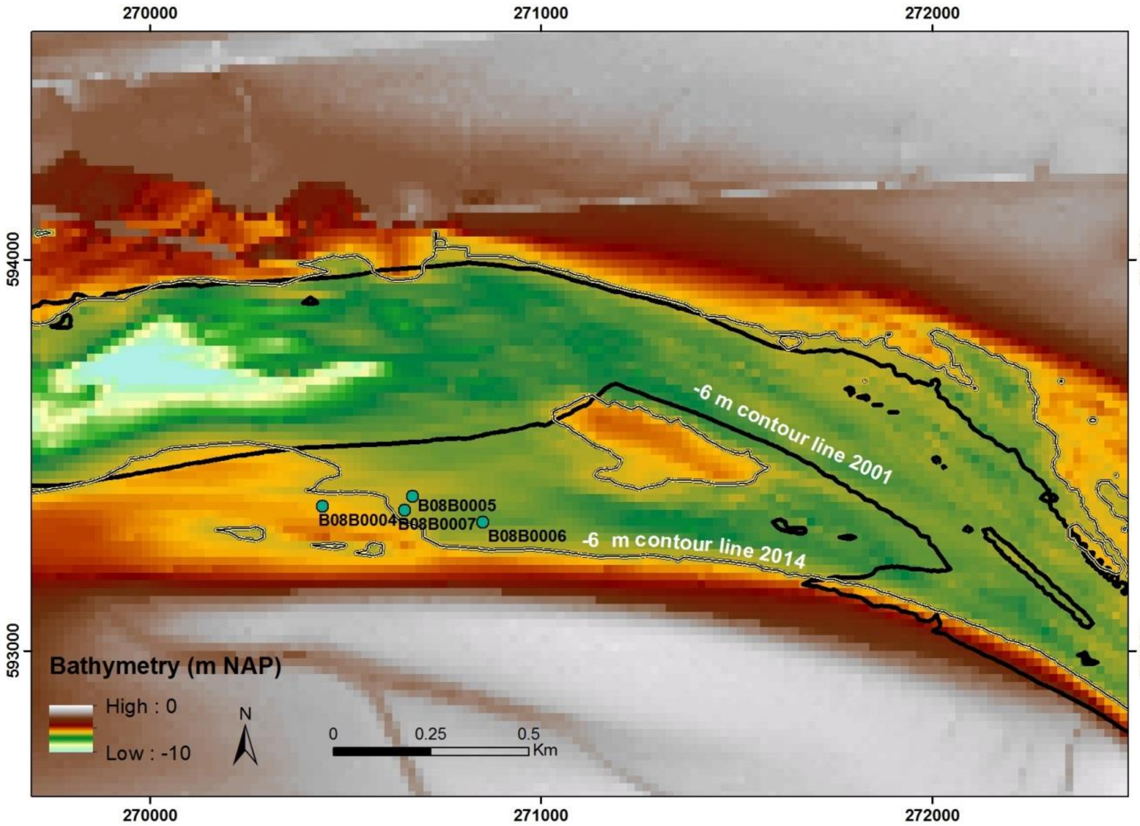


Figure 4.2 Close-up of the Mond van de Dollard-Groote Gat region with the two analysed contour lines from 2001 and 2014. In 13 years the contour line shifted more than 400 m in the central part of the figure, while to the west and east the rate of migration is low or sedimentation occurred.

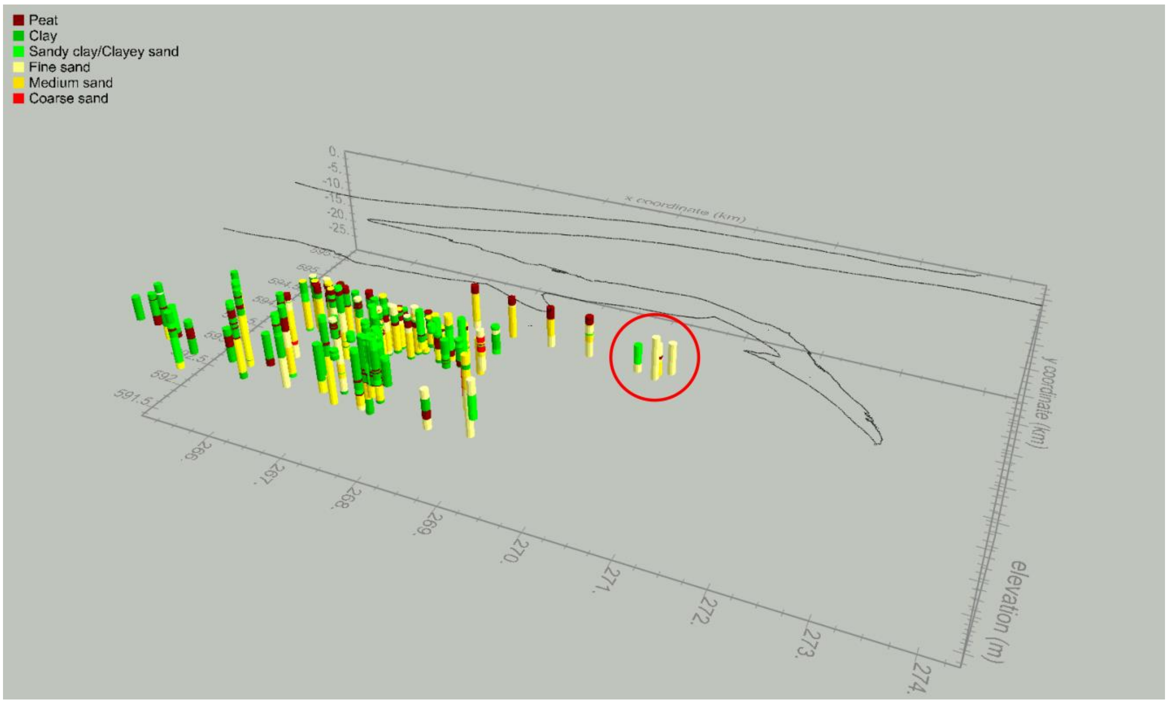
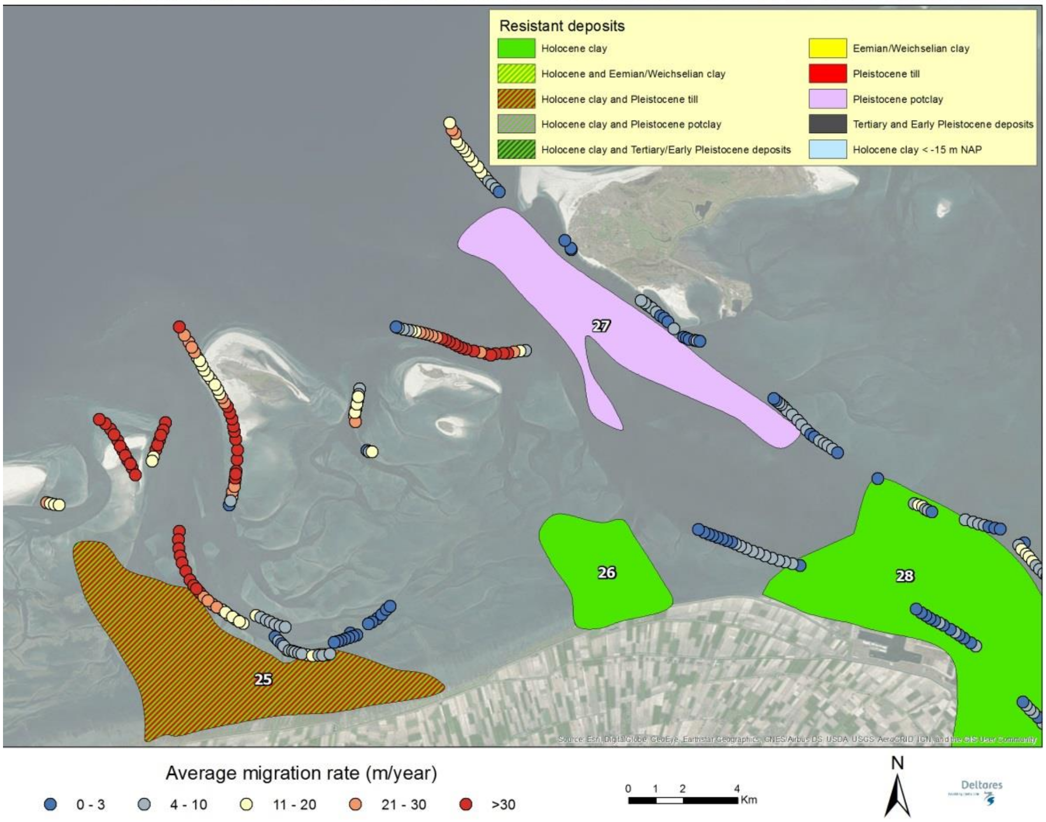


Figure 4.3 3D-plot of several boreholes in the Dollard regional. The black line is the -6 m contour line of 2001 (see also Figure 4.2). The boreholes that are encircled are the four boreholes in Figure 4.2.

Average migration rate (m/year) of the -6 m NAP contourline and the distribution of resistant deposits



Average migration rate (m/year) of the -15 m NAP contourline and the distribution of resistant deposits

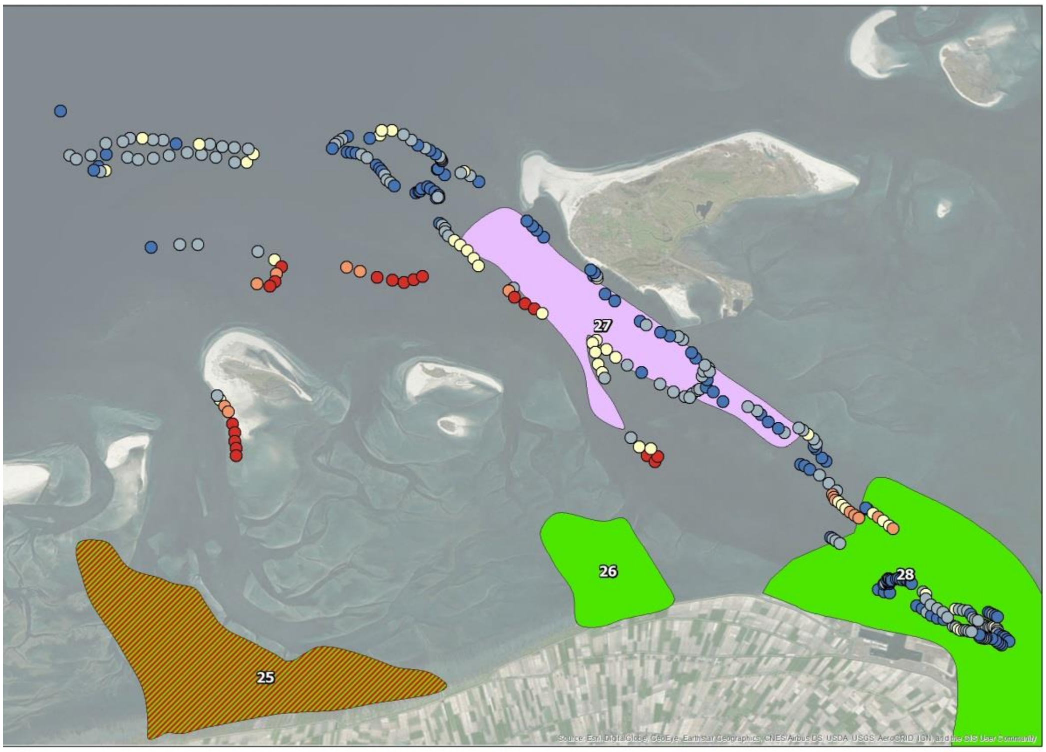


Figure 4.4 Average migration rates for the mouth of the Eems estuary and the Groninger Wad and the distribution of resistant deposits.

4.2 Wadden Sea

When looking at the entire Wadden Sea area there are a few hotspots of -6 m contour line migration. The first one is the area east of Schiermonnikoog that was briefly discussed in section 4.1. A few others are located in the ebb-tidal delta areas of the Borndiep and the Friesche Zeegat. In general there is a landward trend of a decreasing erosion rates that can be attributed to a decrease in size and hence hydrodynamic power of the channels. The importance of hydrodynamics is also apparent from the fact that overall the highest migration rates are observed along the outer bends of the channels.

At -6 m and above, larger patches of erosion-resistant deposits are expected in geological areas *9, 13, 15-17* and *22-23* (mostly Holocene clay and peat layers, possibly till in area *13*). In area *22* no apparent influence of such deposits is present (Figure 4.6); in contrast, the erosion rates are relatively high for channels that far into the basin. In the other areas with erosion-resistant deposits, apart from area *9* where the -6 m contour line of the shoreface was not analysed for this study, migration rates are relatively low. However, in regions where erosion-resistant deposits frequently occur next to sandy deposits, like in the Texel-Vlieland area, no significant differences in migration rates are observed (Figure 4.7, Figure 4.8). A striking feature though is that the mentioned geological areas contain very few tidal channels and that the active tidal channels seem to flow around these areas. Another striking feature is that the tidal inlet between Texel and Vlieland is relatively small and that this is the only inlet that has large patches of erosion-resistant deposits. The question of course is whether the present tidal-channel pattern was influenced by the distribution of the erosion-resistant deposits or if the present distribution of erosion-resistant deposits is the result of erosion by tidal channels. What is known is that this area evolved rather dramatically after the connection of the Flevo Lakes with the North Sea. Before that time the area consisted of relatively high ground with extensive salt marshes, but not with large tidal channels like today (Vos et al., 2011). It is not unlikely that the tidal-channel system that initially evolved and later expanded in size remained rather stable due to the presence of erosion-resistant deposits along the flanks of the channels.

This hypothesis was tested by De Leeuw (2007) who studied the influence of Pleistocene deposits on the apparent stable position of the northern part of the the Vliestroom and the Westmeep. Her conclusion was that indeed these channels have hardly migrated in the last several thousands of years, but that this is very likely not caused by to the presence of erosion-resistant Pleistocene deposits. The channel parts she studied are, however, not embedded within erosion-resistant deposits on both sides and the hypothesis still stands as an explanation for the stable position of the channels in the Texel-Vlieland area. Although the analysis of De Leeuw made use of all available seismic data and borehole information at that time, she rightly concludes that the data density is still insufficient to determine the thickness and distribution of erosion-resistant deposits with enough certainty to assess the influence of these deposits with confidence. A detailed analysis of the profile of channel walls could possibly be used to distinguish between channels that are stable due to certain hydrodynamic conditions or due to the presence of erosion-resistant deposits. In the first case the channel wall is expected to be relatively smooth, while in the latter case the channel wall is expected to be more irregular and featuring one or more plateaus.

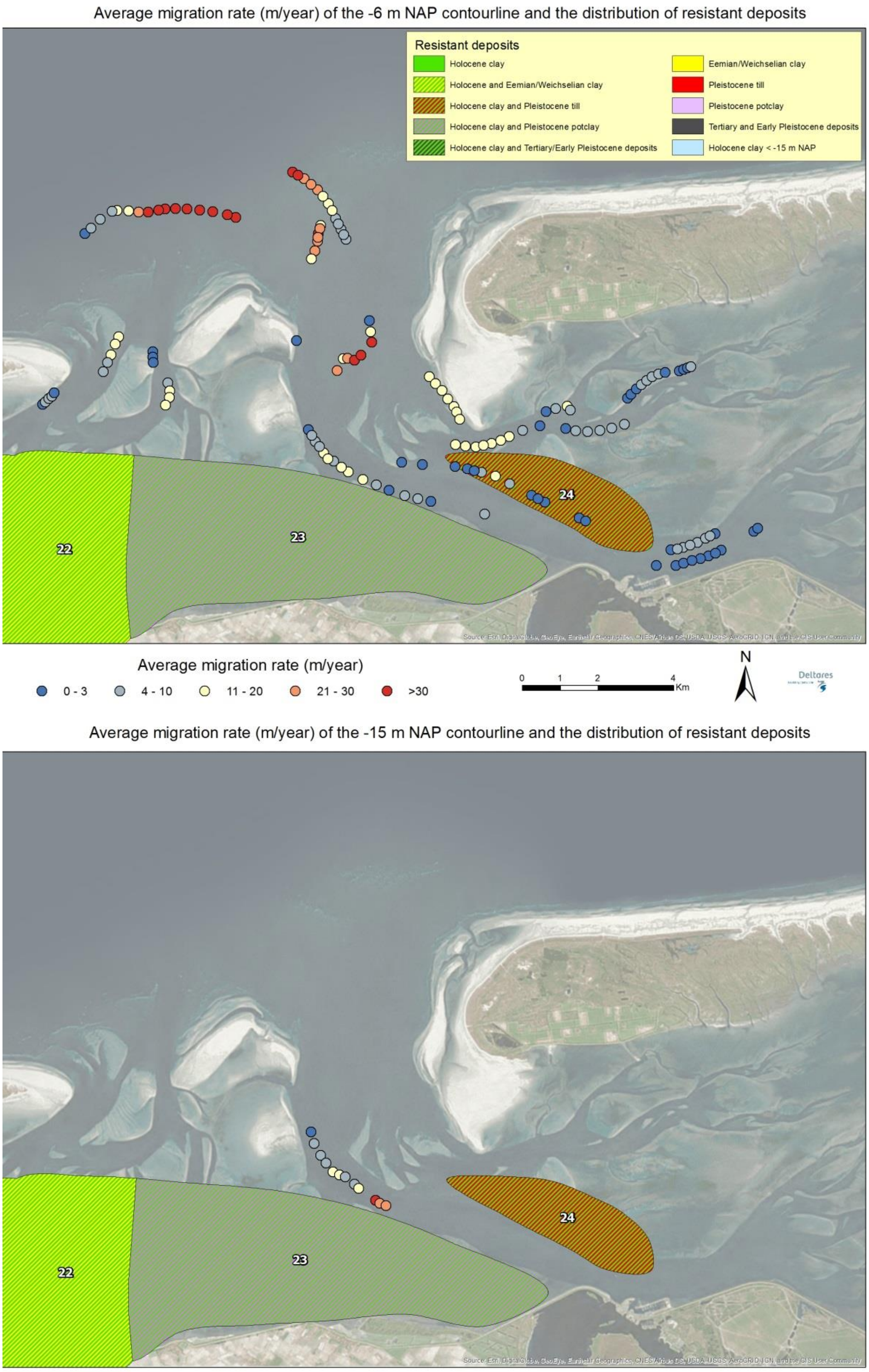


Figure 4.5 Average migration rates for the Friesche Zeegat and the distribution of resistant deposits.

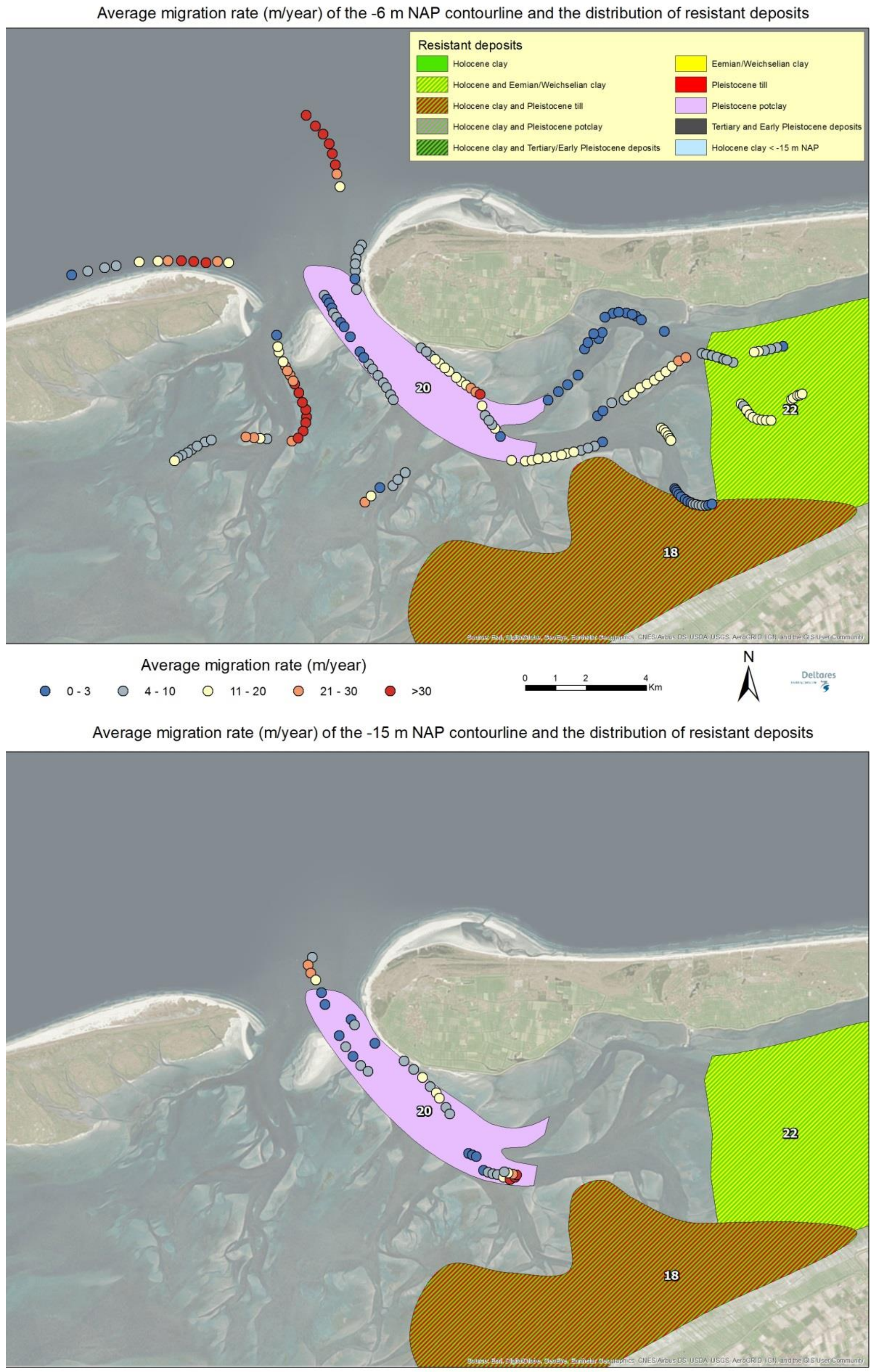


Figure 4.6 Average migration rates for the Borndiep inlet and the distribution of resistant deposits.

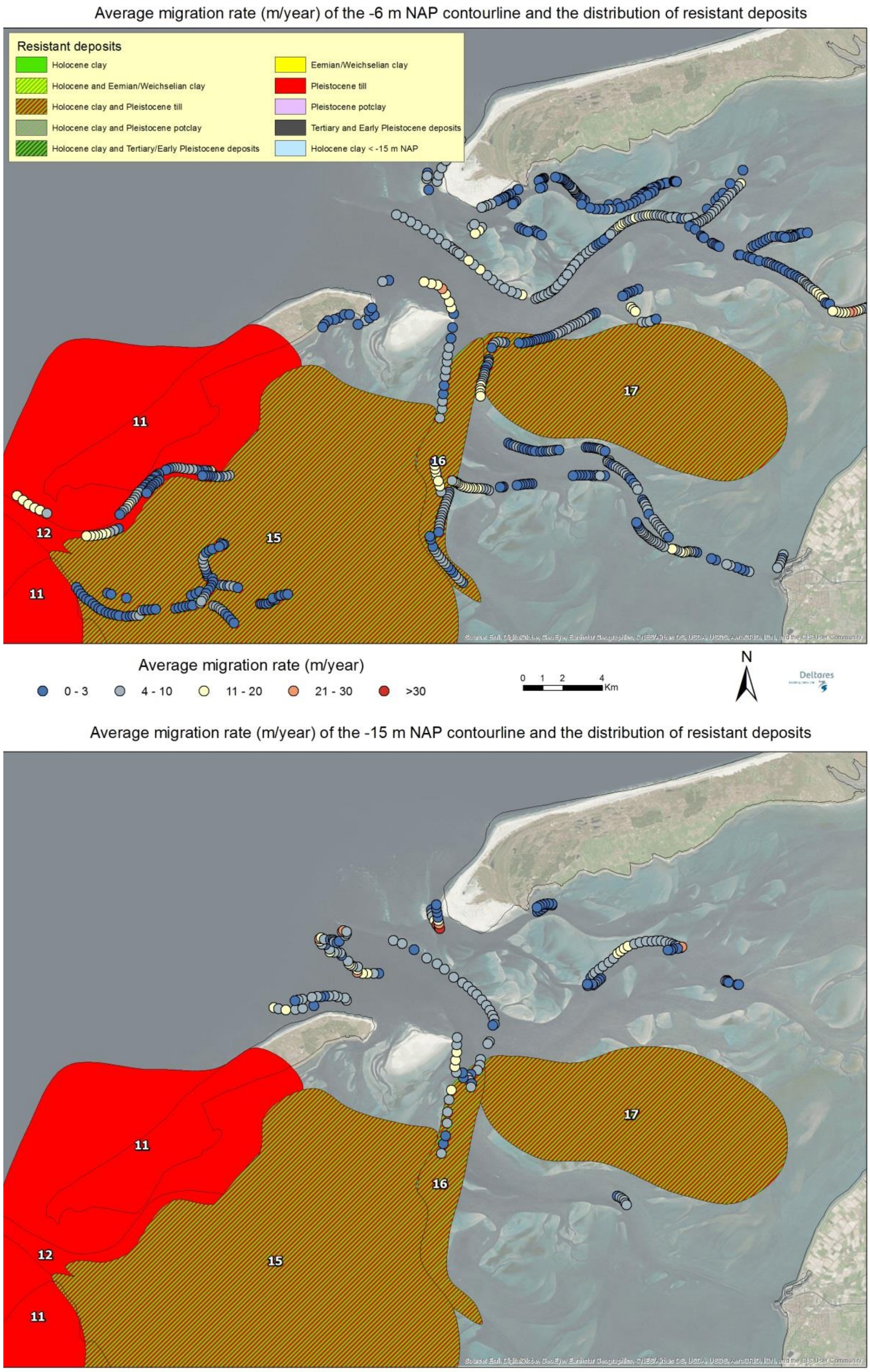


Figure 4.7 Average migration rates for the Vlie-Eierlandsche Gat and the distribution of resistant deposits.

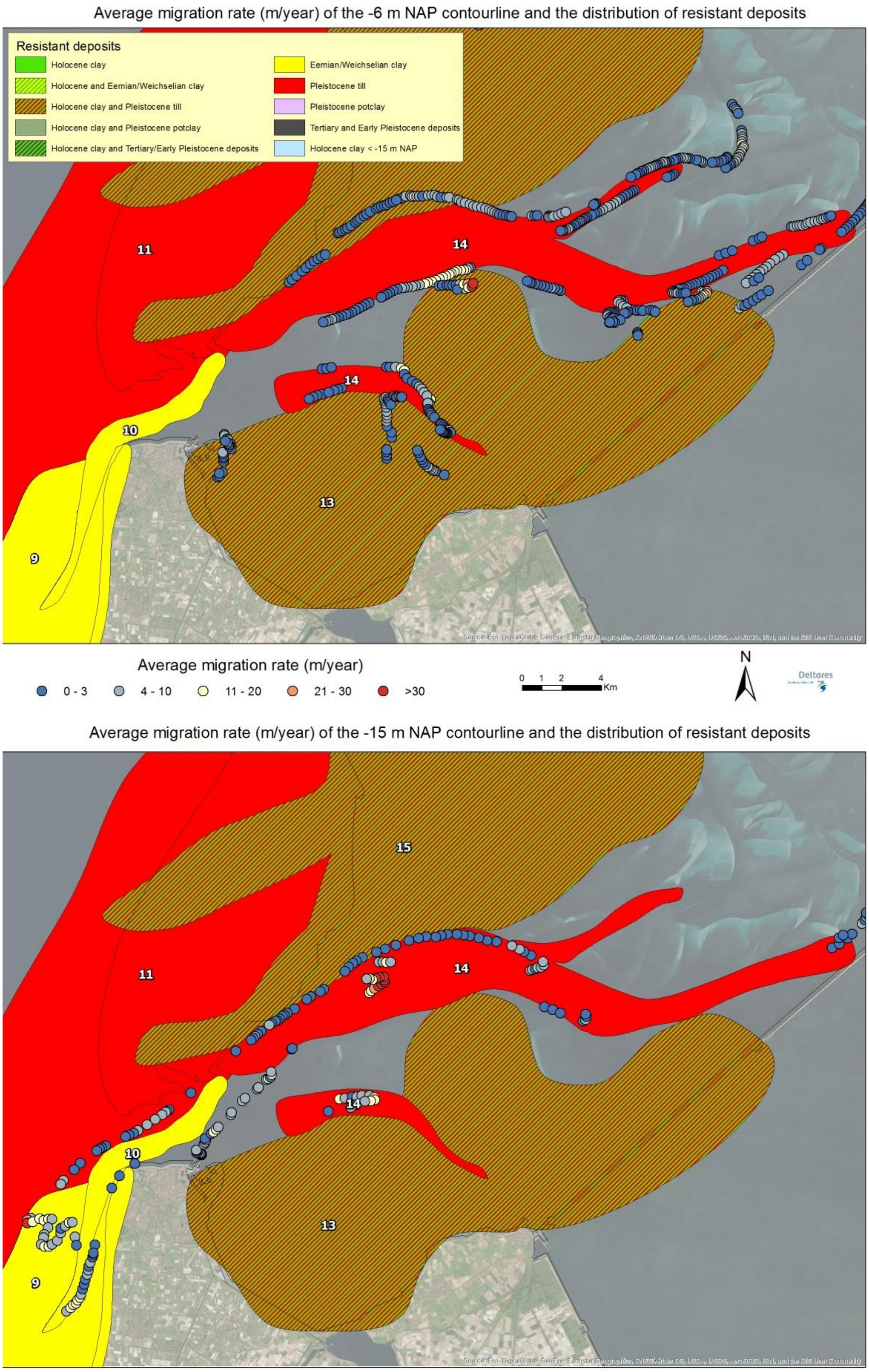


Figure 4.8 Average migration rates for the Texel inlet and the distribution of resistant deposits.

A small section of the Friesche Gat has parts deeper than -15 m NAP. It is located in the outer bend that migrated considerably towards the south. Directly south of this channel lies geological area *23* that has Potclay as high as -12 m NAP in its eastern part. It is likely that this will have an important influence on further southward migration or deepening of the southern part of the Friesche Gat (Figure 4.5). At present it is unknown whether the observed southward migration was caused by erosion of 'old' deposits or whether the channel is meandering within a body of sandy tidal-channel deposits. Such an evaluation requires careful analysis of boreholes or seismic data from before the erosion occurred. Also in geological area *20* (Borndiep, Figure 4.6) Potclay is expected to be of importance, but mainly in preventing the Borndiep from deepening. The Potclay starts at -23 to -25 m NAP (Van der Spek, 1994) and will therefore have limited influence on the rate of migration of the -15 m contour line.

Further towards the west, the -15 m contour line is present in the vicinity of the Vliestroom (Figure 4.7). Except for the southern end of the Vliestroom, where geological area *16* is located, there are no erosion-resistant deposits present that are of influence in this area. In area *16* Pleistocene till is present along the flanks of the channel and the deepest parts of the channel most likely reaches clay layers of the Urk and Eem Formations. In the upper part of the flanks Holocene clay and peat layers are expected. Migration rates are in the order of 2-11 m/yr, so not especially low compared to other sections of the Vliestroom.

In the Marsdiep-Texelstroom area it is clear that in the northeastern part the -15 m contour line has been very stable, while directly northeast of Den Helder it shifted considerably (Figure 4.8). Close to Texel this is most likely related to revetments, but these should not play a role in the part where the channel turns eastward. In that area glacial till is present below -10 m NAP and possibly hinders channel migration, although it is not certain whether the channel wall is in direct contact with the till or that a marine deposit is present in between the channel wall and the till. Since there are no erosion-resistant deposits present directly northeast of Den Helder, the difference in migration rates on different sides of the channel is possibly related to the difference in the build-up of the subsurface.

4.3 Zeeland

Morphological changes in the Western and Eastern Scheldt areas are strongly influenced by human activities, like the construction of the Eastern Scheldt storm-surge barrier and constant maintenance of the Western Scheldt channels by dredging and dumping. This paragraph explores whether the geological build-up of these areas still has an influence on the observed migration rates.

In geological area *4* the erosion-resistant deposits lie deeper than the -15 m contour line and hence they should have no influence on the migration rate of this contour line (Figure 4.9). In the mouth of the Westerschelde (Figure 4.10) the Oostgat channel is relatively stable and has been so for several decades, although this has been achieved only by revetments and nourishments (see also §4.4). Previous work on the Oostgat (Van der Spek, 1997; Hijma, 2017a) showed that on both sides Holocene clay layers can be present around and below -10 m NAP, but not at all places.

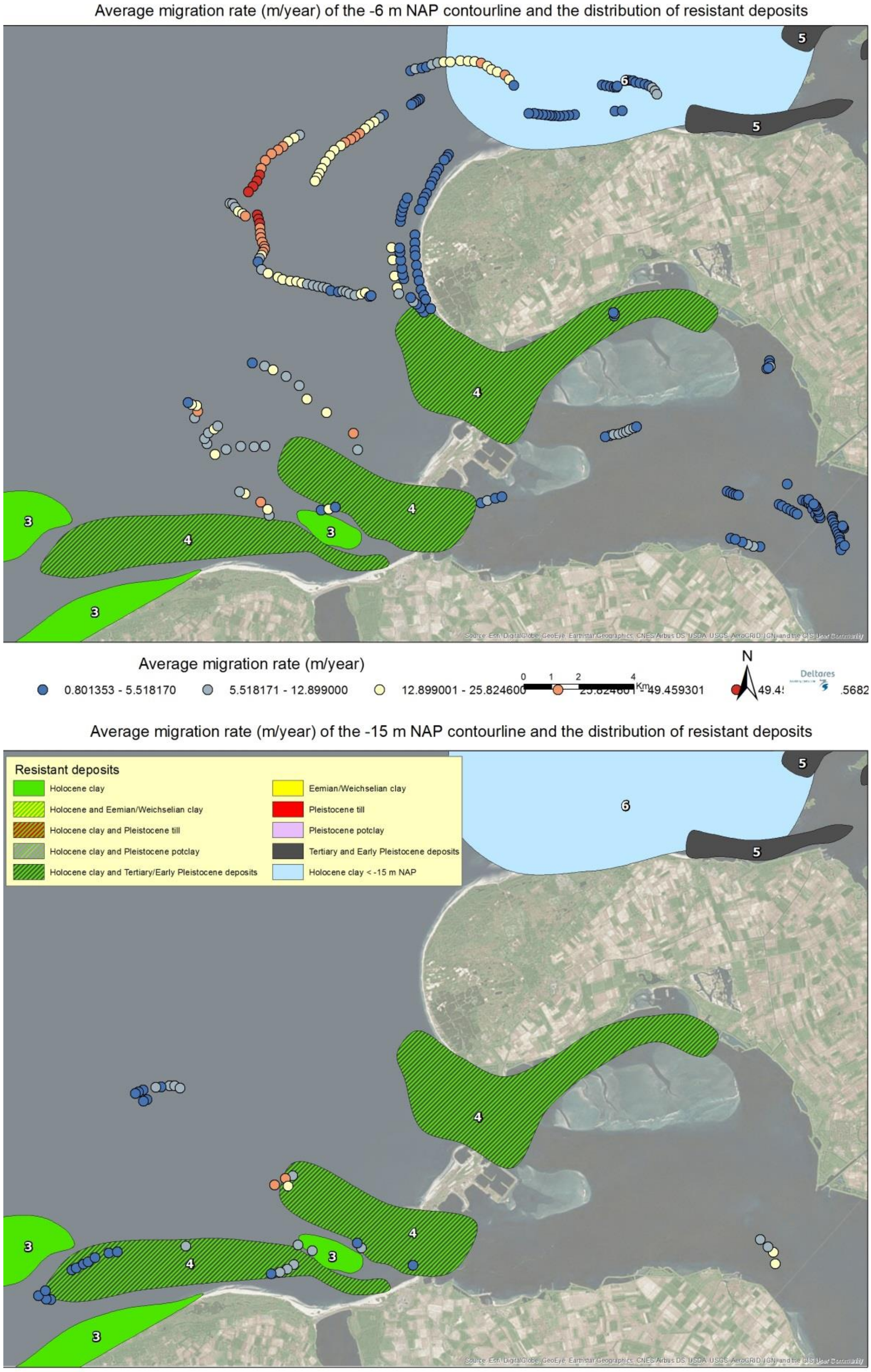


Figure 4.9 Average migration rates for the Oosterschelde-Grevelingen region and the distribution of resistant deposits.

