



Roman and early-medieval habitation patterns in a delta landscape: The link between settlement elevation and landscape dynamics



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ABSTRACT

Settlement locations in delta landscapes change through time because of cultural and natural dynamics. We assessed the impact of natural-landscape dynamics on settlement-location shifts for the Rhine-Meuse delta in the Netherlands during the Roman and early-medieval periods (12 BCE–450 CE and 450–1050 CE respectively). During this time interval major landscape and cultural changes occurred in this area, with river avulsions and changes in flooding frequency coinciding with changing settlement patterns. In the delta plain, the relatively high and dry alluvial ridges of abandoned or active rivers were most favourable for habitation. Settlement location and elevation patterns were reconstructed in these landscape units using a high-resolution elevation map of the alluvial ridges. By integrating high-resolution palaeo-environmental and archaeological datasets for this period, we were able to spatially analyse the trends and to assess the effect of environmental changes on habitation. Results show that settlements progressively shifted towards higher areas between 250 and 750 CE, on average by 20 cm over this period deltawide, which was coeval with an increased frequency of severe Rhine floods. The observed spatial differences demonstrate that this trend is most notable in the least-elevated segments of the study area. In areas where new large river branches developed, settlements show a strong shift towards higher-elevated parts of the landscape or even became completely abandoned. The river probably caused floods to be more frequent and more severe in these areas. Despite the clear link between changing settlement positions and floods during the studied time interval, floods do not seem to have caused long-term abandonment of major parts of the study area.

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1. Introduction

River and delta landscapes were among the most densely populated areas in the world throughout all archaeological periods. In these areas, settlement patterns were susceptible not only to cultural processes (e.g. socio-economic, political) but also to environmental factors (e.g. flooding, elevation, avulsions - e.g. Butzer, 1982; Brown, 1997; Von Nagy, 1997; Guccione, 2008; Funabiki et al., 2012; Hill, 2014; Howard et al., 2015; Pennington et al., 2016). These fluvial landscapes provided fertile substrates and natural resources, and hosted abundant land and water routes for long-distance transport (e.g. Cunliffe, 2004; McCormick, 2007; Van Es and Verwers, 2010; Van Lanen et al., 2016). However the

people living in these wet and dynamic landscapes often were confronted with flooding events. When the frequency or magnitude (flooding regime) of these floods changed, people can be expected to have adapted to this by relocating settlements to more suitable areas. For wetland regions all over the world changes in human-activity have indeed been linked to changes in flooding regimes (e.g. UK: Macklin, 1999; Gila River, Arizona: Waters, 2008; Elbe, Germany: Schneeweiss and Schatz, 2014; Nile delta: Marriner et al., 2013; Macklin et al., 2015). On a larger scale even the rise and fall of civilizations have been attributed to changes in flooding regime (Yangtze delta: Zhang et al., 2005; Shanghai area: Wu et al., 2014). In some areas however increased episodes of flooding do not seem to have affected settlement dynamics (e.g. in the Roman Rhône delta: Arnaud-Fassetta et al., 2010). All these studies correlate trends observed in archaeological and sedimentological records, however deltawide geomorphological approaches have not been carried out as this would require the presence and integration

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of large amounts of data. For most of these areas, data is currently not always available on the desired resolution or spatial coverage and often remains rather fragmented.

In the fluvial-dominated part of the Dutch Rhine-Meuse delta (Fig. 1), large-scale cultural and landscape changes have occurred during the late-Roman period (LRP: 270–450 CE - Table 1) and the early-medieval period (EMP: 450–1050 CE) (e.g. Hendriks, 1983; Willems, 1986; Teunissen, 1988; Jansma et al., 2014). After the abandonment of the Roman *limes* in the delta, which was located along the river Rhine, large-scale depopulation occurred and settlements were relocated (e.g. Willems, 1986; Heeren, 2009; Vos,

2009; Van Dinter, 2013; Verhagen et al., 2016). This coincided with some remarkable environmental changes: (i) the avulsion of the major Rhine branch from its northern course to its currently active southern Waal branch (e.g., Table 2 - Berendsen and Stouthamer, 2000; Van Dinter et al., 2017); and (ii) an increase in flooding frequency of the river Rhine between 250 and 850 CE (Toonen et al., 2013; Cohen et al., 2016). This raises the question to what extent these environmental changes, next to cultural factors, influenced habitation in the area. Recent studies focusing on local settlement dynamics in specific parts of the delta (Bronze Age: Arnoldussen, 2008; Roman and Early medieval situation for the city



Fig. 1. Location and palaeogeography for 900 CE. Pleistocene uplands and peat extent after Vos and De Vries (2013); tidal areas, alluvial floodplains and channels: after Pierik et al. (2016, 2017); situation Gelderse IJssel: after Cohen et al. (2009). Newly formed river channels in the first millennium CE are indicated with arrows (see Table 2 for ages of initiation); red dots indicate avulsion sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

Roman and early-medieval periods and subperiods as defined by the Archaeological Basic Register (ABR) and their chronological projection on the geomorphological reconstructions.

Archaeological Period	Subperiod	Abbreviation	Age	Geomorphological reconstruction
Roman period (RP)	early-Roman period	ERP	12 BCE to 70 CE	100 CE
	middle-Roman period	MRP	70–270 CE	
	late-Roman period	LRP	270–450 CE	
Early Middle Ages (EMP)	early-medieval period A	EMPA	450–525 CE	900 CE
	early-medieval period B	EMPB	525–725 CE	
	early-medieval period C	EMPC	725–950 CE	
	early-medieval period D	EMPD	950–1050 CE	

of Utrecht: Van Dinter et al., 2017) conclude that the flooding regime temporally could have altered settlement distribution, forcing people to move to higher places or leading to abandonment of the area.

For the Rhine-Meuse delta, recent developments in integrating large-scale archaeological datasets (Van Lanen et al., 2015a) and the sedimentary-geomorphological perspective (e.g. Cohen et al., 2012; Toonen et al., 2013; Pierik et al., 2017) for the first time allow the combination of high-resolution cultural and geoscientific data on a delta-wide scale. Here we combine new geomorphological reconstructions, recently assessed environmental changes in the delta, and changing settlement patterns through time. The aims are: 1) to analyse the shifts of settlement location over areas with different elevation through time; and 2) to assess the role of natural dynamics in these settlement shifts.

Already from the Bronze Age (2000–800 BCE) onwards the relatively dry and elevated alluvial ridges with their natural levees and crevasse splays in the Rhine-Meuse delta were the most favourable areas for habitation (Modderman, 1948; Edelman et al., 1950; Hendriks, 1983; Verbraeck, 1984; Willems, 1986; Arnoldussen, 2008; Van Dinter and Van Zijverden, 2010; Van Dinter et al., 2017). Therefore the alluvial ridges are considered to be key landscape elements to study the human-landscape interactions in the delta. However the spatial extent and elevation of the alluvial ridges in this delta are rather variable. Settlements positioned on the ridges therefore experienced different flooding frequencies and amplitude regimes during high-water events. Assuming that settlement elevation determined the sensitivity of the settlement to changes in flooding regime, a more detailed distinction between high and low parts of alluvial ridges is required to better understand the interaction between landscape and settlement dynamics. Because the height of settlements was not always recorded in the archaeological datasets consulted in this study, we inferred settlement elevation from the new high-resolution palaeo-surface maps recently developed by Pierik et al. (2017). Integrating geoscientific and archaeological datasets is an important step towards further understanding of the relative

contribution of environmental factors (e.g. floodings) to explain settlement distribution in the Rhine-Meuse delta.

2. Materials and methods

Settlement data for the Roman and early-medieval periods were collected, updated and enhanced for the study area (Van Lanen et al., 2015a, 2015b; Van Lanen and Pierik, in this issue). Next we determined the landscape units where the settlements were located and assigned a palaeoelevation to each settlement using geomorphological-reconstruction and palaeo-topography maps. