Lithological Control on Scour Hole Formation in the Rhine-Meuse Estuary

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Abstract

River deltas commonly have a heterogeneous substratum of alternating peat, clay and sand deposits. This has important consequences for the river bed development and in particular scour hole formation. When the substratum consists of a poorly erodible top layer, erosion is retarded. Upon breaking through a resistant top layer and reaching an underlying layer with higher erodibilty, deep scour holes may form within a short amount of time. The unpredictability and fast development make these scour holes difficult to manage while stability of dikes and infrastructure may be at stake. In this paper we determine how subsurface lithology controls the bed elevation in net incising river branches, particularly focusing on scour hole initiation, growth rate and direction. For this, the Rhine-Meuse Estuary forms an ideal study site, as over 100 scour holes have been identified in this area and over 40 years of bed level data and thousands of core description are available. It is shown that the subsurface lithology plays a crucial role in the emergence of scour holes, their shape and evolution. Although most scour holes follow the characteristic exponential development of fast initial growth and slower final growth, temporally strong variations are observed, with sudden growth rates of several meters per year in depth and tens of meters in extent. In addition, we could relate the characteristic build-up of the subsurface lithology to typical scour hole development like large elongated expanding scour holes or confined scour holes with steep slopes. As river deltas commonly have a heterogeneous substratum and often face channel bed erosion, the observations likely apply to many delta rivers. These findings call for good knowledge of the subsurface lithology as without, scour hole development is hard to predict and can lead to sudden failures of nearby infrastructure and flood defence works.

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1 Introduction

Scour holes are common features to occur in rivers and estuaries. With their steep slopes and large depths, these scour holes can form a risk for the stability of nearby structures and infrastructure like embankments, bridge piers, tunnels and pipelines (e.g. Beltaos et al., 2011; Gharabaghi et al., 2007; Liang et al., 2020; Pandey et al., 2018; Wang et al., 2017). The formation and development of local scour, bend scour and confluence scour are widely studied (e.g. Andrle, 1994; Beltaos et al., 2011; Best, 1986; Best & Rhoads, 2008; Blanckaert, 2010; Engelund, 1974; Ferrarin et al., 2018; Gharabaghi et al., 2007; Ginsberg & Perillo, 1999; Kjerfve et al., 1979; Liang et al., 2020; Mosley, 1976; Odgaard, 1981; Ottevanger et al., 2012; Pandey et al., 2018; Pierini et al., 2005; Vermeulen et al., 2015; C. Wang et al., 2017; Zimmermann & Kennedy, 1978, 1978). These studies however generally focus on scour hole development in a homogeneous sandy subsurface. The influence of heterogeneities in the subsurface lithology on scour hole formation is hardly studied, while this may greatly impact the scour hole evolution or even induce scour hole formation (Figure 1), provided there is enough hydraulic forcing. In case of large-scale bed degradation in channel beds composed of fluvial sand and with no constructions or local river narrowing, erosion is evenly distributed. However, when the substratum is composed of layers with strongly varying erodibility, local depressions form at locations with higher erodibility (Cserkész-Nagy et al. 2010; Huismans et al. 2016; Sloff et al. 2013).

Many of world's large rivers in deltas face channel bed degradation. Examples are the Yangtze, the Rhine-Meuse Estuary, the Mississippi and the Mekong rivers (Luan et al. 2016; Brunier et al. 2014; Galler et al. 2003; Hoitink et al. 2017; Sloff et al. 2013; Wang and Xu 2018). Causes are mainly anthropogenic and range from extracting sediment by dredging and sand mining, a reduction in sediment supply due to the presence of upstream dams and levees and interventions that enhance flow velocities. As river deltas commonly have a heterogeneous substratum of alternating peat, clay and sand deposits (e.g. Aslan & Autin, 1999; Aslan et al., 2005; Berendsen & Stouthamer, 2001, 2002; Cohen et al., 2012; Gouw & Autin, 2008; Hanebuth et al., 2012; Kuehl et al., 2005.; Stefani & Vincenzi, 2005) and are among the regions with the highest population density (Best 2019; Syvitski et al. 2009), understanding how the lithology controls the scour hole development is highly relevant.

One of the first papers to discuss the influence of a heterogenous subsurface lithology on the channel bed morphology is by Nittrouer et al. (2011). Based on multibeam surveys, high intensity radar pulse seismic data and grab samples, they map five sediment facies for the lowermost Mississippi river, of which three consisting of modern alluvial deposits and two of relict substratum. They show that the sediment facies associated with relict substratum are mainly exposed in the regions with the most erosion, namely the deeper parts of the channel bed and at the sidewalls of the outer bends. Erosion of the sidewall substratum is furthermore inhomogeneous, due to the spatially heterogeneous fluvio-deltaic sedimentary deposits that have variable resistance to erosion. Cserkész-Nagy et al. (2010) show a strong lithological control on the erosion and lateral migration of the Tisza river (Hungary) in response to engineering measures. Erosion is either found to be promoted, in case sandy deposits are incised, or suppressed when resistant silty-clayey substratum prohibits further erosion. For the Ems estuary (Pierik et al., 2019) demonstrate how the composition of the subsurface lithology controlled the evolution of eb-tide channels over a 200 years timespan. The clear link to the emergence of scour holes is made by Sloff et al. (2013), who observed deep scour holes in the Rhine-Meuse estuary and demonstrated the principle of scour hole formation in heterogeneous subsurface both conceptually as with a numerical model. In a follow up paper by Huismans et al. (2016), the link between scour hole occurrence and the composition of the subsurface lithology was directly made, by combining multibeam surveys and detailed geological maps constructed based on lithological data from corings.

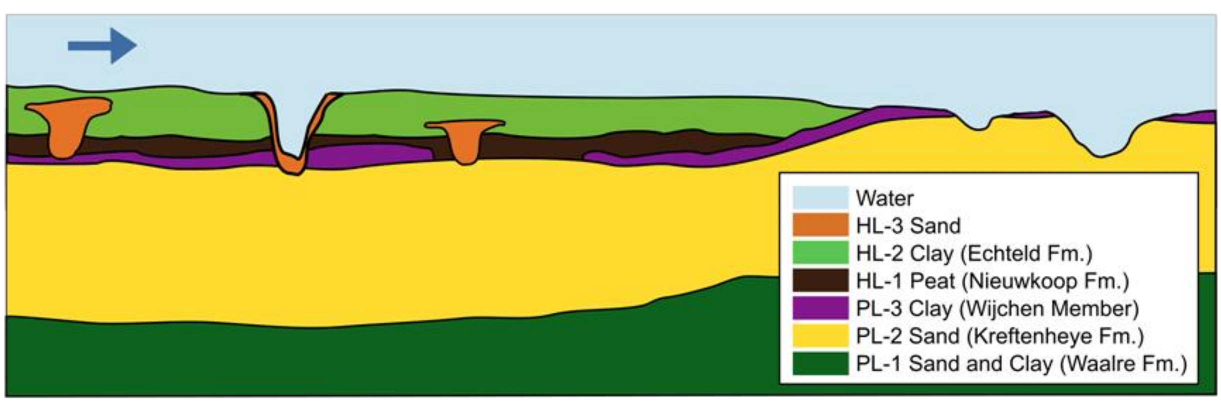

Figure 1. Conceptual longitudinal subsurface lithological section of a river bed. Arrow indicates flow direction. Scour holes form in layers or patches composed of sandy material with lower erodibility compared to the surrounding resistant clay or peat layers.

This paper builds on the work of Huismans et al. (2016), by analysing in detail how the subsurface lithology influences the bed elevation in net incising river branches, particularly focusing on scour hole initiation, growth rate, direction and shape, as this is essential information in judging whether scour holes form a risk for the stability of river banks, dikes or other nearby infrastructure. The Rhine-Meuse Estuary in the Netherlands forms an ideal study area, as more than a hundred scour holes are identified in this area, of which many are expected to be influenced or triggered by heterogeneities in the subsurface lithology (Huismans et al., 2016). In addition, over 40 years of yearly single- and multibeam data and lithological data from many corings are available. This allows analysing decades of bed level evolution and linking it to the subsurface composition. Upon identifying how the location, growth direction and rates are influenced by the heterogeneity of the subsurface lithology, first a reconstruction of the subsurface lithology is made based on thousands of core descriptions along the main river branches of the Rhine-Meuse Estuary. Subsequently the recent 5-year scour hole growth is mapped for the set of over 100 scour holes. For a subset of 18 scour holes, the evolution since 1976 is analysed and linked to the subsurface lithology. In a final step, scour hole characteristics in three sub-reaches with distinct lithological composition are analysed, highlighting the differences in lithological control on the size, growth rate and direction of scour holes.

2 Study Area

The Rhine-Meuse Estuary is located in the western part of the Netherlands, where the rivers Rhine and Meuse debouch into the North Sea (Figure 2). During the Late Pleistocene Younger Dryas stadial (12.900-11.700 cal yr. BP), the area consisted of a wide braided river valley. During the early Holocene (11.700 - 8.200 cal yr. BP), the braided river system gradually transformed into a meandering system, due to climatic warming and restoration of vegetation (Berendsen & Stouthamer, 2000; Berendsen et al., 1995; Cohen, 2003; Gouw & Erkens, 2007; Hijma, 2009; Janssens et al., 2012; Pons, 1957). The sandy sediments deposited by the braided rivers, predominantly consist of gravel and coarse sand (Kreftenheye Fm., PL-2, Figure 1). At the top, finer grained sand is found, with grain sizes varying from 150 µm to 300 µm (Vos & Cohen, 2014). During flood events fine sediments were deposited on the floodplains, forming a strong resistant silty clay loam layer (Wijchen Member, PL-3) (Busschers et al. 2007; Hijma et al. 2009; Törnqvist et al. 1994). In most of the study area, this silty clay loam layer (Wijchen Mb.) covers the Pleistocene sandy deposits. Due to rapid early Holocene sea level rise, the area changed from a wide river valley into an estuary (T. de Haas et al., 2018; Hijma, 2009). During this stage peat lands formed in response to the higher ground water tables (Nieuwkoop Fm., HL-1), which regionally got covered by clay from tidal deposits in the west (Naaldwijk Fm.) and floodplain deposits in the east (Echteld Fm., HL-2) (Hijma et al., 2009). The rapid growth in accommodation space triggered a peak in avulsion frequency around 8000 – 7200 cal yr. BP (Stouthamer & Berendsen, 2000; Stouthamer et al., 2011a). A second peak in avulsion frequency occurred around 3300-1800 cal yr. BP and was triggered from upstream, where due to deforestation the sediment supply to the river doubled (Erkens, 2009; Stouthamer & Berendsen, 2000). During this time, a major avulsion caused the Rhine to shift its mouth from the area near Leiden to the south near Rotterdam, close to its current outlet position (Figure 3a) (Berendsen & Stouthamer, 2000; De Haas et al., 2019; Pierik et al., 2018). A detailed geological mapping of the past river course development is available for the entire Rhine-Meuse Delta (Cohen et al., 2012), showing where the river and tidal channel deposits are preserved in the subsurface lithology (HL-3).

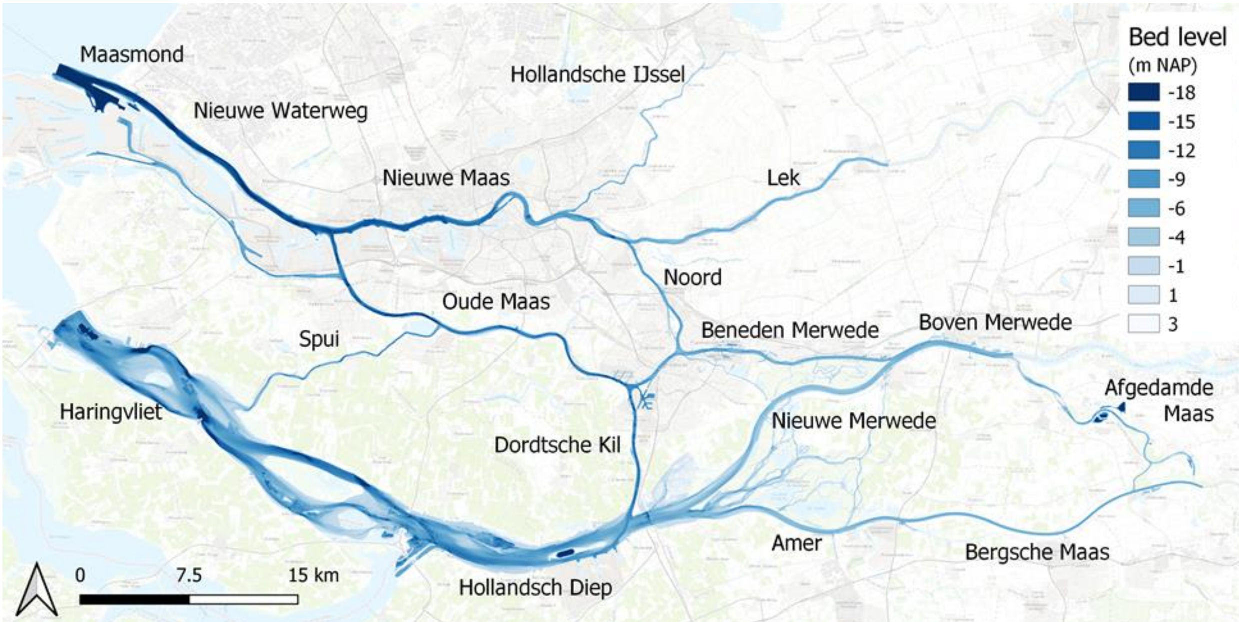

Figure 1 Overview of the river channels forming the Rhine-Meuse Estuary (the Netherlands). In colour the bed level is represented (year 2013, 2014). Map is created in QGIS with the Esri-TOPO base map.

Since the High Middle Ages (~1000 AD), human impacts on the delta increased. Floodplains were cultivated, parts of the peat land excavated, and rivers were constraint by dikes. This was followed by major changes to the river planform, when in the second half of the 19th century, two new channels were constructed, the Nieuwe Merwede and Nieuwe Waterweg (Figure 2). Since that time, continuous deepening of channels and closure or reconstruction of river branches impacted the Rhine-Meuse Estuary. The most recent large intervention is the closure of one of its tidal outlets in 1970, the Haringvliet (Figure 2). The latter caused a major change in the hydrodynamics (Vellinga et al., 2014), leading to enhanced flow velocities in the connecting channels which triggered severe erosion (Hoitink et al. 2017; Sloff et al., 2013) of up to several meters in about 40 years' time (this paper). In the southern part of the estuary, flow velocities strongly decreased, which resulted in sedimentation of mostly fine silt.

Nowadays the Rhine-Meuse Estuary carries an average annual discharge of 2110 m^3/s, of which 1590 m^3/s exits through its main outlet, the Maasmond, and 510 m^3/s through the Haringvliet sluices (average values in timeframe 2006-2015). During high river discharges, the net river discharge can reach up to about 10.000 m^3/s, while during dry periods it may drop below 600 m^3/s. During low discharge events the Haringvliet sluices entirely close and all water leaves the system via the Maasmond to restrain salt intrusion in the Maasmond and ensure the fresh water supply in the estuary.

The Rhine-Meuse Estuary receives sediment from both the North Sea and its upstream river branches Waal, Lek and Maas. The marine input of sand, silt and clay is estimated at 5.8 Mt/year, while only 1.3 Mt/year of sediment is exported to sea (Frings et al., 2019). Though these numbers have a large uncertainty, the marine input is certainly large compared to the combined input of all upstream river branches, which is 2.6 Mt/year (Frings et al., 2019). These numbers show the system has a natural trend to import sediment. However, as dredging exceeds the sediment import, the Rhine-Meuse Estuary loses net sediment.

The genesis of the area with avulsions, infilling and abandoning channels and development of marshes, has resulted in a heterogeneous substratum composed of layers and patches of sand, clay and peat. The grain size distribution and sediment characteristics of the top layer of the channel bed, vary strongly within the system. In the easterly branches (Beneden Merwede, Nieuwe Merwede, Lek, Bergsche Maas), the top layer is mostly sandy, with median grain sizes ranging from 0.25 to 4 mm (Frings et al., 2019; Fugro, 2002). Locally the top layer consists of erosion resistant peat or clay. In the southern part (Haringvliet, Hollandsch Diep, Amer), silt and clay contents dominate the bed, of which most has settled since the closure of the Haringvliet by a gated barrier in 1976. In the connecting branches (Oude Maas, Noord, Dordtsche Kil, Spui), large areas of erosion resistant clay and peat form the top layer, but also areas with sand or silt are found (Frings et al., 2019; Fugro, 2002).

3 Data and methods

To investigate the influence of the subsurface lithology on scour hole initiation, growth rate and direction, an extensive set of geological data and bed level data is analysed. The method in essence consists of analysing and interpreting the geological records to reconstruct the subsurface lithology and analysing single and multi-beam surveys to evaluate the bed level evolution and scour hole growth in relation to the lithology. The subsurface lithology reconstruction resulted in longitudinal lithological sections along the centrelines of most of the river branches. The data-analysis of the bed level surveys is carried out in three phases. First a general overview is created, by mapping the recent five-year growth characteristics for all scour holes in the estuary. Secondly, for two branches the evolution of the overall bed level since 1976 has been analysed, as well as the growth rates of their scour holes. The observed trends are linked to the subsurface lithology. In the last step, three distinct scour holes are analysed in full detail. These three scour holes distinguish in growth rate, growth direction and size, which can be related to differences in surrounding geological layers.

