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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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 for scour hole formation. When the substratum consists of an erosion resistant 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 of these scour holes makes them difficult to manage, particularly where the stability of dikes and infrastructure is 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 descriptions are available. It is shown that the subsurface lithology plays a crucial role in the emergence, shape, and evolution of scour holes. Although most scour holes follow the characteristic exponential development of fast initial growth and slower final growth, strong temporal variations are observed, with sudden growth rates of several meters per year in depth and tens of meters in extent. In addition, we relate the characteristic build-up of the subsurface lithology to specific geometric characteristics of scour holes, 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 thorough knowledge of the subsurface lithology, as without it, scour hole development is hard to predict and can lead to sudden failures of nearby infrastructure and flood defence works.

Keywords: Scour holes, morphology, geology, delta rivers

1 Introduction

Scour holes are common features in rivers and estuaries. With their steep slopes and large depths, these scour holes can threaten the stability of nearby infrastructure like embankments, bridge piers, tunnels and pipelines (e.g. Gharabaghi et al., 2007; Beltaos et al., 2011; Wang et al., 2017; Pandey et al., 2018; Liang et al., 2020). The formation and development of local scour, bend scour, and confluence scour are widely studied (e.g., Engelund, 1974; Mosley, 1976; Zimmermann & Kennedy, 1978; Kjerfve et al., 1979; Odgaard, 1981; Best, 1986; Andrle, 1994; Ginsberg & Perillo, 1999; Pierini et al., 2005; Gharabaghi et al., 2007; Best & Rhoads, 2008; Blanckaert, 2010;

Beltaos et al., 2011; Ottevanger et al., 2012; Vermeulen et al., 2015; Wang et al., 2017; Ferrarin et al., 2018; Pandey et al., 2018; Liang et al., 2020). 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, although this may greatly impact the scour hole evolution or even induce scour hole formation (Fig. 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; Sloff et al. 2013; Huismans et al. 2016).

Many of world's large rivers in deltas face channel bed degradation, such as the Yangtze, the Rhine-Meuse Estuary, the Mississippi and the Mekong rivers (Galler et al. 2003; Sloff et al. 2013; Brunier et al. 2014; Luan et al. 2016; Hoitink et al. 2017; Wang and Xu 2018). The causes of this degradation are mainly anthropogenic and range from extracting sediment by dredging and sand mining, to a reduction in sediment supply due to the presence of upstream dams, or to 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; Berendsen & Stouthamer, 2001, 2002; Aslan et al., 2005; Kuehl et al., 2005.; Stefani & Vincenzi, 2005; Gouw & Autin, 2008; Cohen et al., 2012; Hanebuth et al., 2012), and are among the regions with the highest population density (Syvitski et al. 2009; Best 2019), understanding how lithology controls the scour hole development is highly relevant to sustainable river management.

A detailed analysis of the influence of a heterogenous subsurface lithology on the general channel bed morphology is carried out 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, three of which consist 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. The heterogeneous

channel deposits are furthermore found to influence the depth of meander pools in the Lower Mississippi river (Hudson, 2002; Gibson et al., 2019). 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 ebb-tidal 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 subsurfaces both conceptually and with a numerical model. In an exploratory study by Huismans et al. (2016), the link between scour hole occurrence and the composition of the subsurface lithology was made directly by combining multibeam surveys with detailed geological maps constructed based on lithological data from corings.

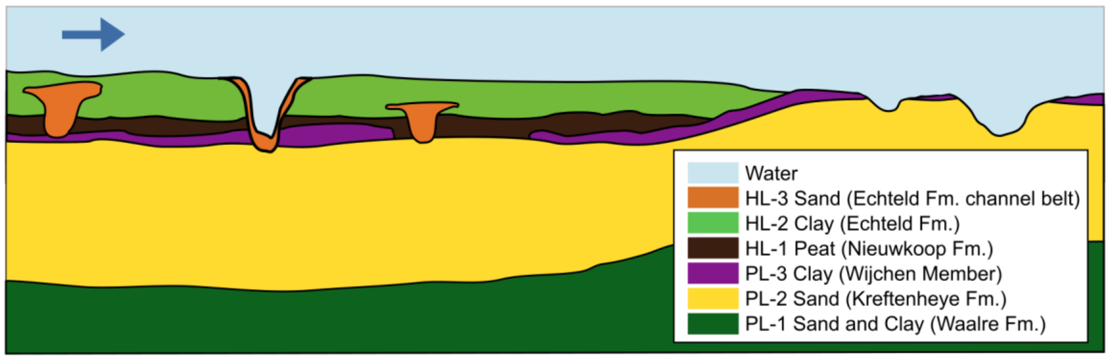

Figure 1. Conceptual longitudinal subsurface lithological longitudinal section of a river bed, with typical distances of 10 to 20 meters in depth and 10 to 20 km in length. Arrow indicates flow direction. In colour the lithological formations (Fm.) and members are indicated. Scour holes form in layers or patches composed of sandy material with lower erodibility compared to the surrounding resistant clay or peat layers.

The influence of lithology on the time- and spatial evolution of scour holes has never been studied. In this paper we analyse in detail how the subsurface lithology influences the bed elevation in net incising river branches. We focus 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. We hypothesise that the lithology can trigger scour hole formation and that it can be a dominant factor in controlling the growth rates and shape.

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 surveys and lithological data from many corings are available. This allows the analysis of decades of bed level evolution and linking it to the subsurface composition. Because much fewer scour holes are found upstream from the tidally- influenced Rhine Meuse Estuary and the subsurface lithology is less heterogeneous, this study focusses on the Rhine Meuse Estuary and is not extended further upstream. 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 five-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 two 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 (Fig. 2). During the Late Pleistocene Younger Dryas stadial (12.900-11.700 cal yr. BP), the area consisted of a 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 (Pons, 1957; Berendsen et al., 1995; Berendsen & Stouthamer, 2000; Cohen, 2003; Gouw & Erkens, 2007; Hijma, 2009; Janssens et al., 2012). The sandy sediments deposited by the braided rivers predominantly consist of gravel and coarse sand (Kreftenheye Fm., PL-2, Fig. 1). At the top of these deposits finer grained sand is found, with grain sizes varying from 150 µm to 300 µm (Vos & Cohen, 2014). During flood events, fine-grained sediments were deposited on the floodplains, forming a resistant silty clay layer (Wijchen Member, PL-3) (Törnqvist et al. 1994; Busschers et al. 2007; Hijma et al. 2009). In most of the study area, this silty clay layer (Wijchen Mb.) covers the Pleistocene sandy deposits (PL-2). Due to rapid early Holocene sea level rise, the area changed from a wide river valley into an estuary (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 became regionally 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 sediment supply to the river increased (Stouthamer & Berendsen, 2000; Erkens, 2009). 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 (Fig. 3a) (Berendsen & Stouthamer, 2000; Pierik et al., 2018; De Haas et al., 2019). 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).

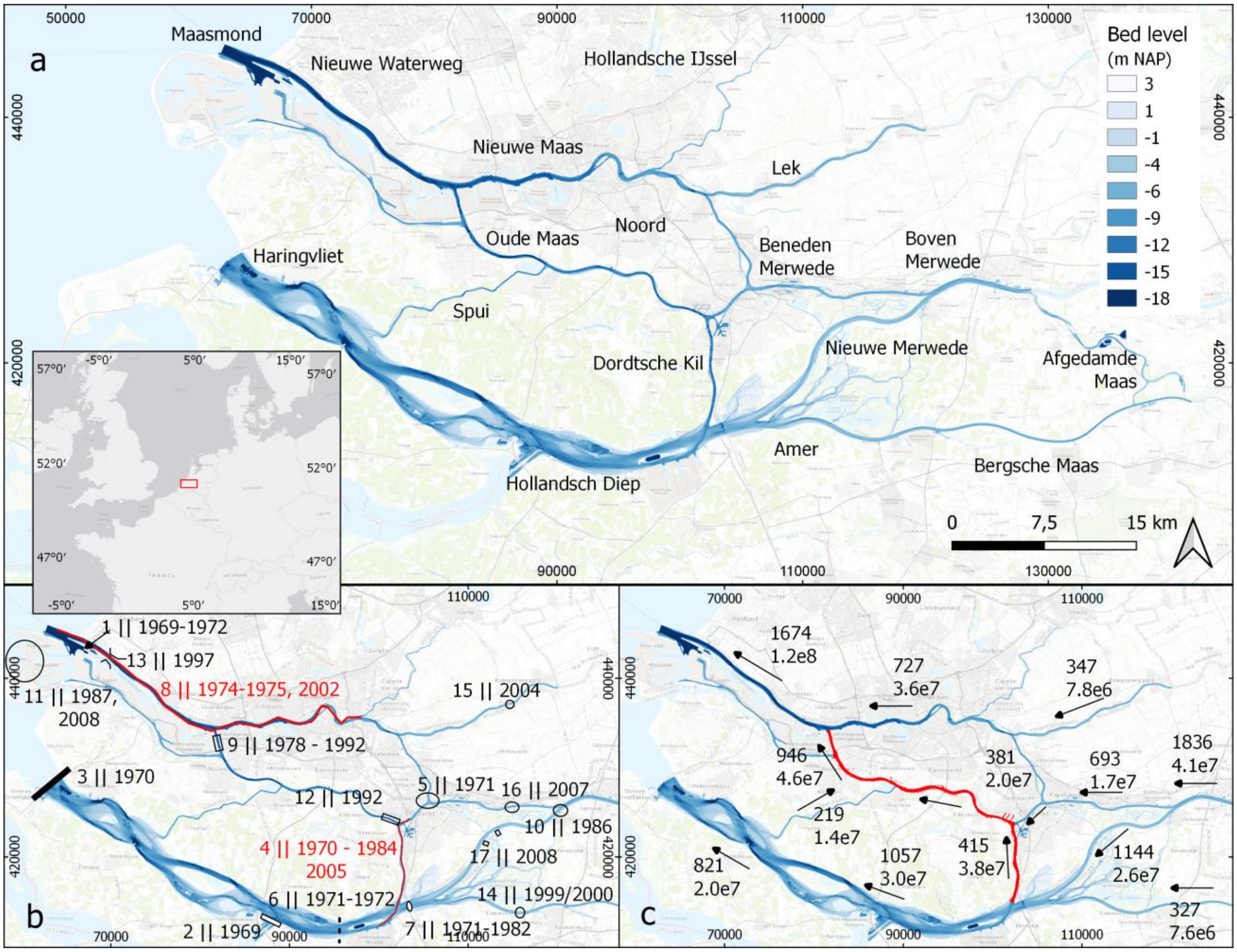

Figure 2 a) Overview of the river channels forming the Rhine-Meuse Estuary (the Netherlands). In colour the bed level is represented (year 2013, 2014). Coordinates in Amersfoort/ RD-new. The inset shows the location of the study area in NW-Europe. b) Overview of the most relevant engineering modifications since 1970, with details in table 1. c) Overview of averaged values of net river discharges (top numbers, in m^3/s) and tidal volumes (lower numbers, in m^3), from a one-dimensional numerical-model simulation for the year 2013 (Cox et al., submitted). The branches that are studied in more detail in this paper are indicated in red. Maps are created in QGIS with the Esri-TOPO base map and Esri-Grey (light) base map (inset).

Table 1. Overview of the most relevant engineering measures since 1969 (Rijkswaterstaat, 2005; Sloff et al., 2011).

Year	**no**	**branch**	**Measure**
1969-1972	1	Nieuwe Waterweg	Construction of a dam between Nieuwe Waterweg and the access channel to Europoort.
1969	2	Hollandsche Diep	Closure Volkerak from Hollandsch Diep with a dam and ship locks.
1970	3	Haringvliet	Closure Haringvliet with sluices.
1970-1984	4	Dordtsche Kil/ Hollandsch Diep/ Oude Maas	Reconstruction Dordtsche Kil and deepening navigation channel (-8 m NAP).
1971	5	Beneden Merwede	Adjustment bifurcation with Noord and Oude Maas.
1971-1972	6	Hollandsche Diep	Construction of pipelines.
1971-1982	7	Hollandsche Diep	Dumping of sediment in deeper parts between Moerdijkbridges.
1974-1975	8	Nieuwe Waterweg, Nieuwe Maas	Construction "Trapjeslijn" a staircased bed with a stepwise increasing bed level.
1978 - 1993	9	Oude Maas	Construction of dams in the river bed (1978), filling up of deeper parts (1985-1986) and removal of two of the dams (1993).
1986	10	Nieuwe Merwede	Construction Beatrixhaven (Werkendam)
1987	11	Maasmond/ offshore	Construction of sludge depot Slufter
1992	12	Oude Maas	Shortening of groynes
1997	13	Nieuwe Waterweg	Construction storm surge barrier "Maeslantkering" finalised
1999-2000	14	Amer	Adjustment connection Wilhelminakanaal and Amer
2000, 2002	7	Nieuwe Waterweg, Nieuwe Maas	Deepening Trapjeslijn between km 1005 and 1013
2004	15	Lek	Bed cut-off, right bank near Bergambacht
2005	3	Dordtsche Kil/ Hollandsch Diep	Deepening navigation channel (-9.4 m NAP)
2007	16	Beneden Merwede	Construction open connection with polders
2008	11	Maasmond/ offshore	Start of construction ”Tweede Maasvlakte”.
2008	17	Nieuwe Merwede	Open connection Spieringpolders and polder Hardenhoek

Since the onset of 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 (Fig. 2). Since that time, continuous deepening of channels, construction of groynes and longitudinal dams (~1850-1920), and closure or reconstruction of river branches impacted the Rhine-Meuse Estuary. An overview of the most relevant interventions since 1969 is given in

Figure 2b and Table 1. The measure which had the largest impact on the system as a whole is the closure of one of its tidal outlets in 1970, the Haringvliet (no. 3, Table 1). The closure caused a major change in the hydrodynamics (Vellinga et al., 2014), leading to enhanced flow velocities in the connecting channels which triggered erosion of the river bed (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. To keep the navigation channels open, an average of about 1.7 Mm^3 of sediment per year was dredged between 2000-2018 (Cox et al., submitted). At present, most dredging occurs in the northern channels (1.09 Mm^3/year), the Merwedes (0.37 Mm^3/year) and the Hollandsche Diep (0.20 Mm^3/year). In the connecting channels, only limited amount of dredging is carried out (0.04 Mm^3/year).

The hydrodynamics in the Rhine Meuse Estuary are driven by a combination of river discharge and tide (Fig. 2c). From upstream the system is fed by three rivers, the Lek, Waal, and Meuse. During normal conditions, the dominant discharge route is through the Nieuwe Merwede, Dordtsche Kil and Oude Maas to the Nieuwe Waterweg and Maasmond, which forms the main outlet. During high river discharges, the net river discharge entering the system 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 completely close, and all water leaves the system via the Maasmond to limit salt intrusion in the Maasmond and ensure the fresh water supply in the estuary. The tidal influence decreases landwards. Due to closure, the tidal volumes in Hollandsche Diep and Haringvliet have dimished, and are small compared to their dimensions. In Table 2, details on the net discharges and ebb- and flood velocities are given for the Dordtsche Kil and Oude Maas, the two branches for which we analyse historic scour hole growth in relation to their geology.

Table 2. Overview of the velocity (v) and discharge (Q) conditions for the Oude Maas and Dordtsche Kil river. As no continuous measurements are available, values are extracted from a one dimensional numerical-model simulation for the year 2013.

Branch	**v average (m/s)**		**v 90 percentile (m/s)**		**v max (m/s)**		**Q (m^3/s)**
	ebb	flood	ebb	flood	ebb	flood	
Dordtsche Kil	0.65-0.72	0.63-0.73	0.98-1.09	0.87-1.02	1.24-1.36	1.15-1.39	415
Oude Maas (between Dordtsche Kil and Spui)	0.49-0.80	0.30-0.53	0.69-1.09	0.50-0.85	0.96-1.45	0.78-1.25	727
Oude Maas (between Spui and Nieuwe Waterweg)	0.62-0.83	0.39-0.55	0.88-1.18	0.63-0.88	1.33-1.72	1.06-1.43	946

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 has a net loss of sediment (Cox et al., submitted).

The genesis of the delta area with avulsions, infilling and abandoning channels and development of marshes, has resulted in a heterogeneous substratum composed of clay and peat layers and encased channel belts of sand. The grain size distribution and other 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 channel bed is mostly sandy, with median grain sizes ranging from 0.25 to 4 mm (Fugro, 2002; Frings et al., 2019). Locally, the channel bed consists of erosion-resistant peat or clay. In the southern part (Haringvliet, Hollandsch Diep, Amer), silt and clay fractions dominate the bed, of which most has settled since the closure of the Haringvliet by a gated barrier in 1970. In the connecting branches (Oude Maas, Noord, Dordtsche Kil, Spui), large areas of erosion resistant clay and peat form the channel bed, but also areas with sand or silt are found (Fugro, 2002; Frings et al., 2019). In the Oude Maas, the channel bed is mostly composed of clay from the Naaldwijk Fm. and Wijchen Mb., and sand from the Kreftenheye Fm. In the Oude Maas reach between the confluences with the Dordtsche Kil and Spui, Basal peat is occasionally found at the channel bed. In the Dordtsche Kil, the channel bed is mostly composed of clay from the Echteld Fm. and sand from the Kreftenheye Fm.

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 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 lithological longitudinal 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, we created a general overview by mapping the recent five-year growth characteristics for all scour holes in the estuary. Secondly, we analysed the evolution of the overall bed level since 1976 for two branches, as well as the growth rates of their scour holes. The observed trends are linked to the subsurface lithology. In the last step, we analysed two sets of distinct scour holes in full detail. These two sets of scour holes differ 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 a digital database with lithological core descriptions (Dino-database: TNO-Geological Survey of the Netherlands, 2010, 2014). For the area of interest, core descriptions from within a range of 2 km of the river channel were selected (Fig. 3). Most descriptions are from cores adjacent 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. 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.

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

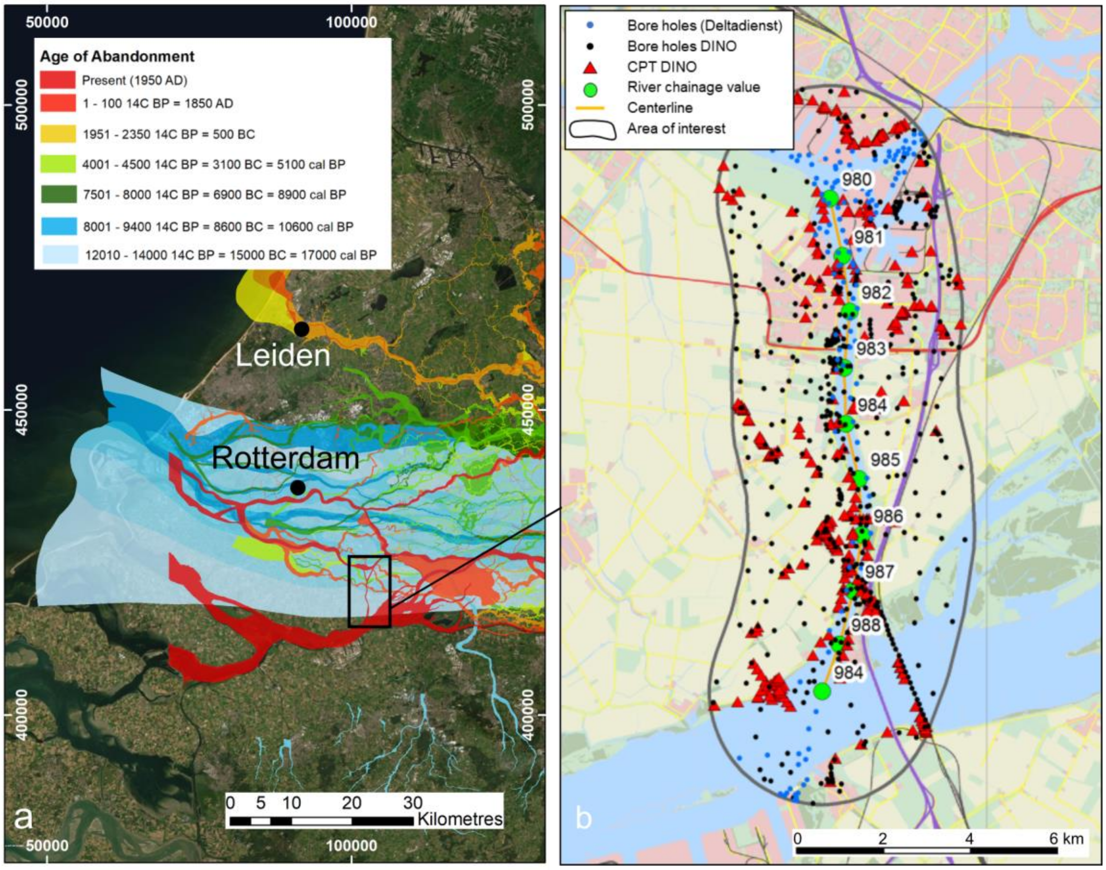

Figure 3 Overview of the main data sources used for the reconstruction of the subsurface lithology, a) overview of the age of abandonment of Holocene channel belts (Cohen et al., 2012), map created with ArcGIS and with World Imagery used as background (Esri, Maxar, Earthstar Geographics, CNES/Airbus 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). The scour holes are detected by visual inspection of the bed topography of 2012. The database is available at Mendeley Data and excludes groyne scour holes, as these develop by local turbulence from the groynes. The groyne scour holes are therefore not typical for the Rhine-Meuse estuary. The 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 bed topography data for the river branches Haringvliet and Brabantsche Biesbosch, the scour holes in those branches were left out from the growth analysis. Based on the multi-beam measurements from 2009 and 2014 the change in extent and depth over five 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.