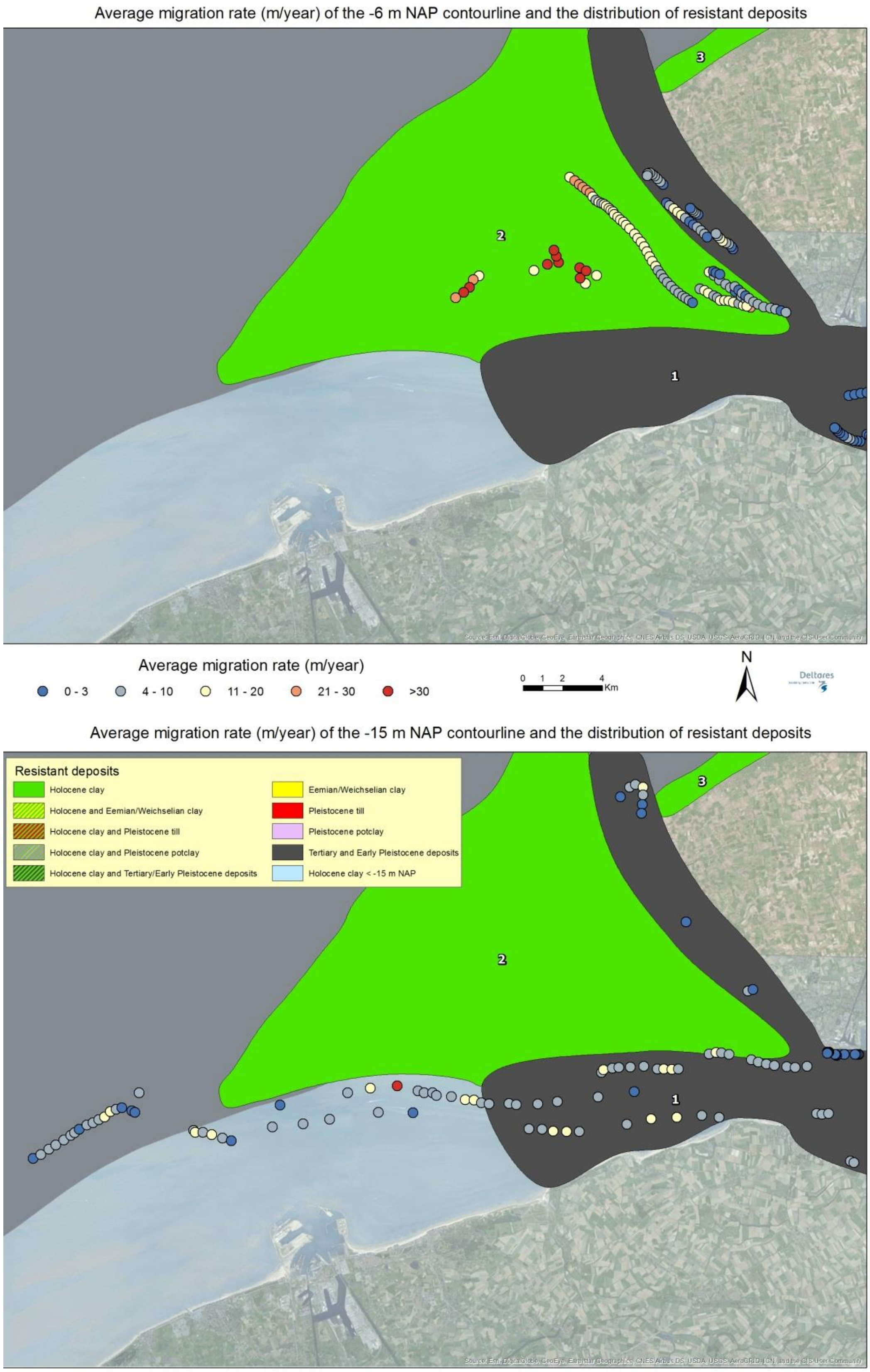


Figure 4.10 Average migration rates for the mouth of the Westerschelde and the distribution of resistant deposits.

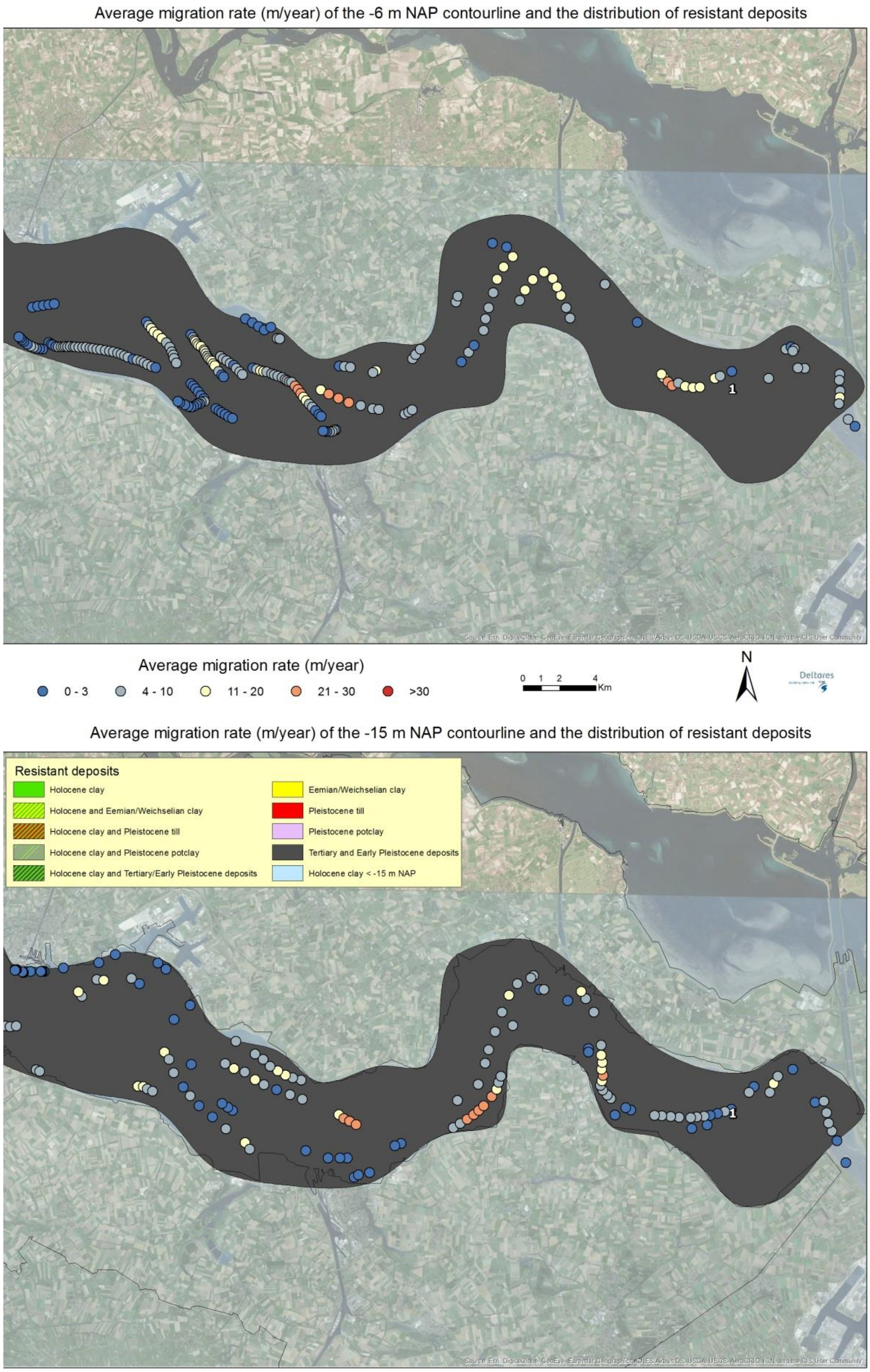


Figure 4.11 Average migration rates for the Westerschelde estuary and the distribution of resistant deposits.

In other parts of the Westerschelde no erosion-resistant deposits are present around the -15 m contour line and hence no influence of this type of deposits exists. An indirect influence of erosion-resistant deposits on the -15 m contour line is the fact that some of the deepest parts are in contact with stiff Tertiary and Pleistocene deposits (Van der Spek, 1997; Hijma, 2017a) that hinder deepening, but could stimulate widening. At the southern edge of the Vlakte van de Raan clay layers can be expected at -15 m, but this seems not to result in relatively low migration rates.

Near the landward sides of several shoals and channels, patches of Holocene peat- and clay layers have been preserved, possibly influencing migration rates. Careful comparison of rates and distribution of these patches is needed in order to relate patterns in migration rates to the presence of erosion-resistant deposits. This was not feasible within the scope of the present study.

4.4 Thalweg migraton during the last 30-90 years

Recently a report by Arcadis (Cleveringa and Geleynse, 2017) was published alongside hand-drawn shapefiles of the position of the thalweg of tidal channels in The Netherlands. For some tidal channels the oldest map used dates from 1983, while for other channels data from 1926 were available. The figures below plot all shapefiles and hereby give an impression of the lateral migration of the tidal channels during the last decades, so over longer periods than analysed in this study. The Arcadis report does not discuss the observed patterns.

When comparing the position of thalwegs over time with migration rates of shallower contour lines, it must be realized that these should not necessarily display the same pattern. The results in Chapter 3 show that several channels have widened on both sides, and hence a migration rate has been calculated, but the deepest part of the channel could have stayed at the same position. Nonetheless, when comparing the calculated migration rates with the thalweg shapefiles, there is a clear relationship: in areas with relatively high migration rates, like east of Schiermonnikoog (Figure 4.12), the thalwegs shifted considerably over the last decades, while in areas with low migration rates, like near the Vliestroom (Figure 4.13), the thalwegs were relatively stable. This seems to suggest that the pattern in migration rates between 1997-2002 and 2009-2014 is not just characteristic for that period, but that this pattern could be characteristic for much longer periods.

In the Wadden Sea there seems to be a distinction between thalweg migration west and east of Terschelling: west of Terschelling the overall migration rates are relatively low and east of Terschelling they are relatively high. This is not only true for the thalweg, but also for both the -15 and -6 m contour line. The largest tidal-channel system, the Vliestroom and Marsdiep, are located in the part with low rates, so there seems to be no obvious link between stream power and migration rates. Another effect that could also play a role, however, is that large systems move relatively slow anyway, because of the large volumes of sand that have to be transported in order to move.

In the Eems Estuary migration rates are somewhat lower again. Since in both the western Wadden Sea and in the Eems Estuary there are large areas with relatively shallow occurrences of erosion-resistant deposits, it is tempting to link the relatively low migration rates in these areas to the presence of these deposits. Especially tidal channels in the till area east of Den Helder and in between Texel and Vlieland have been remarkably stable. Still, also the Meep-channels north of geological area *17* were very stable, confirming De Leeuw (2007), but without an apparent influence of erosion-resistant deposits. Clearly, also other factors than the local subsurface build-up, e.g. hydrodynamic or human, play a role in determining the stability of a tidal channel.

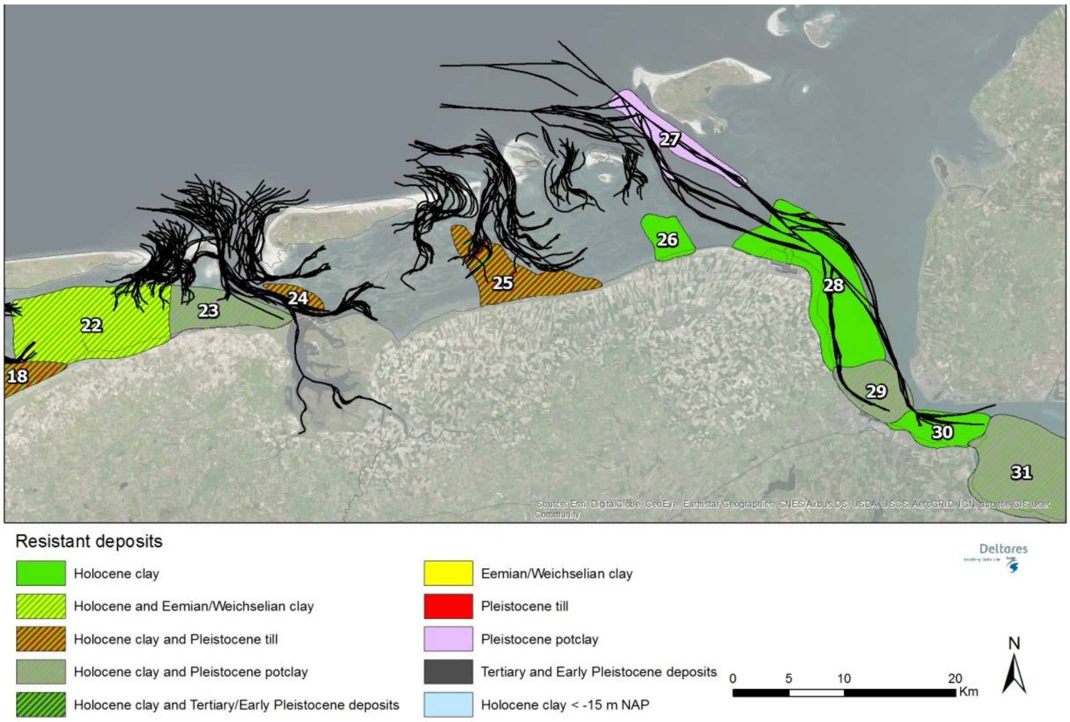


Figure 4.12 Mapped thalwegs over several decades in the eastern Wadden Sea (Cleveringa and Geleynse, 2017) plotted with the areas with erosion-resistant deposits (Hijma, 2017a).

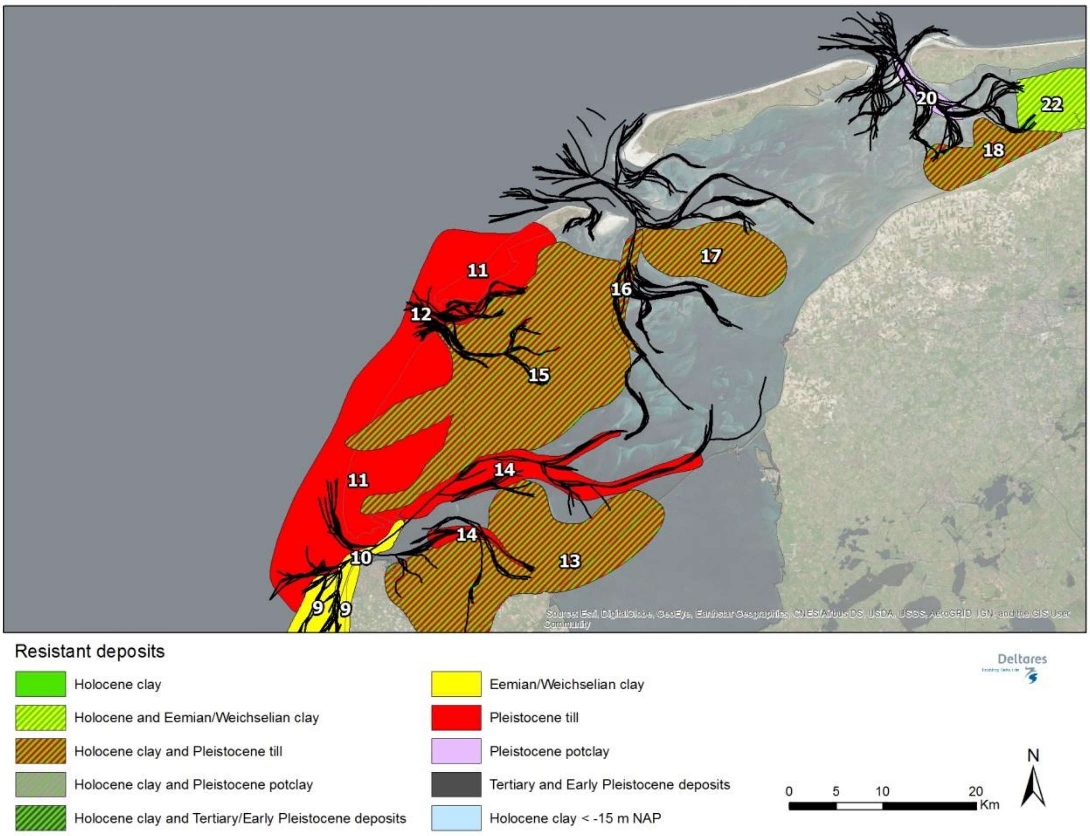


Figure 4.13 Mapped thalwegs over several decades in the western Wadden Sea (Cleveringa and Geleynse, 2017) plotted with the areas with erosion-resistant deposits (Hijma, 2017a).

In the Scheldt-area the positions of most of the thalwegs have been very stable during the last decades (Figure 4.14). This especially true for the Wielingen, the channels along the tip of Walcheren, the Roompot north of Walcheren and main navigation channel south of Walcheren (Rede van Vlissingen-Everingen). As mentioned earlier, especially the main navigation route in the Wielingen-Western Scheldt is heavily maintained and migration of the thalweg is obviously strongly influenced by these activities. In parts of the Wielingen-Western Scheldt the deepest parts are in touch with erosion-resistant deposits, hereby preventing rapid deepening, and this could have an influence on the stable position of the thalwegs as well. More active areas are channels in the ebb-tidal delta of the Oosterschelde and the channel systems in the central and southern part of the Western Scheldt.

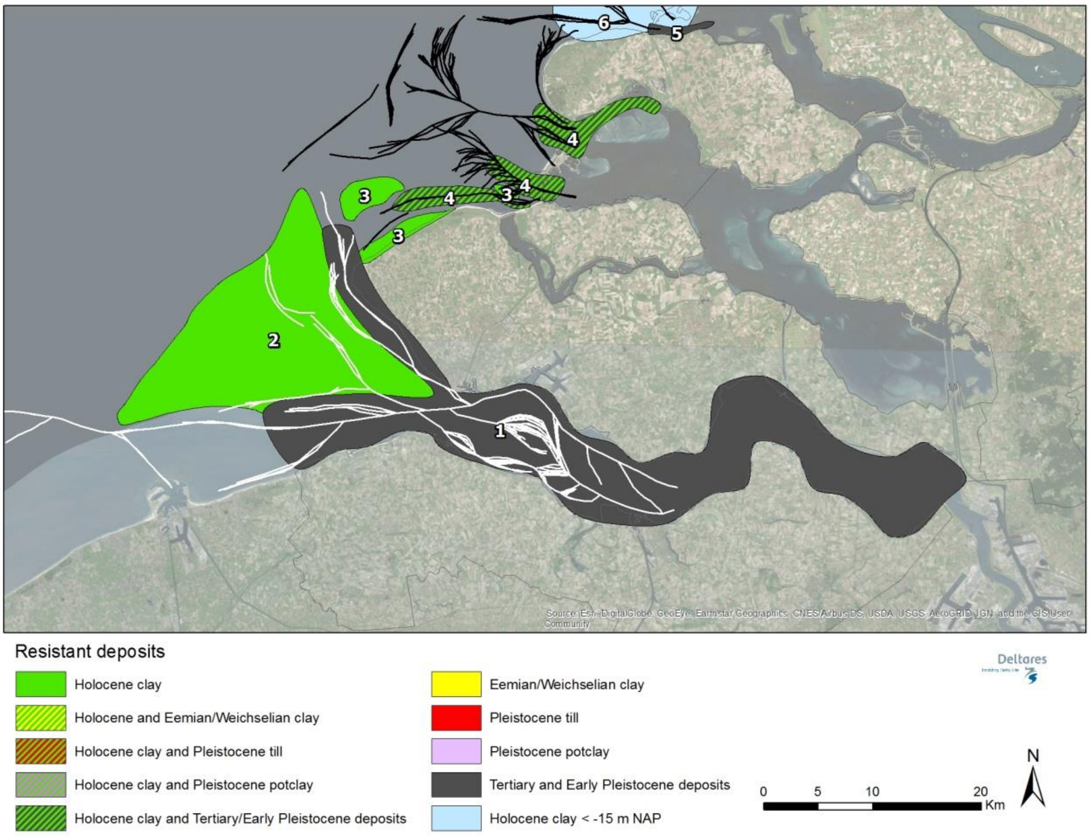


Figure 4.14 Mapped thalwegs over several decades in the Scheldt-area (Cleveringa and Geleynse, 2017) plotted with the areas with erosion-resistant deposits (Hijma, 2017a).

5 Conclusions

This study presents the first quantification of average rates of tidal-channel migration due to erosion on a national scale. For this a semi-automated method was developed using mosaicked bathymetric datasets (Vaklodingen) from different time periods, hereby calculating the migration rate of the -15 and -6 m NAP contour lines. In a next step these migration rates were compared with mapped distributions of erosion-resistant deposits in the coastal zone to make a first assessment of the relation between migration rates and the build-up of the subsurface. From this is concluded that:

1) There are large variations in average migration rates between the periods 1997-2002 and 2009-2014. The highest rate of migration for the -15 m contour line is ~70 m/yr, for the -6 m contour line 90 m/yr. On average the -15 m contour line migrated ~7 m/yr, the -6 m contour line ~8 m/yr. The standard deviation (2σ) around the migration rates is estimated to be 0.8 m/yr.

2) The highest rates are generally found in the outer bends of the tidal channels and in general the migration rates decrease in a landward direction. These two general observations are related to hydrodynamic processes and are not related to the presence of erosion-resistant deposits.

3) In the Eems-Dollard-Groninger Wad region erosion-resistant deposits are abundantly present and within relevant depths. There are distinct changes in the rate of migration for which indications exist that they can be attributed to changes in the build-up of the subsurface, but the data density is not sufficient to test this hypothesis.

4) In the Wadden Sea, the tidal channels associated with the Groninger Wad, Friesche Zeegat and Borndiep inlet show on average much higher migration rates that the tidal channels associated with the other inlets. An analysis of thalweg migration of tidal channels during the last 30-90 years (Cleveringa and Geleynse, 2017) indicates that also on longer time scales this difference can be observed.

5) This distinct difference in migration rates between the western Wadden Sea and the eastern Wadden Sea is tentatively linked to the presence of large patches of till-peat-clay sequences in the western Wadden Sea. There are, however, also some channels that show low rates of migration that seem not embedded within erosion-resistant deposits, indicating that under certain hydrodynamic conditions migration rates can be low as well.

6) In the Scheldt-area the highest rates of migration are found in the ebb-tidal deltas and along some shoals in the Western Scheldt.

7) In most of the Scheldt-region there seems to be little to no influence of erosion-resistant deposits of the migration rate of the studied contour lines. Some of the deepest parts in the Western Scheldt, below -15 m NAP, are likely in contact with erosion-resistant deposits that hinder deepening and possibly stimulate widening. Along the edges of the Western Scheldt there are relatively large patches of clay and layers present at shallow

depths, but at this points it is uncertain how close to the active channels they are present and if they have any influence on migration rates.

8) A more general conclusion is that although the direct influence of erosion-resistant deposits on migration rates is not always easy to “prove”, the migration rate in areas with large patches of erosion-resistant deposits is on average quite low. This applies especially to areas with the presence of till-peat-clay sequences and in areas with Potclay-peat-clay sequences. There is certainly a potential to further explore the assessed relation between migration rates and the build-up of the subsurface, see also the recommendations.

6 Recommendations

To take this line of research a step further and to make progress in integrating this type of knowledge into numerical models that are used to predict morphodynamic evolution in general and tidal-channel migration in particular, the following recommendations are given:

1) To increase the dataset that can be used to improve our understanding of patterns in rates of migrations as well as the predictive value of numerical models, the analysis should be expanded to periods before 1997-2002.

2) Since several of the larger tidal channels are much deeper than -15 m, it would be needed to include an analysis of the migration of deeper contour lines.

3) If erosion-resistant deposits hinder the lateral migration of tidal channels, it is expected that the channel walls of such channel are irregular and possibly contain plateaus. A comparison should be made of the profiles of channels walls for which the influence of erosion-resistant deposits is expected and channel walls where such an influence is not expected. This could possibly also allow distinguishing between channels that are stable due to the presence of erosion-resistant layers and those that are stable due to certain hydrodynamic conditions.

4) It would be fruitful to have a discussion with numerical modellers about the results of this study and how they can be integrated or used in their models. This discussion is also needed to be able to understand the combined influence of hydrodynamic processes and the build-up of the subsurface on migration rates.

5) A literature study is still needed to distil knowledge about differential erodibility and its influence on tidal-channel migration and long-term coastal evolution

6) The analysis of the influence of erosion-resistant deposits on migration rates in this study was explorative and often hindered by a lack of data. To bring this research further more focused analyses are needed in order to be able to quantify the erodibility of different types of deposits. This quantification is needed as input for the numerical models. At present, the most logical focus areas would be the western Wadden Sea, the Eems-Dollard region and parts of the Western Scheldt. These are the areas where the influence of erosion-resistant deposits seems most apparent.

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