3.1 Subsurface lithology

The main source of geological data is the digital DINO-database with lithological core descriptions (TNO, 2010, 2014). For the area of interest, core descriptions from within a range of 2 km of the river channel are selected (Figure 3). Most descriptions are from cores taken next to the river channel. For the river branches Dordtsche Kil, Nieuwe Maas, Boven Merwede and the

Nieuwe Waterweg about 684 lithological core descriptions and grab samples taken within the river are available, which originate from the Deltadienst and the Dutch Directorate-General for Public Works and Water Management (Rijkswaterstaat) and its predecessors, and which are added to the DINO-database. In addition to the core descriptions, the Digital Basemap for Delta evolution and Paleogeography of the Rhine-Meuse Delta (Cohen et al., 2012) is used for the location and age of the channel belts. The mapping of the channel belts is based on cores from Utrecht University and the DINO-database, lidar imagery (www.ahn.nl), and sedimentological and geomorphological principles. The dating is based on a combination of archaeological findings, C14 dating, historical sources and maps, and geological cross-cutting principles. The third source used is the 3D geological GeoTOP model (Stafleu et al., 2011), which for each voxel of 100 x 100 x 0.5 m, contains information on the lithostratigraphy and lithological classes up to a depth of 50 m below NAP (Dutch Ordnance Level).

Based on the core descriptions, cone penetration tests, channel belt mapping, GeoTOP results and previous paleogeographic reconstruction of the delta (Hijma & Cohen, 2011; Hijma et al., 2009), lithological long and cross sections are constructed for the Nieuwe Waterweg, Nieuwe Maas, Oude Maas, Noord, Dordtsche Kil, Spui, Merwedes and Lek (Huismans et al., 2013; Stouthamer & De Haas, 2011; Stouthamer et al., 2011b-d; Wiersma, 2015).

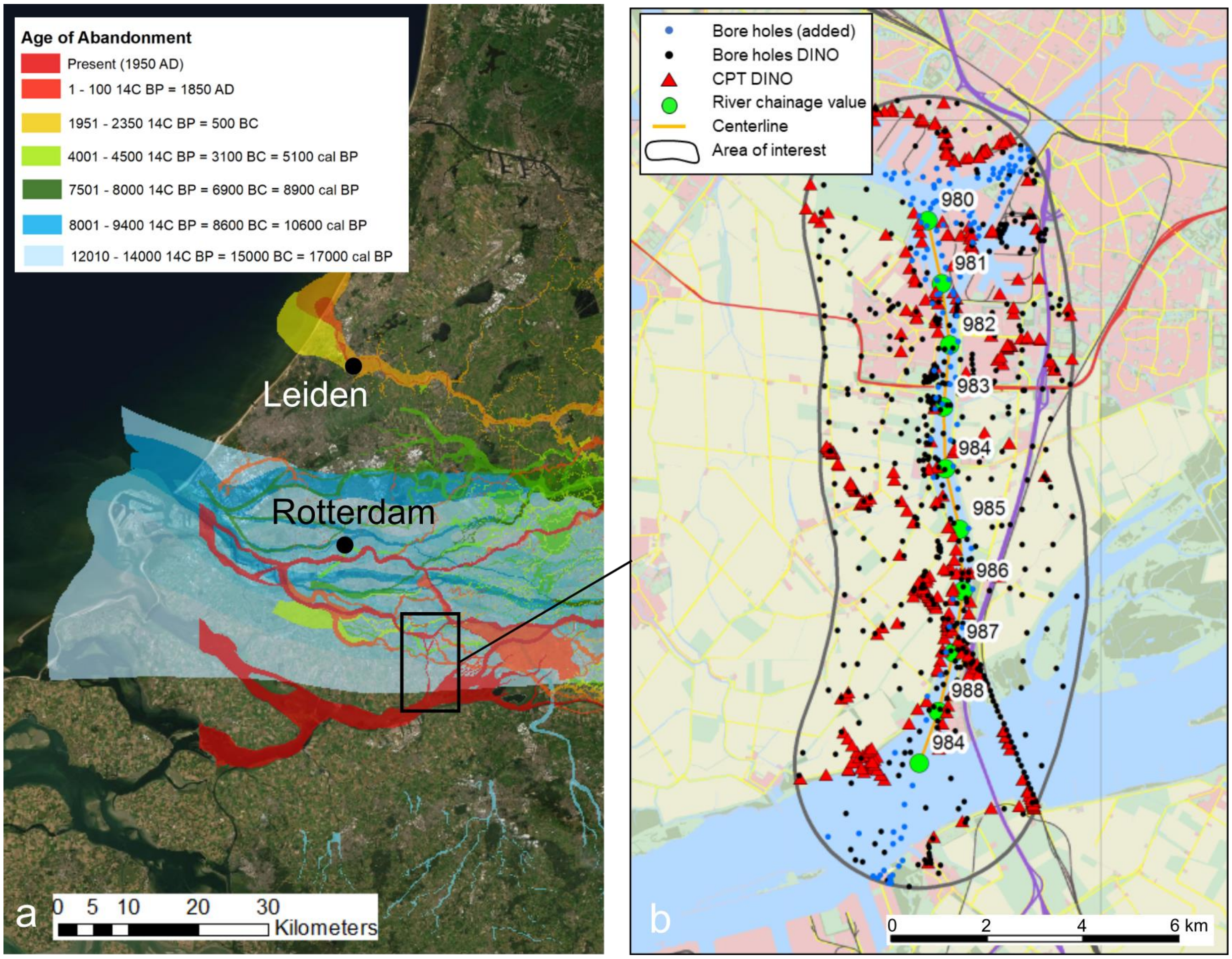

Figure 3 Overview of the main data sources used for the reconstruction of the subsurface lithology, a) overview of the age of abandonment of Holocene channel belts (Cohen et al., 2012),map created with ArcGIS and with World Imagery used as background (Esri, Maxar, Earthstar Geographics, CNES/Airbus DS, USDA FSA, USGS, Aerogrid, IGN, IGP, and the GIS User Community), b) overview of the available core descriptions and cone penetration tests for the Dordtsche Kil river (Wiersma, 2015).

3.2 Bed level

For the analysis of the bed level evolution, single beam data is available for the period 1976 – 2005 and multibeam surveys are available from 2006 onwards, all provided by the Dutch Directorate-General for Public Works and Water Management. For the period 1976 – 1993, the single-beam data consists of yearly cross sections at every 100 m to 125 m, with 10 m spacing between each measurement point within each cross section. For the period 1994 – 1999, cross sections are measured at every 25 m to 100 m with generally 1 m spacing between each measurement point within the cross section. During this period, some areas were surveyed more intensively with both cross and longitudinal sections. From the year 2000 the resolution increases and the provided single beam measurements are interpolated onto a 5 x 5 m grid. The multi-beam data from 2006 onwards consist of yearly surveys and are available on a 1 x 1 m resolution grid. For areas that are surveyed more frequently, the last measured value is taken.

In the first step of the analysis, the growth characteristics over the period 2009 - 2014 are determined for all scour holes identified in the study of Huismans et al. (2016). This database consists of 81 scour holes, or groups of scour holes if they are located close to each other. In the analysis all individual scour holes are regarded, such that in total 107 scour holes are analysed. Due to insufficient data for the river branches Haringvliet and Brabantsche Biesbosch, the scour holes in those branches were left out from the analysis. Based on the multi-beam measurements from 2009 and 2014 the change in extent and depth over 5 years' time is determined. The change in depth is defined as the difference between the level of the deepest point in 2009 and 2014. Note that the location of the deepest point may change over time. The change in extent is based on the evolution of the depth contour that marks the area of the scour hole.

The analysis subsequently zooms in onto two branches, the Dordtsche Kil and Oude Maas. For these branches the bed level evolution from 1976 to present is analysed, by plotting the maximum depth along the river. For each river chainage value interval, the deepest point over the width of the river is determined. For the single beam, the maximum depth per measured cross section is taken, which results in resolution between 25 m to 125 m, depending on the spacing of the original single beam tracks. For the interpolated single beam data and multibeam data the deepest point per river chainage value is taken with an interval of 100 m for 2000 and 2004 and 10 m for all other years.

To evaluate the depth development of the scour holes of the Dordtsche Kil and Oude Maas between 1976 and 2015, the deepest point within the scour hole is plotted against time. This enables to determine whether a scour hole grows steadily in depth or whether it faces a sudden acceleration or deceleration in growth, and whether it is reaching its equilibrium depth. Because the size of the scour holes may be comparable to the distance between the various single beam cross sections, only points within a range of 50 m from the current deepest point of the scour hole are considered.

In the last step of the analysis three reaches are analysed in full detail. For this, multi-beam data is visualized in GIS. To clearly distinguish the structures in the river bed "hill shade" is used.

4 Results

4.1 Recent growth characteristics of all scour holes

An overview of the scour holes in the Rhine-Meuse Estuary is given in Figure 4, together with the bed level trends, as taken from the most recent sediment budget of the Rhine-Meuse Estuary (Becker, 2015) for the period 2002-2012. Scour holes are found in all river channels throughout the entire delta, even in branches that are aggrading. Scour holes in these branches are presumably related to either the presence of structures like bridge piers, which cause local scour, or are relics of old tidal channels that have not been infilled yet.

The overview of the scour hole development between 2009-2014 (Figure 4), shows that most of the scour holes still grow in depth or extent. Only about 10% of the scour holes shows a depth increase of more than 50 cm or an increase in extent of more than 50% over 5 years' time.

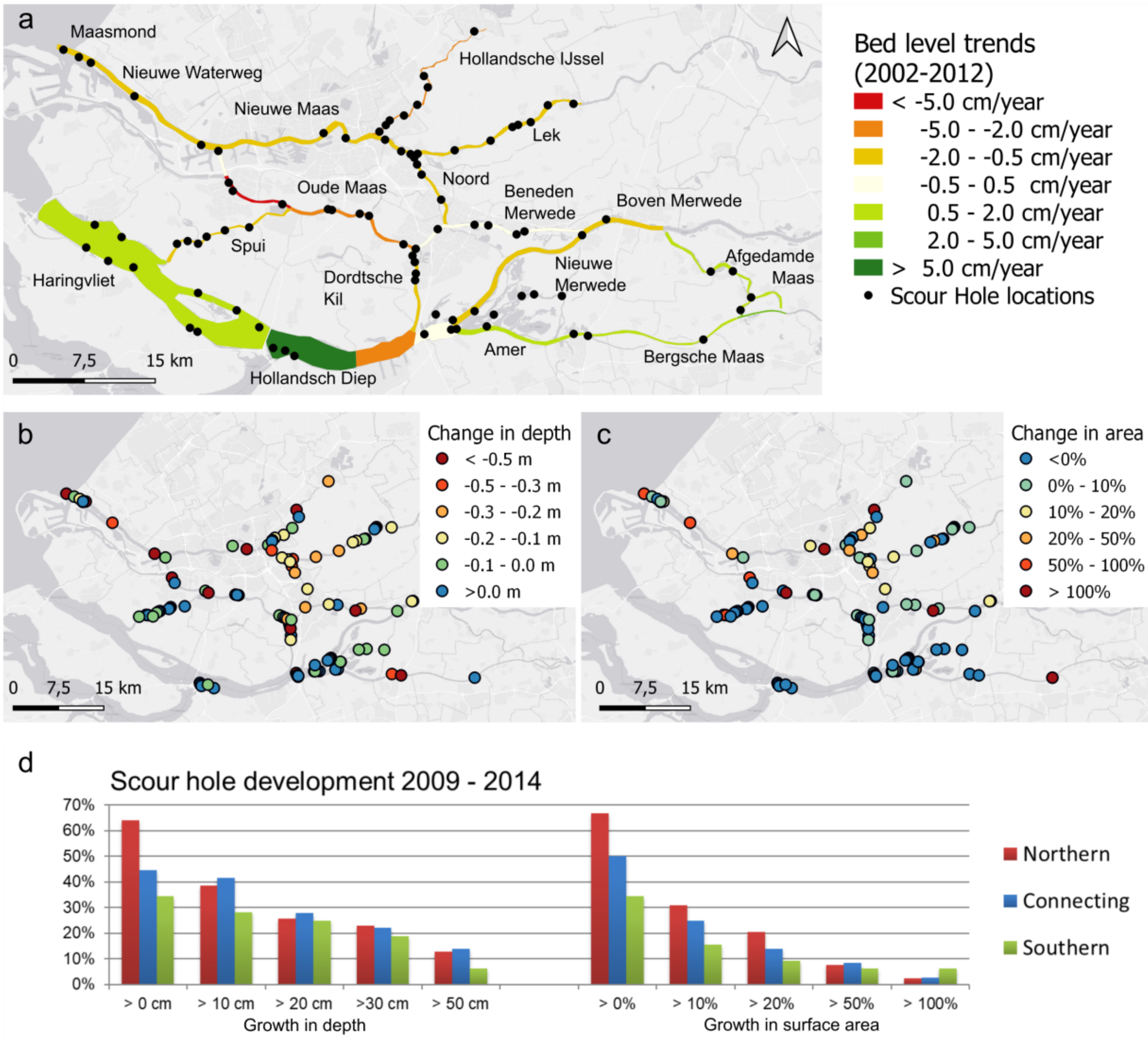

Figure 4 a) overview of the bed level trends 2002-2012 from Becker (2015) and the identified scour holes (Huismans et al., 2016) of the Rhine-Meuse Estuary. b-c) 5-year scour hole growth in depth (left) and extent (right). d) Bar plot of the growth rates per region, namely southern branches (Merwedes, Bergsche Maas, Amer, Haringvliet, Hollandsch Diep), connecting branches (Spui, Oude Maas, Dordtsche Kil and Noord) and northern branches (Maasmond, Nieuwe Waterweg, Nieuwe Maas, Hollandsche IJssel and Lek). Maps are created in QGIS with the Esri-Grey (light) base map.

The scour holes in the southern branches (Merwedes, Bergsche Maas, Amer, Haringvliet, Hollandsch Diep) show the smallest growth. The strongest growth is found in the connecting (Spui, Oude Maas, Dordtsche Kil and Noord) and northern channels (Maasmond, Nieuwe Waterweg, Nieuwe Maas, Hollandsche IJssel and Lek). Note that without dredging the northern branches would on average show aggradation instead of degradation. This means that the strongest scour hole growth is not necessarily found in the branches with the highest erosion rate.

4.2 Scour hole formation in the eroding branches

To understand how the subsurface lithology controls bed degradation and scour hole development, the bed level evolution from 1976 to 2015 is studied for two eroding branches, the Dordtsche Kil and Oude Maas. Figure 5 shows the development of bed elevation in time of the Dordtsche Kil. In four decades, several meters of erosion have occurred. There is a distinct difference between the northern part (between river chainage value rkm 980 – 983) and the southern part (rkm 983 – 989) of the river. In the southern part, the river bed eroded rather homogeneously. In the northern part, the erosion is less and spread unevenly. This coincides with the composition of the subsurface lithology, which in the southern part is homogeneous, consisting of Pleistocene sand, allowing for homogeneous erosion. The subsurface lithology in the northern part is heterogeneous and composed of poorly erodible clay interspersed with highly erodible sand bodies from old channel belts. At locations where the river bed is composed of clay, erosion rates are suppressed, while in the highly erodible sand patches, scour holes have emerged or existing scour holes have undergone further erosion.

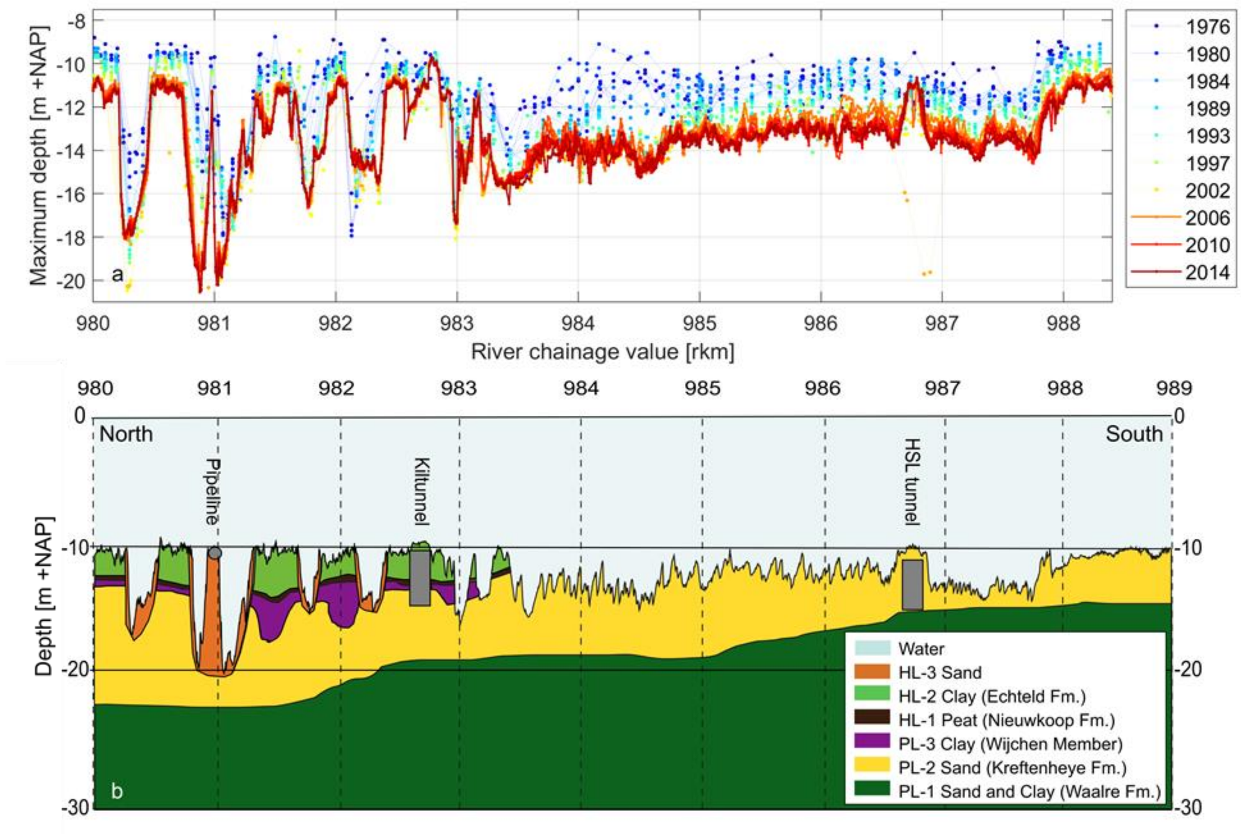

Figure 5 a) evolution of the deepest points in the Dordtsche Kil river bed from 1976 to 2014. b) lithological longitudinal section of the Dordtsche Kil (Wiersma, 2015).

For 18 scour holes in the Oude Maas and Dordtsche Kil river, the evolution of the scour hole depth is analysed for the period 1976 – 2014 (Figure 6). All scour holes have been subject to the same change in trend, namely an increase in flow velocities and resulting transport gradient due to closure of the Haringvliet. All scour holes have consequently grown in depth. The net increase in depth however strongly varies per scour hole. The largest net increase observed is 13 m, which occurred in 35 years (scour hole 14, Figure 6), the smallest net increase is approximately 1 m, which occurred in 29 years (scour hole 13). The rate at which the depth changes strongly varies as well. Some scour holes show a more gradual growth, others show clear trend breaks. In addition, the timing of acceleration or deceleration in growth is different for each scour hole.

Recent rates of depth change are generally lower than the overall growth rates. For 14 out of the 18 scour holes the average growth rate over the last five years is less than the average growth rate over the total period. Five scour holes even show net sedimentation instead of erosion. This suggests that most of the scour holes reached an equilibrium depth or are close to reaching this. The exception may be scour hole 12, for which the timing of sedimentation coincides with an increase in erosion of the neighbouring scour hole 11. As the tidal averaged flow is directed from scour hole 11 to 12, this suggests that sedimentation in scour hole 12 is caused by an increase in sediment availability from scour hole 11.

To get an indication on whether changes in growth rate can be related to the composition of the subsurface lithology, the interpretation of the local subsurface lithology has been presented in the coloured graphs. For the Oude Maas the interpretation was based on limited data (Stouthamer & De Haas, 2011), and at some scour hole locations no interpretation could be made due to lack of data. For these scour holes, either the closest subsurface lithology is taken as an indication (scour holes 6-9, 11, 14, 15 and 16, data on average available within 800 m from the scour hole location), or an interpolation of the closest by subsurface lithology is taken (scour holes 12 and 13).

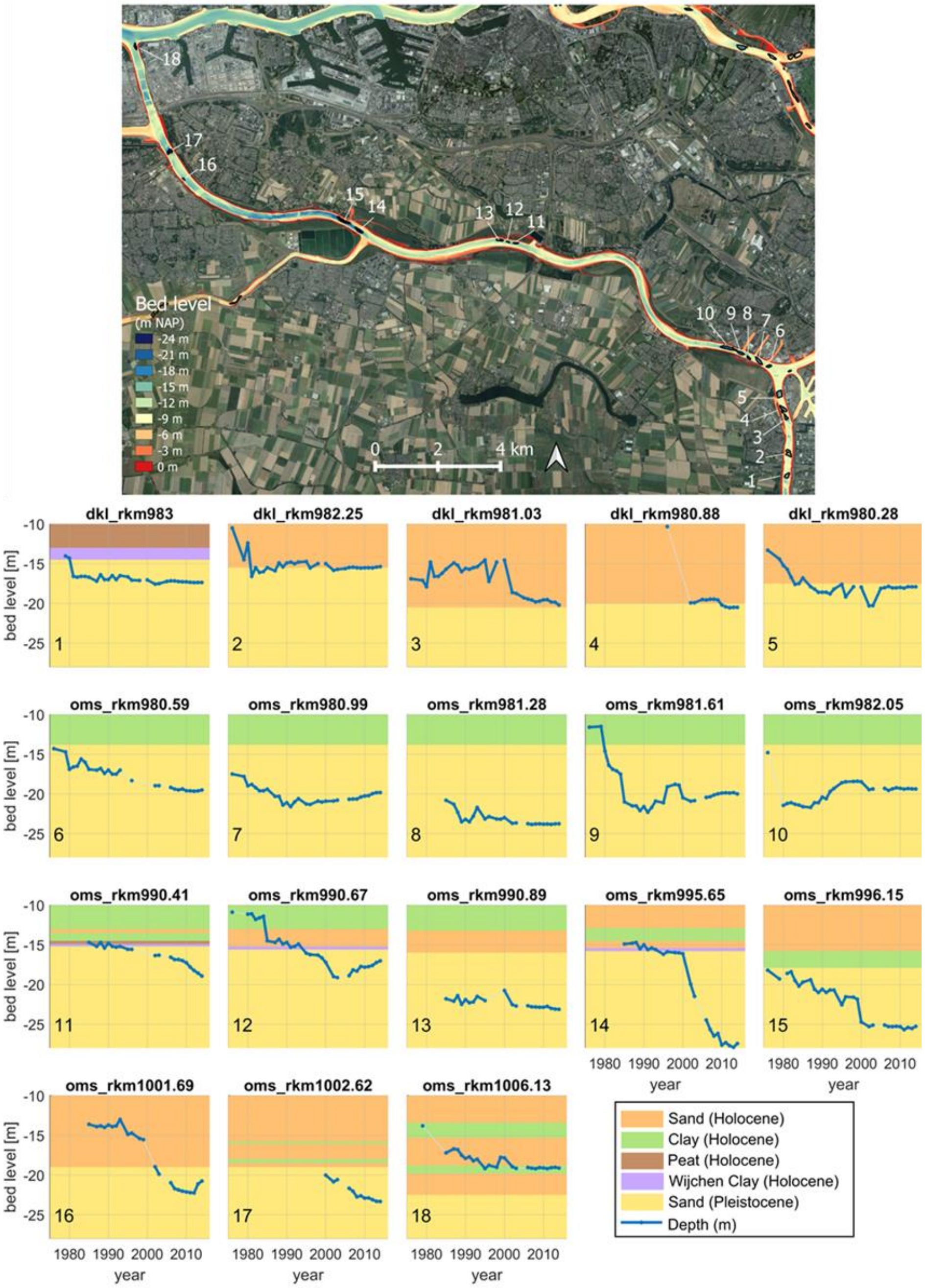

Figure 6 Top panel: map with scour hole locations considered for this analysis. Bed level is from 2014. Map is created in QGIS with the Esri-Satellite base map. Bottom panel: scour hole evolution over four decades. For each scour hole the evolution of the deepest point is shown in blue. In colour the subsurface lithology is presented. For the locations for which no subsurface lithology interpretation is available, either the closest by subsurface lithology is taken (scour holes 6-9, 11, 14, 15, 16, data on average available within 800 m from the scour hole location), or an interpolation of the closest by subsurface lithology is taken (scour holes 12 and 13).

The graphs show that for scour holes 1, 9, 10, 12 14 and 18, the increase in growth rate corresponds with a transition to a layer with a higher erodibility. For scour holes 2, 4, 5 and 18, a decrease in growth rate coincides with a transition to a layer with lower erodibility. For some scour holes (11, 15 and 16), the increase in growth rate cannot directly be related to changes in erodibility. For scour holes 11 and 15, the transition to faster growth happens at larger depth than the transition from clay to Pleistocene sand. As no interventions are known that can explain the increase in growth rate, it is likely that locally the clay to sand transition is lower than suggested by the lithological longitudinal section. For scour hole 16 the depth at which the growth rate increases is in the middle of a sand layer. The nearby subsurface lithology is however very heterogeneous. Within 1 km a clay layer is present at -16 m NAP, exactly the depth at which the growth rate increased. This gives a strong indication that the transition to a faster growth is induced by a transition from clay to sand.

4.3 Detailed growth in relation to the subsurface lithology

To estimate the risk of scour holes on the stability of nearby structures and river banks, predictions on the scour hole growth rate and direction are required. For this purpose, three river sections with scour holes of distinct size, shape, growth rate and direction are analysed in relation to their subsurface lithology.

In Figure 7, the present bed level and evolution of the deepest points along the river (1976-2015) are shown for a 2 km river section of the Oude Maas and Dordtsche Kil. The bed topography of the Oude Maas section shows an elongated scour hole of over 1 km length and two smaller ones at rkm 995.7 and 997.5. The evolution of the deepest points indicates that the elongated scour hole initially consisted of two or three scour holes which developed in depth and extent and merged together. Both smaller scour holes are not present in the 1976 surveys and only emerge around

2000 and 2005 for respectively the scour hole at rkm 997.5 and 995.7. The scour hole at rkm 995.7 is extending mostly in eastward direction but also westward, in the direction of the elongated scour hole. If this trend continues, this scour hole will merge with the elongated scour hole to form an even larger one.

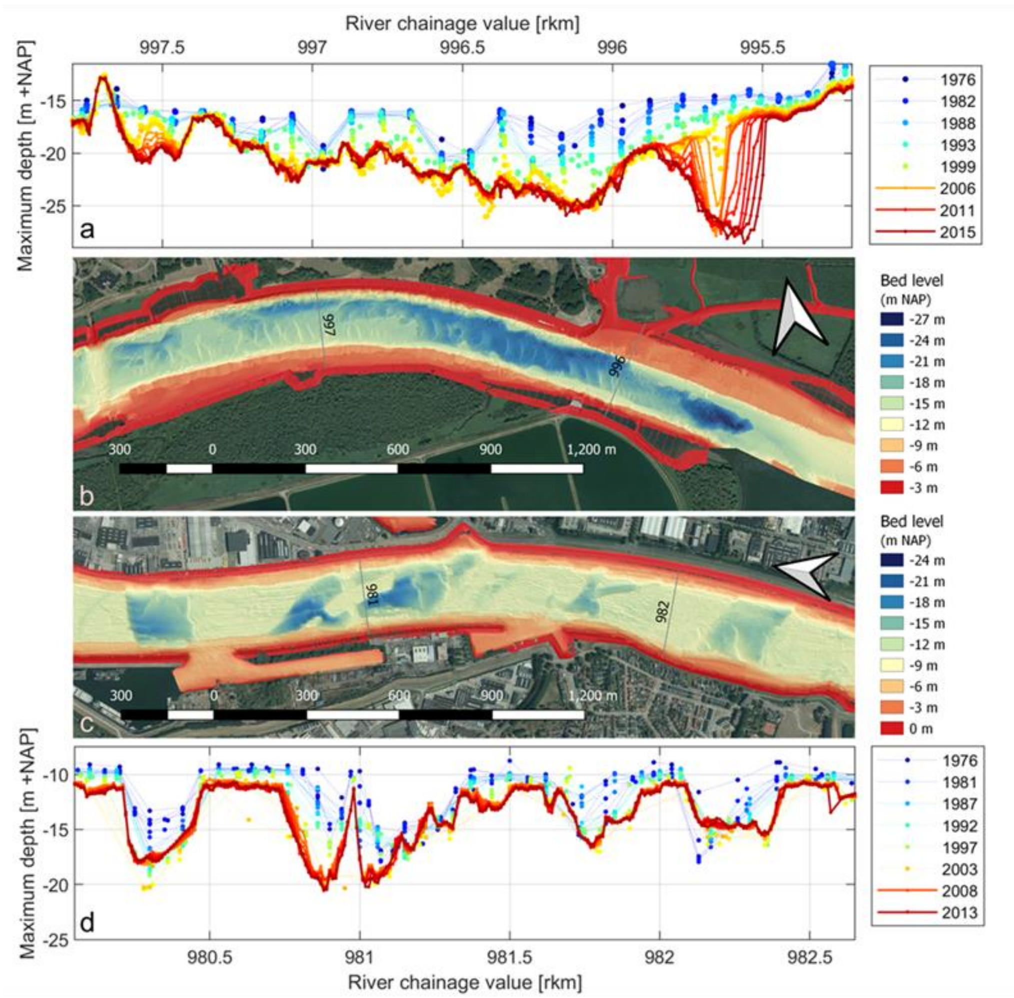

Figure 7 Detailed scour hole evolution for two locations. a) Evolution of the deepest points in the Oude Maas (rkm 997.25 – 995.75), b) corresponding bed topography in 2014. Residual or net sediment-transport direction is westward (to the left in the figure). c) Bed topography Dordtsche Kil (rkm 980.1 – 982.6) in 2014 and d) corresponding evolution of the deepest points. The residual or net sediment-transport direction is northward (to the left in the figure). Maps are created in QGIS with the Esri-Satellite base map.

The scour hole size, growth and shape observed in the displayed section of the Dordtsche Kil, are very different from the scour holes in the Oude Maas section. The scour holes are smaller, with a length of about 200 to 300 m and are irregularly shaped, with seemingly artificial shapes containing sharp angles and rectangular like features. None of the scour holes merged, nor trends are observed which suggest that scour holes will merge. Over the last 8 years, the scour holes show only minor evolution.

A close up of the bed topography around Oude Maas rkm 995.7 and Dordtsche Kil rkm 980.2 is given in Figure 8. The bed topography east of the scour hole in the Oude Maas (rkm $<$ 995.5, bed elevation around NAP -16 m) is very smooth, suggesting the presence of a clay layer, which prevents the formation of bed forms. Nearby core descriptions indicate this is likely clay from the Wijchen Mb., which is found to be present at an elevation of about NAP -16 m (see also the subsurface lithology at rkm 995.65 in Figure 6). In and westward of the scour hole, big blocks of material are observed, which are hypothesized to be blocks of clay that crumbled from the edges in response to undermining of the clay layer by the force of the flow. The bed topography around the scour hole in the Dordtsche Kil shows elongated scratches. Distinct scratches from dredging activities and shipping scours indicate a resistant soil type in which marks do not easily smooth or vanish, likely clay. The subsurface lithological longitudinal section supports this hypothesis.

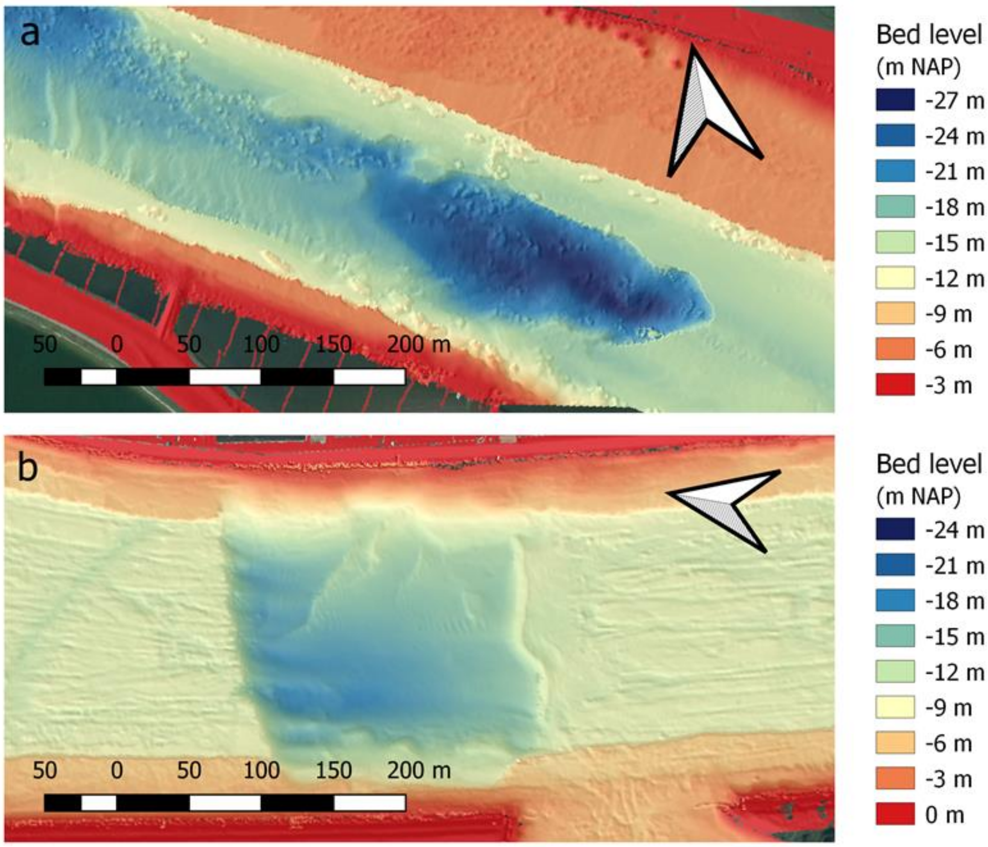

Figure 8 a) Bed topography of the scour hole in the Oude Maas at rkm 995.7 b) and of the scour hole in the Dordtsche Kil at 980.2, both 2014. The smooth bed in the top figure is attributed to a clay layer. The blocks of material in- and downstream of the scour hole are hypothesized to be blocks of clay that crumbled off the edges. The scratches in the bottom figure are attributed to the occurrence of a resistant soil type, likely clay. They do not show a development over time. Maps are created in QGIS with the Esri-Satellite base map.

Based on these observations, the difference in shape and opposite trends in scour hole evolution in the displayed Oude Maas and Dordtsche Kil reach, can be related to the subsurface lithology. The scour holes in the Oude Maas are formed by abrasion of the clay layer and ultimately breaching through of this layer, such that the underlying Pleistocene sand gets exposed to the flow. The edges of the scour holes consist of a relatively thin layer of clay (1 to 2 m), which is thin enough to get crumbled at the edges (Figure 8). As a result, scour holes develop both in depth and area and eventually merge. The Dordtsche Kil scour holes are formed in the sandy channel-belt sand bodies that are crossed by the current river course. According to the lithological longitudinal section in Figure 5, the subsurface flanking the channel-belt sand bodies consists of thick layers of poorly erodible peat and clay with a varying thickness of 3 to 8 meter, suppressing erosion in lateral direction and confining the scour holes to the size of the channel belt. This may also explain the typical rectangular like shape of some of the scour holes, as the current river channel crosses the channel-belt sand bodies. The sharp edges observed may be related to outcrops of peat. Though the thick peat layer currently confines the scour holes to the area of the channel belt, slopes within the scour holes are observed to slowly get steeper, indicating that growth has not stopped entirely.

The third in detail investigated location is in the Noord River (Figure 9). At this location an elongated scour hole developed at the eastern side of the river. The evolution of the cross sections shows a slight asymmetry already present in 1976. Between 1976 and 2016, 0 to 2 m erosion occurred in depth at the western side, while up to 6 m erosion occurred at the eastern side, leading to a total asymmetry of about 6 m. At the western side the bed topography displays irregular features that show up as small yellow patches in the top view presented in Figure 9a and oscillations in the cross sections in Figure 9b. Core descriptions also indicate an asymmetry in the subsurface lithology, with a thicker layer of peat at the western side and deep down at about -14 m NAP erosion resistant Wijchen Mb. clay and a thinner layer of peat on the eastern side and deep down at about -12 m NAP Pleistocene sand.

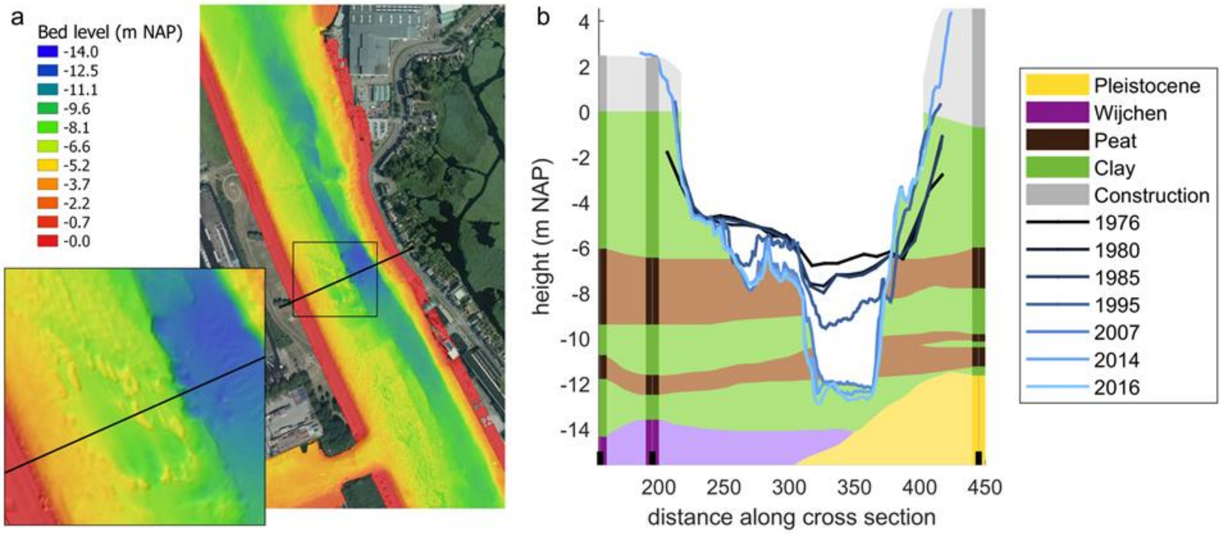

Figure 9 a) bed topography of a scour hole in the Noord (2014). Map is created in QGIS with the Esri-Satellite base map. b) evolution of the river bed at several moments in time, superposed on a reconstruction of the subsurface lithology (Stouthamer & De Haas, 2011). Boreholes are shown in bright colour; the interpolation is shown in faded colour.

As the river narrows locally, the river bed is expected to be deeper at this location. The strong asymmetric development is hypothesized to be an interplay between asymmetries in both the hydrodynamic conditions and in the subsurface lithology. The initial asymmetry, as observed in 1976, is likely caused by asymmetric flow patterns induced by the local channel narrowing at the eastern side of the channel. The observed irregularities on the western part are attributed to the presence of peat, showing that this part of the river is located in a poorly erodible peat layer which is only slowly degrading. Due to the asymmetry in the flow, the eastern side of the channel succeeded to completely erode this poorly erodible peat layer and reached its base at around 1995. Since then the erosion accelerated, as it reached the underlying clay layer, which generally has a higher erodibility, especially when some sand is mixed. This has further enhanced the asymmetric development.

To confirm this hypothesis, new corings should be carried out. These could also shed light on the recent evolution of the scour hole. Since 2007 the scour hole is only slowly growing in depth. This suggests that the peat layer that is interpreted to be located at about -10 to -11 m NAP, may actually be located a bit deeper, at about -12 m NAP, as is the case on the western side of the channel (see borehole data in Figure 9). This would then match the observation of a fast growth between -9 m NAP (1995) and -12 m NAP (2007) and the limited growth since then.

5 Discussion

5.1 Lithological control on scour hole formation

Most prominent from the analysis is the diversity of the size, shape and growth characteristics of the scour holes. Various factors likely contribute. Firstly, the causes that trigger scour hole formation range from bend scour (e.g. Andrle, 1994; Beltaos et al., 2011; Blanckaert, 2010; Engelund, 1974; Gharabaghi et al., 2007; Odgaard, 1981; Ottevanger et al., 2012; Vermeulen et al., 2015; Zimmermann & Kennedy, 1978), confluence scour (e.g. Best, 1986; Best & Rhoads, 2008; Ferrarin et al., 2018; Silvia S. Ginsberg & Perillo, 1999; Ginsberg et al., 2009; Kjerfve et al., 1979; Mosley, 1976; Pierini et al., 2005), local channel narrowing and local scour induced by the impact of a structure on the flow, like bridge piers, groynes and bed protection (e.g. Liang et al., 2020; Pandey et al., 2018; Wang et al., 2017). These types of scour holes evolve differently, have different shapes and as a result different relations for predicting their equilibrium depth (Hoffmans & Verheij, 1997). Secondly, conditions like flow velocity, water depth and grain size that influence scour hole growth, vary throughout the estuary. Third reason is the lithological influence on scour hole formation, which in current analyses proofs to be a major influence on scour hole initiation, growth rate and shape and which in certain cases even overrules the above listed causes and controls. In figure 10 the three lithological controls are illustrated.

Firstly, lithology may trigger scour hole formation (Fig. 10a). A prominent example is the large-scale incision of the Dordtsche Kil river into the heterogeneous subsurface lithology, leading to formation of scour holes of up to two times the average water depth at locations with higher erodibility. At these locations no other causes for scour hole formation are present. In the southern part, where the river incises into a homogeneous sand layer, no scour holes are found, while the hydrodynamic conditions are similar. This forms the most direct proof that variations in lithology cause scour hole formation. It is in line with observations by Cserkész-Nagy et al. (2010), who reasoned scour holes observed in a straight river section to be triggered by variations in the subsurface lithology and with Sloff et al. (2013) who demonstrated this process conceptually and numerically. Secondly, lithology determines whether and when a scour hole can form and when fluctuations in growth rate occur (Fig. 10b). An insightful example is the scour hole at the confluence of the Spui and Oude Maas river (Figs. 6-7). Though the confluence in its present outline already exists for over a century (www.topotijdreis.nl), no confluence scour emerged until recently in 2005. Only after reaching a transition from resistant clay to sand, in ten years' time a scour hole with a depth of -27 m NAP emerged, i.e. an average growth in depth of 11 m in 10 year. These abrupt changes in growth in depth are observed for various scour holes in the Rhine-Meuse Estuary (Figure 6) and can in most cases be related to a transition in lithology with different erodibility. Though not proven, it is also the most likely cause for abrupt changes in growth for the other scour holes, as other causes like a strong increase in flow, a newly placed construction, or failure of bed protection do not apply.

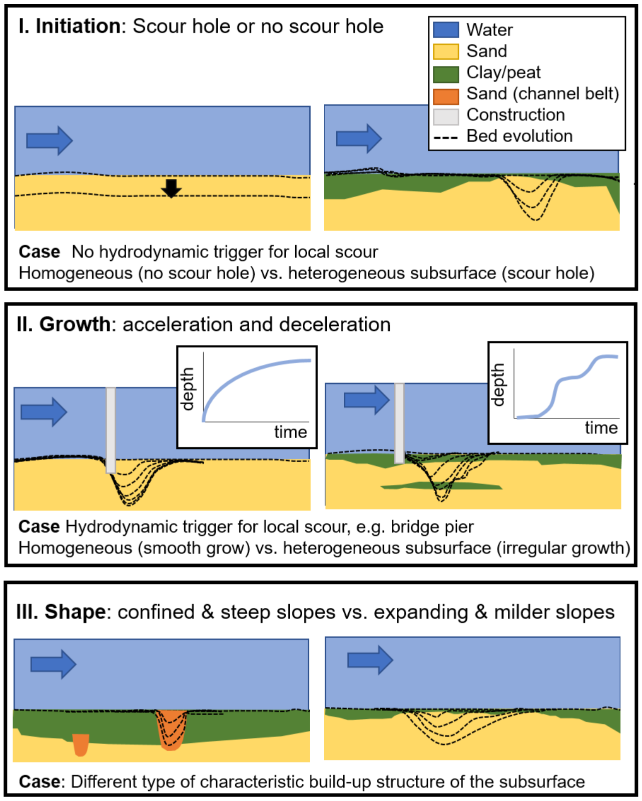

Figure 10. Summary of the observed lithological controls on scour hole development. All figures display a longitudinal section of a river reach, with the blue arrow indicating the flow direction. Dashed lines represent the bed level development over time.

Thirdly, in horizontal direction the subsurface lithology can be a dominant factor in determining the shape or growth rate (Fig. 10c). Scour holes with edges composed of thin layers of clay (< 2 m thickness), are observed to grow in extent. In high resolution multibeam surveys, indications are found that these clay layers are undermined and crumble, enabling the scour hole to grow laterally and merge with nearby scour holes. As a resultant scour holes form of more than a kilometre in length. The opposite is observed for the scour holes in the Dortdsche Kil, which are relatively small (< 300 m in length) and show only subtle changes in horizontal direction. These scour holes are formed in former channel belts and their edges consist of thick layers of peat and clay (3 to 8 m thickness), confining the scour holes to the extent of the channel belt, suppressing further growth in extent.

In case of variations in subsurface lithology over the river cross section, scour holes can take an asymmetric shape and get confined to only one side of the channel. In this case, there may be an extra positive feedback with the flow. In the deeper part flow attraction may occur, with higher relative flow velocities with respect to the shallower part of the cross section (Sloff et al., 2013), as a result of lower relative friction. Due to the enhanced relative flow velocities, shear stresses at the deeper part of the river bed are higher than at the sides, which further enhances the asymmetry in erosion.

The strong lithological control on scour hole formation is in line with the reported effect of the subsurface lithology on the formation of eb-tidal channels in the Ems (Pierik et al., 2019) and erosion and lateral migration of the Tisza river (Cserkész-Nagy et al., 2010). It may also explain the deviations in expected scour depth, location and shape observed in the Venice Lagoon (Ferrarin et al., 2018).

5.2 Equilibrium

There is no clear relation between recent 5-year scour hole growth and overall bed level degradation. This means that the strongest scour hole growth is not necessarily found in the branches with the highest erosion rate. The occurrence of local scour and sand mining may explain some of these cases, but a closer look at the 40-year depth evolution of the scour holes in the eroding Dordtsche Kil and Oude Maas branches shows that for most of the scour holes, the recent depth growth rates have decreased or even reversed to sedimentation. In response to the higher flow velocities due to closure of the Haringvliet, the scour hole depth increased for all cases. As Haringvliet was closed decades ago, it is likely that most scour holes are reaching an equilibrium depth, like also occurs for local scour induced by constructions (Hoffmans & Verheij, 1997). That an equilibrium depth also applies for the scour holes induced or influenced by a heterogeneous subsurface lithology is plausible, as the same physics apply. The deeper the scour hole gets, the more effort it takes to transport sediment up the slope while, depending on how the flow structures evolve, generally the flow velocities within the scour hole decrease with depth. Another explanation for a slower or reversed depth development may be the presence of a poorly erodible layer at the bottom of the scour hole (Cserkész-Nagy et al., 2010). This is clearly the case for scour hole 18 (Figure 18), which reached a poorly erodible clay layer. It may also be a factor for the scour holes in the Dordtsche Kil, as the depth of the channel-belt sand bodies in which the scour holes formed is interpreted to be close to the current scour hole depth (Figure 5). As the channel-belt bodies are commonly composed of finer grained sands than the coarser grained Pleistocene sand layer below (e.g. Berendsen, 1982; Gouw & Erkens, 2007; Weerts & Busschers, 2003), the erodibility is lower, reducing the scour hole depth growth. According to the lithological longitudinal sections, most of the Oude Maas scour holes are already based within the Pleistocene sand and are not at a depth close to reaching a transition in lithological composition. However, as the Pleistocene sand gradually coarsens with depth (Busschers et al., 2005, 2007), this may still have an impact. For these scour holes, it is likely that a combination of coarsening of sediment with reduced hydraulic forcing due to reaching a larger depth, results in a reduced growth or stabilization of depth. To further quantify the relative contributions of each process a combination of flow measurements and calculations with data on the grainsize distribution in the lower part of the scour hole is needed.

5.3 Consequences and risks for other rivers and estuaries

Provided enough hydraulic forcing, the subsurface lithology can have a large impact on when and where scour holes form, or even be dominant. The observed influences and controls on initiation, growth rates and size, as illustrated in Figure 10, apply to any system with a heterogeneous substratum of alternating peat, clay and sand deposits. Though little has been reported, these controls are therefore likely not unique to the Rhine-Meuse Estuary. Channel bed degradation, also occurs in other large delta rivers like the Yangtze, the Mississippi and the Mekong (Brunier et al., 2014; Galler et al., 2003; Hoitink et al., 2017; Luan et al., 2016; Sloff et al., 2013; B. Wang & Xu, 2018). And as causes are mainly anthropogenic, more delta rivers are expected to follow. Given the fact that river deltas commonly have a heterogeneous substratum of alternating peat, clay and sand deposits (e.g. Aslan & Autin, 1999; Aslan et al., 2005; Berendsen & Stouthamer, 2001, 2002; Cohen et al., 2012; Gouw & Autin, 2008; Hanebuth et al., 2012; Kuehl et al., 2005.; Stefani & Vincenzi, 2005), scour hole formation in heterogeneous subsurface is expected to become a problem in more deltas. Hints are there that for the Ems river (Pierik et al. 2019), the Venice Lagoon (Ferrarin et al., 2018), Mississippi river (Nittrouer et al., 2011) and the Mekong river, the subsurface lithology already plays a role in the scour hole development, as scour holes in these studies show deviating location, shape or depth, while the subsurface is heterogeneous. When for these systems only the hydraulic component is taken into account, as commonly the case, there will be a misprediction of the scour hole evolution, depth, shape and location. In case scour holes are close to infrastructure or river banks, stability is at stake. As accurate predictions on scour hole formation are of high importance, especially in densely occupied areas like deltas (Best, 2019; Syvitski et al., 2009), we therefore advocate to explicitly include the geology, when predicting scour hole formation and growth. This requires knowledge of the subsurface lithology, acquired with a combination of measurements and geological interpretation, as elaborated in the methods section. Based on the specific geological structure, the risk of new scour hole formation can be assessed, as well as the likelihood whether scour holes stay confined or expand. Given the other controls of lithology on the lateral behaviour of river branches (Cserkész-Nagy et al., 2010) and the evolution of eb-flood channels (Pierik et al., 2019), it is important to include the lithology into numerical models (van der Wegen & Roelvink, 2012). Therefore, measuring subsurface lithology and including these parameters in scour-hole risk-assessments and numerical models will be an important improvement over current analysis, which focus mainly on the hydraulic forcing assuming a homogenous substrate.

6 Conclusions

Although a vast amount of research has been carried out on scour holes, little is known on how the lithology influences the location, size, shape and growth rates of scour holes. This is, however, essential information in judging whether scour holes form a risk for the stability of river banks, dikes or other nearby infrastructure. The present study presents a first in depth analysis on how the lithology controls the bed topography and scour hole growth in particular. The Rhine-Meuse estuary is used as a study area, as over 100 scour holes are present and detailed data are available on both bed level evolution and subsurface lithological composition.

From analysing over 40 years of bed level evolution in relation to the geology, it is shown that subsurface lithology can play a crucial role in the emergence of scour holes, their shape and evolution. In the Rhine-Meuse Estuary several branches are eroding in response to closure of one of its tidal outlets. Reaches with a sandy subsurface erode evenly, while in reaches with a heterogeneous subsurface lithology erosion is retarded at locations with a poorly erodible top layer and promoted at locations where locally a sandy subsurface is present. At these locations, deep scour holes form with depths of up to two times the average water depth. Their shapes can be very irregular and strongly deviating from an oval like shape. These shapes are imposed by the poorly erodible top layer, inhibiting the scour hole to more naturally grow in width or length. The consequent growth characteristics are often erratic, with sudden changes in depth or extent. Naturally, scour holes follow an exponential development with a fast initial growth and slower final growth. Though this analysis shows that scour holes in heterogeneous subsurface generally follow the same growth curve, temporally strong variations in development in depth or extent are observed.

The direction of growth is also strongly determined by the composition of the subsurface. Scour holes with edges composed of thin layers of clay are observed to grow in extent. Indications are found that the thin clay layers crumble and enable scour holes to grow laterally and merge with nearby scour holes, forming elongated scour holes of more than a kilometre in length. The opposite is observed for scour holes that are formed in channel belts with thick peat and clay layers at their edges, confining the scour holes to the extent of the channel-belt sand body crossed by the river channel and allowing for limited growth in horizontal direction. In case of asymmetries in the erodibility over the channel width, scour holes take an asymmetric shape and can get confined to only one side of the channel, nearing a channel bank.

These findings emphasize the crucial role that geology plays in the spatial and temporal evolution of river bed erosion. It co-determines the pace of erosion and the related long-term evolution of river branches and tidal channels and it can initiate and influence scour hole formation. It therefore calls for good knowledge of the subsurface lithology as without, the erratic scour hole development is hard to predict and can lead to sudden failures of nearby infrastructure and flood defence works. In addition, for making proper morphodynamic predictions, information on the subsurface lithology needs to be included in numerical models.

Data Availability Statement

There is no restriction on the data used in this study. Bed topography data can be requested at Rijkswaterstaat via https://www.rijkswaterstaat.nl/formulieren/contactformulier-servicedesk-data.aspx. Lithological core descriptions can be downloaded from the DINO loket: www.dinoloket.nl. Lithological sections constructed from the lithological core descriptions are available in (Huismans et. al., 2013; Stouthamer & De Haas, 2011; Stouthamer et al., 2011b-d; Wiersma, 2015). Channel belt reconstruction can be downloaded from http://dx.doi.org/10.17026/dans-x7g-sjtw (Cohen et al., 2012).

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