To analyse the decadal evolution of the scour hole growth in relation to the geology, we focus on two branches, the Dordtsche Kil and Oude Maas. These branches were selected as they face a strong overall bed degradation and have the most comprehensive datasets regarding geology and bed level surveys. For these branches the bed level evolution from 1976 to present is analysed, by plotting the maximum depth along the river. For each river km interval, the deepest point over the width of the river is determined (thalweg). For the single beam measurements, the maximum depth per measured cross-section is taken, which results in resolutions ranging between 25 m to 125 m, depending on the spacing of the original single beam tracks. For the interpolated single beam and multibeam data, the thalweg has a resolution 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 the depth is stabilising. 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, we analyse two reaches in full detail. To determine the length-width ratio of the scour holes, the smallest possible rectangle is fitted around each scour hole. The elevation of the scour hole edge is inferred from the elevation profile. The elevation at which the inflection point is located is regarded as the scour hole edge. In some cases the slope changes gradually and no clear inflection point is present. For these cases the elevation at which the bed becomes horizontal is taken as the scour hole edge.

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 (Fig. 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 five years’ time.

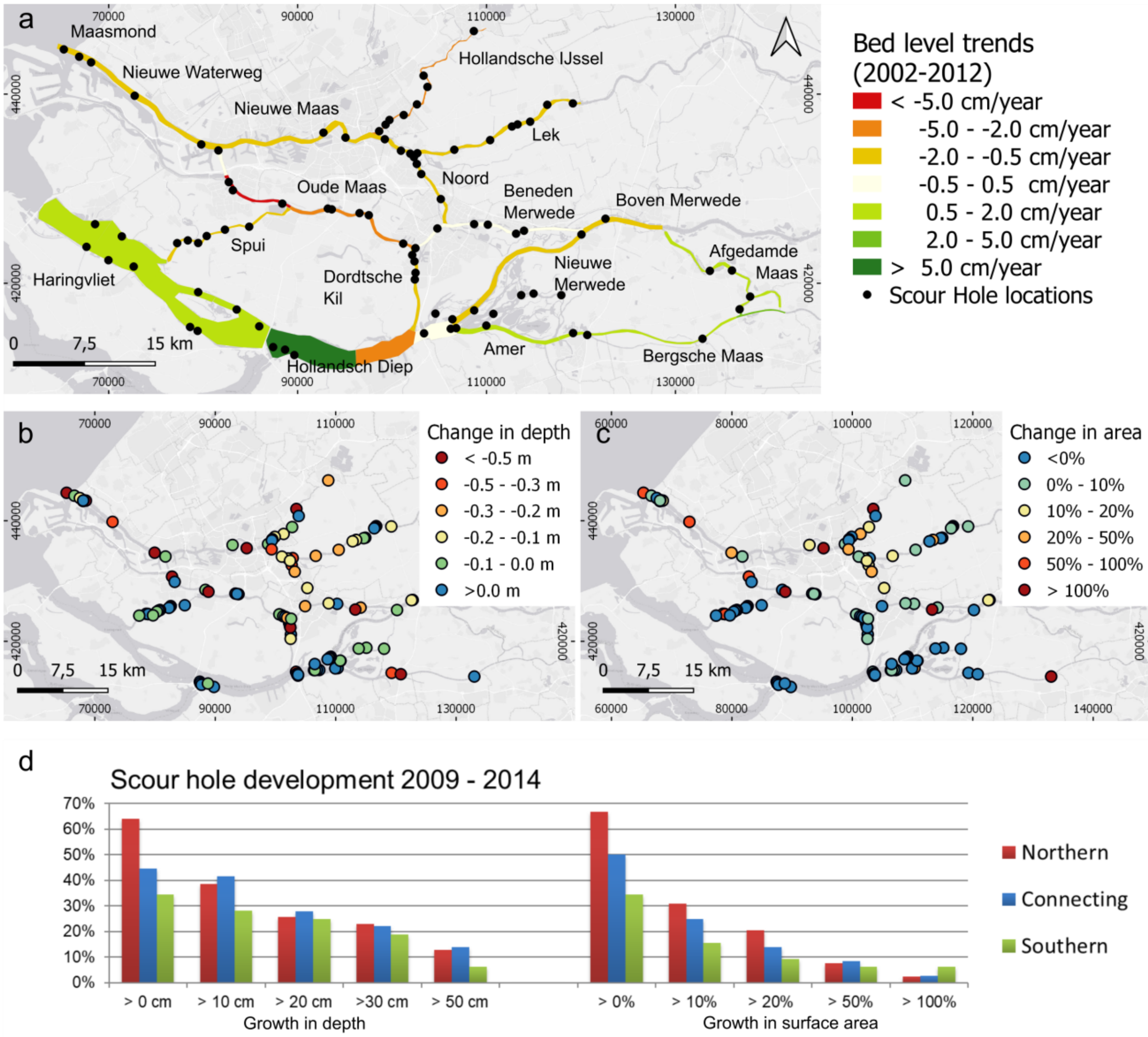

Figure 4 a) overview of the bed level trends 2002-2012 (data from Becker (2015)) and the identified scour holes (locations from Huismans et al., 2016) of the Rhine-Meuse Estuary. b-c) Five-year scour hole growth in depth (left) and extent (right) (this paper). d) Bar plot of the growth rates per region, 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 (Merwede rivers, 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. First, the geometric setting is introduced in Figure 5, because this can influence the scour hole growth via turbulent flows induced by e.g., confluences, bends, and structures. Scour holes are found in both straight and curved parts of the river, where they are superimposed on a mild pool-riffle morphology (Leopold & Wolman, 1960; Leopold et al., 1964). Note that most bends are mildy curved with radii greater than 2 km. Only three bends show somewhat stronger curvatures with radii ranging between 1 – 1.7 km. Scour hole number 17 is caused by bridge piers, while scour holes 6, 7 and 14 are located less than 500 m downstream from a river confluence. This shows that a clear trigger is present for some of the scour holes. To explain the rest of the scour holes, we must also account for the underlying geology.

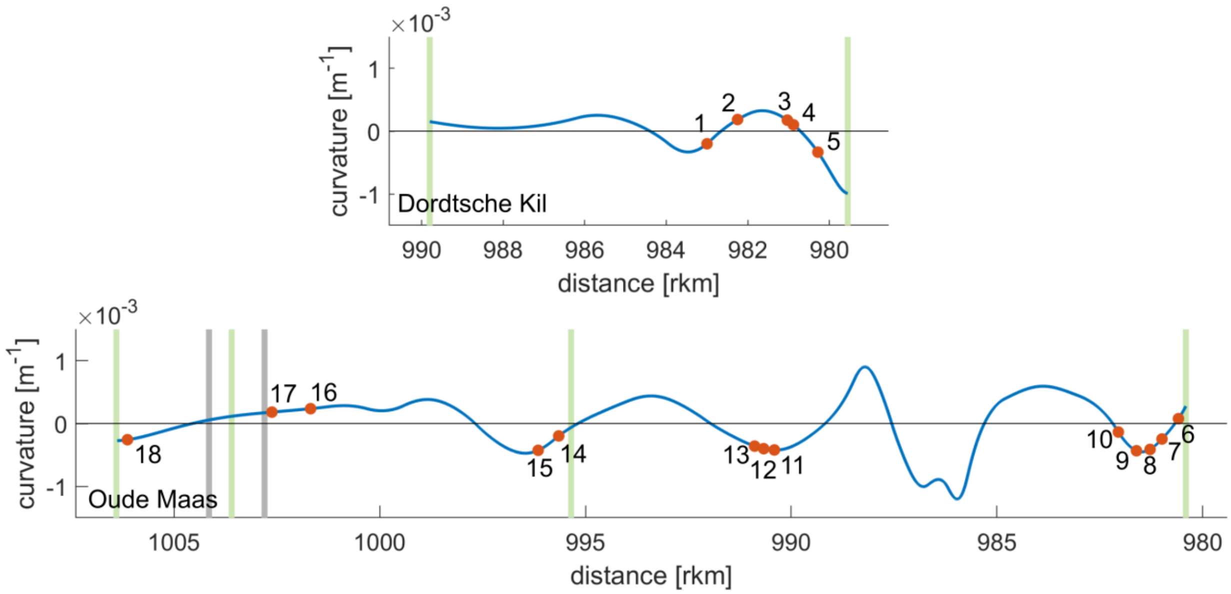

Figure 5. Inverse value of the radius of curvature plotted against the distance along the river. Red dots indicate the scour hole locations, the green bars the confluences and the grey bars the bridges. As groyne scours are excluded from the database, these are not indicated.

Figure 6 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 km 980 – 983) and the southern part (river km 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 resistant clay interspersed with highly erodible sand bodies from abandoned and burried channel belts. At locations where the river bed is composed of clay, erosion rates are suppressed, while in the highly erodible sand bodies, scour holes have emerged or existing scour holes have undergone further erosion. Hence, the palaeo-channel belts mapped on land on both sides of the river are clearly visible in the river morphology as scour holes.

A major engineering intervention that may have affected the scour hole growth is the reconstruction of the Dordtsche Kil, where the navigation channel was modified and deepened to -8 m NAP between 1970 – 1984 (Table 1). Figure 6a shows that most of the scour holes were already present in 1976, though mostly with limited depth. It cannot be verified whether the scour holes were initiated by natural erosion, or whether dredging to -8 m NAP caused a resistant layer covering the channel belts to be removed, allowing for faster erosion in the channel belts than in the surrounding resistant clay and peat bed. Regardless of the cause of erosion, without heterogeneous subsurface lithology, no scour holes would have emerged, as there are no triggers present for causing such local scour, like constructions, sharp bends or confluences.

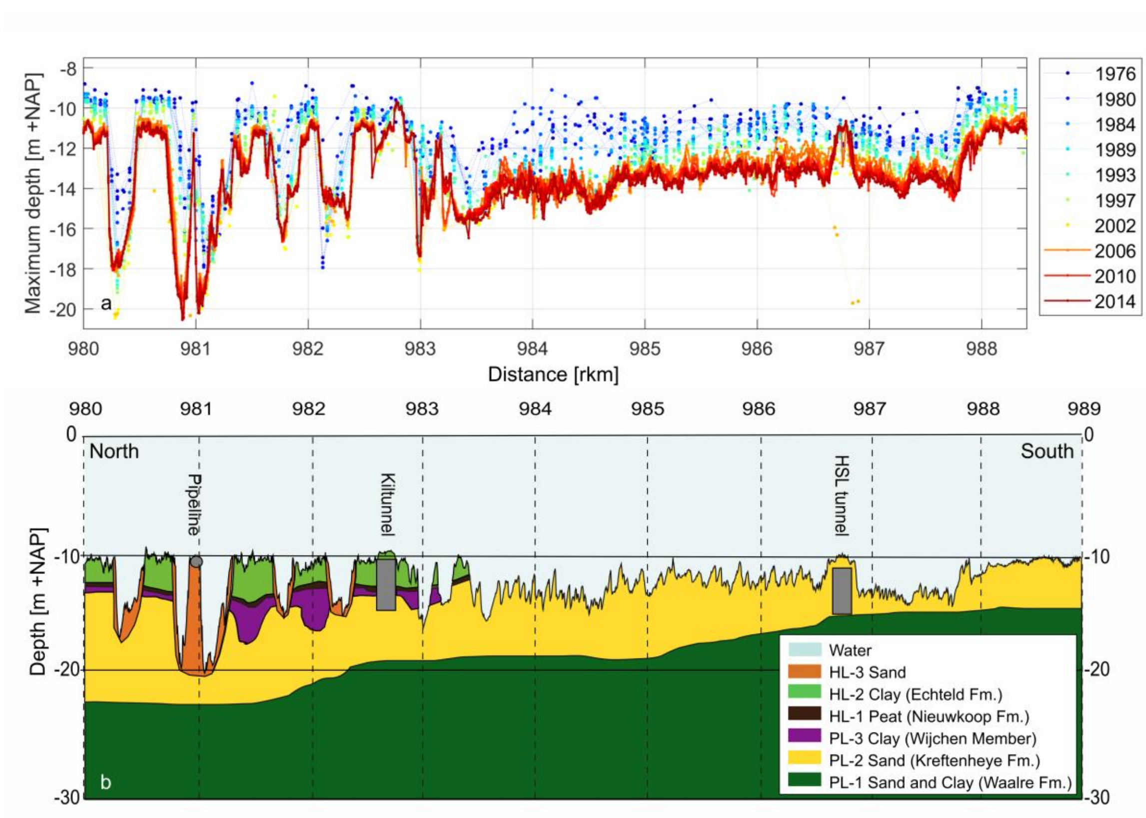

Figure 6 a) evolution of the thalweg in the Dordtsche Kil river bed from 1976 to 2014. b) lithological longitudinal section of the Dordtsche Kil (figure based on the report by Wiersma, 2015).

For 18 scour holes in the Oude Maas and Dordtsche Kil river, we analyse the evolution of the scour hole depth for the period 1976 – 2014 (Figure 7). 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 7), and the smallest net increase is approximately 1 m, which occurred in 29 years (scour hole 13). The depth growth rates strongly vary as well. Some scour holes show a more gradual growth, whilst the growth of others is episodic. 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 over the last five years.

To get an indication of whether changes in growth rate can be related to the composition of the subsurface lithology, the interpretation of the local subsurface lithology is presented in colour in the graphs in Figure 7. 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).

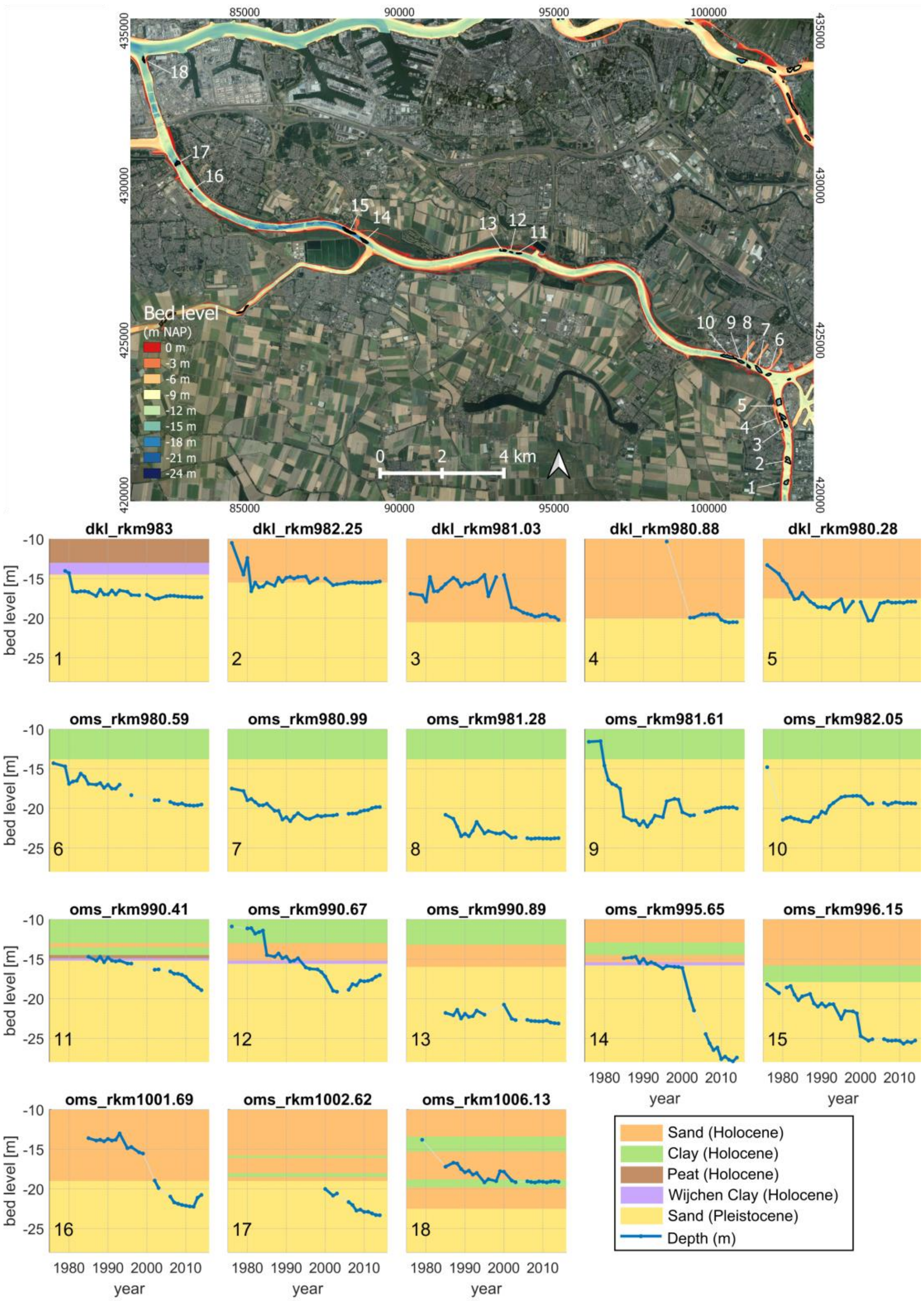

Figure 7 Top panel: map with scour hole locations considered for this analysis. Bed level is from 2014. Map is created in QGIS with the Esri-Satellite base map. Bottom panel: scour hole evolution over four decades. For each scour hole the evolution of the deepest point is shown in blue. In colour the subsurface lithology is presented.

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 and cannot be related to abrupt flow changes in response to engineering interventions (Table 1). It is furthermore unlikely that dredging has caused these strong variations in depth, as dredging is limited to the shallow areas. 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 (Table 1), it is likely that the clay to sand transition is locally 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, two river sections with scour holes of distinct size, shape, growth rate, and direction are analysed in relation to their subsurface lithology.

In Figure 8, the present bed level and evolution of the thalweg (1976-2015) is 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 river km 995.7 and 997.5. The evolution of the thalweg 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 river km 997.5 and 995.7. The scour hole at river km 995.7 mostly extends in an 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.

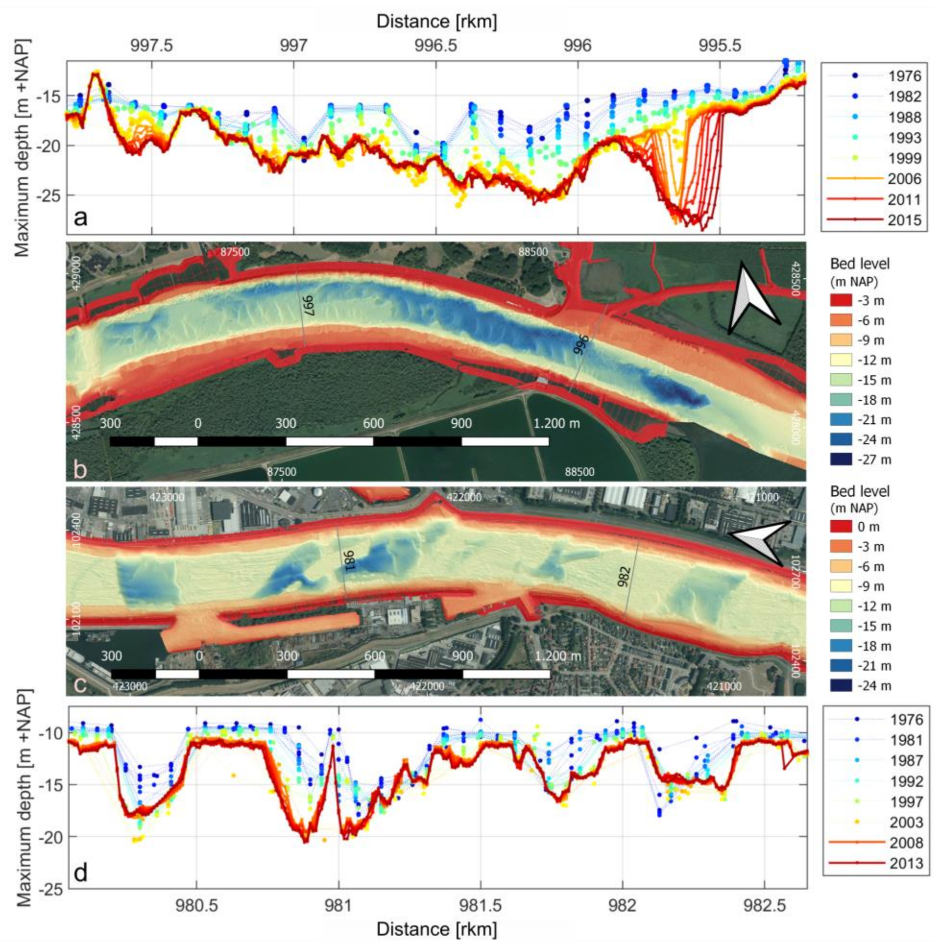

Figure 8 Detailed scour hole evolution for two locations. a) Evolution of the thalweg in the Oude Maas (rkm 997.25 – 995.75), b) corresponding bed topography in 2014. Residual or net sediment-transport direction is westward (to the left in the figure). c) Bed topography Dordtsche Kil (rkm 980.1 – 982.6) in 2014 and d) corresponding evolution of the thalweg. 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 features. None of the scour holes merged, nor are trends observed which suggest that scour holes will merge. Over the last 8 years, the scour holes show only minor evolution.

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 (Fig. 9). Adjacent 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 7). In and westward of the scour hole, large blocky objects are visible thatare interpreted 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 grooves. Distinct grooves from past dredging activities or shipping scours indicate a resistant soil type in which marks do not easily smoothen or vanish, likely clay. The subsurface lithological longitudinal section (Fig. 6) supports this hypothesis.

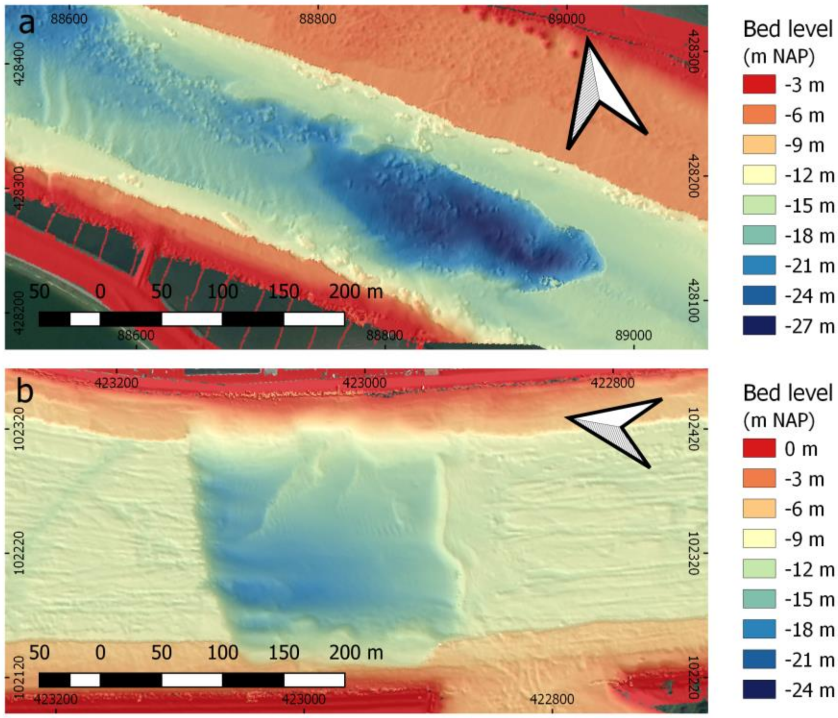

Figure 9 a) Bed topography of the scour hole in the Oude Maas at rkm 995.7 b) and of the scour hole in the Dordtsche Kil at 980.2, both 2014. The smooth bed in the top figure is attributed to a clay layer. The blocks of material in- and downstream of the scour hole are hypothesised to be blocks of clay 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 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 (Fig. 9). As a result, scour holes extend 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 6, the subsurface flanking the channel-belt sand bodies consists of thick layers of resistant 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 angles in the scour contour may be related to outcrops of peat/clay. Though the thick peat and clay 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.

To further verify whether the shape of the scour hole indeed relates to the subsurface lithology, we determined the length and width of the scour holes in the Dordtsche Kil and Oude Maas and related them to the composition at the scour edge (Fig. 10). The analysis confirms that scour holes with edges composed of sand or a thin layer of clay are generally more elongated than scour holes of which both edges are composed of a thick layer of poorly erodible material.

Though these observations are a strong indication of the dominant role of lithology in the horizontal scour hole growth, the role of the flow remains to be verified, especially as the difference between confined and elongated scour holes largely coincides with the branch in which they are located. According to one dimensional flow simulations presented in Table 2, the velocities in the Dordtsche Kil and Oude Maas are very comparable. The only notable difference is the asymmetry in ebb and flood flow velocities, which is stronger for the Oude Maas. The potential effect is a stronger erosion during ebb tidal currents than during flood tidal currents in the Oude Maas, and a more equal erosion during ebb and flood tidal current in the Dordtsche Kil. This can however not explain the differences in shape and horizontal growth. Scour holes of which the scour hole edges are composed of sand or a thin layer of clay (all in the Oude Maas) are observed to erode in both ebb- and flood flow direction. This suggests that both ebb and flood tidal flow velocities are strong enough to cause erosion. In the Dordtsche Kil, both the ebb and flood tidal flow velocities are comparable to the ebb current and stronger than the flood current of the Oude Maas. If the scour edges were composed of the same material as in the Oude Maas, the scour holes in the Dordtsche Kil would also erode in both directions. As the ebb flow velocities in the Dordtsche Kil exceed the ebb flow velocities in the Oude Maas, the erosion potiential in the ebb- current direction would even be stronger, causing potentially even more elongated scour holes. However, this is the opposite from what is observed. The observations of scour holes in the Dordtsche Kil show that they stay confined and barely expand in the ebb or flood flow direction; only their internal edges steepen. Therefore, we conclude that the difference in flow conditions between the Dordtsche Kil and Oude Maas cannot explain the differences in confined versus more elongated expanding scour holes. This further strengthens the evidence that the lithology causes the observed differences.

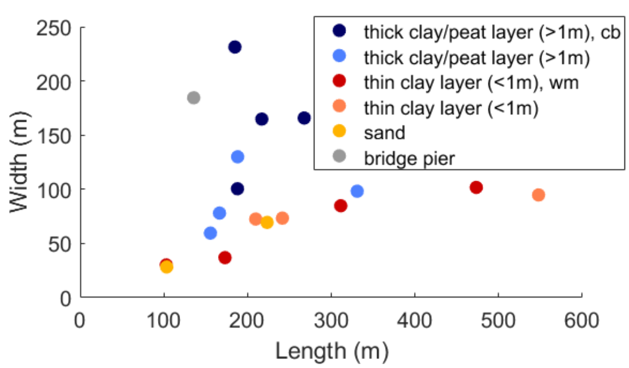

Figure 10. Length-width ratios of the scour holes from the Dordtsche Kil and Oude Maas. In color the composition and thickness of the scour hole edge is displayed, where "cb" indicates a scour hole formed in a channel belt and "wm"indicates that the scour hole edges are composed of clay from the Wijchen Mb. A separate class is made for the bridge pier scour, as these are scour holes formed around two bridge piers and the surrounding bed is (partially) stabilised with Riprap.

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 include turbulent flows induced by river bends (e.g., Engelund, 1974; Zimmermann & Kennedy, 1978; Odgaard, 1981; Andrle, 1994; Gharabaghi et al., 2007; Blanckaert, 2010; Beltaos et al., 2011; Ottevanger et al., 2012; Vermeulen et al., 2015), confluences (e.g., Mosley, 1976; Kjerfve et al., 1979; Best, 1986; Ginsberg & Perillo, 1999; Pierini et al., 2005; Best & Rhoads, 2008Ginsberg et al., 2009; Ferrarin et al., 2018), local channel narrowings and structures, like bridge piers, groynes and bed protection (e.g., Wang et al., 2017; Pandey et al., 2018; Liang et al., 2020). These types of scour holes evolve differently, have different shapes, and as a result have different relations for predicting their equilibrium depth (Hoffmans & Verheij, 1997). As illustrated in Figure 5, some of the scour holes are indeed triggered by such turbulent flows. Secondly, conditions that influence scour hole growth like flow velocity, water depth, and grain size vary throughout the estuary. The third reason is the lithological influence on scour hole formation, which in current analyses proves to be a major influence on scour hole initiation, growth rate, and shape, and which in certain cases even overrules the above causes and controls. In Figure 11, the three lithological controls are illustrated conceptually. Firstly, lithology may trigger scour hole formation (Fig. 11a). 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 where the erosion resistant peat and clay layers are interrupted by channel belt sand bodies. Though it cannot be determined whether the protecting top layer covering the sand bodies was removed by natural erosion or by deepening the Dordtsche Kil to -8 m NAP (1970-1984), in both cases the heterogeneous subsurface lithology is the only explanation for the presence of scour holes. Without the heterogenous subsurface lithology, the river branch would have dropped evenly in response to natural erosion or deepening, as happened in the southern part. 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 that scour holes observed in a straight river section were 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. 11b). An insightful example is the scour hole at the confluence of the Spui and Oude Maas river (Figs. 7-8). Though the confluence in its present outline has already existed for over a century as visible in historical maps (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 (Fig. 7) 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 such as a strong increase in flow, new constructions, dredging or failure of bed protection do not apply.

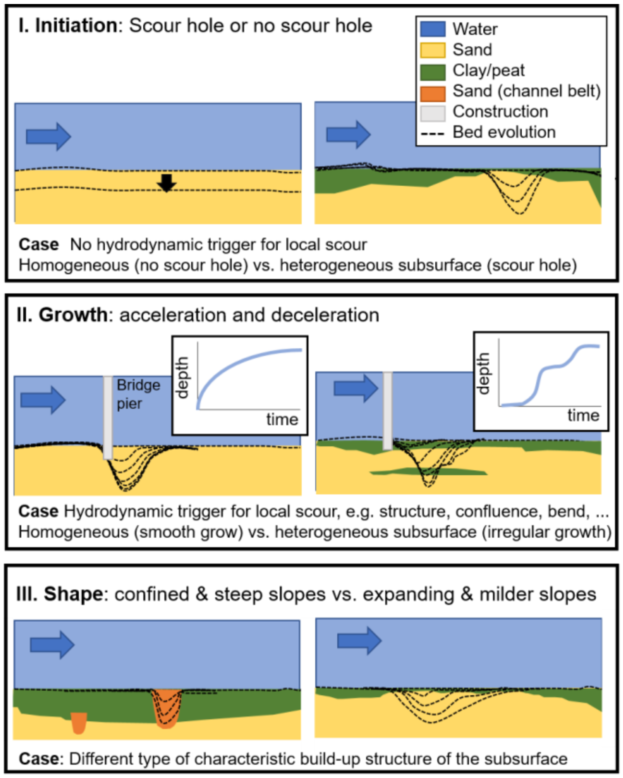

Figure 11. Summary of the observed lithological controls on scour hole development. All figures display a longitudinal section of a river reach, with the blue arrow indicating the flow direction. Dashed lines represent the bed level development over time.

Thirdly, in horizontal direction the subsurface lithology can be a dominant factor in determining the shape or growth rate (Fig. 11c). 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 result, scour holes of more than a kilometre in length form. 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 sand bodies 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.

The strong lithological control on scour hole formation is in line with the reported effect of the subsurface lithology on the formation of ebb-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 five-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 energy 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 an erosion resistant layer at the bottom of the scour hole (Cserkész-Nagy et al., 2010). This is clearly the case for scour hole 18 (Fig. 7), which reached a resistant 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 (Fig. 6). As the channel-belt bodies are commonly composed of finer grained sands than the coarser grained Pleistocene sand layer below (e.g. Berendsen, 1982; Weerts & Busschers, 2003; Gouw & Erkens, 2007), 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 grain size distribution in the lower part of the scour hole is needed.

5.3 Consequences and risks for other rivers and estuaries

Provided sufficiently strong 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 11, apply to any system with a heterogeneous substratum of alternating peat, clay and sand deposits. Though little has been reported, these controls are likely not unique to the Rhine-Meuse Estuary. Channel bed degradation by natural erosion or channel deepening, also happens in other large delta rivers like the Yangtze, the Mississippi and the Mekong (Galler et al., 2003; Sloff et al., 2013; Brunier et al., 2014; Luan et al., 2016; Hoitink et al., 2017; Wang & Xu, 2018). And as causes are mainly anthropogenic, more delta rivers are expected to follow. Because river deltas commonly have a heterogeneous substratum of alternating peat, clay and sand deposits (e.g. Aslan & Autin, 1999; Berendsen & Stouthamer, 2001, 2002; Aslan et al., 2005; Kuehl et al., 2005; Stefani & Vincenzi, 2005; Gouw & Autin, 2008; Cohen et al., 2012; Hanebuth et al., 2012), scour hole formation in heterogeneous subsurface is expected to become a problem in more deltas. Data suggest that for the Ems river (Pierik et al. 2019), the Venice Lagoon (Ferrarin et al., 2018), lower 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 where scour holes are close to infrastructure or river banks, stability is at stake. Also, in case of channel deepening, it is important to know the subsurface lithology. In case a resistant clay or peat layer gets removed, sudden scour hole formation can occur in response to deepening, as potentially happened in de Dordtsche Kil. As accurate predictions of scour hole formation are highly important, especially in densely occupied areas like deltas (Syvitski et al., 2009; Best, 2019), we advocate to explicitly consider the underlying geology when predicting scour hole formation and growth. This requires knowledge of the subsurface lithology, acquired via 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 depth of meander pools (Hudson, 2002; Gibson et al., 2019), the lateral behaviour of river branches (Cserkész-Nagy et al., 2010) and the evolution of ebb-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 analyses, 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 an erosion resistant top layer and promoted at locations where sand bodies are present in the subsurface. 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 classical oval shapes. These shapes are imposed by the erosion resistant top layer, inhibiting the scour hole to grow more naturally 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 limiting growth in horizontal direction.

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 cross-sections and longitudinal 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). The scour hole database is made available via Mendeley Data.

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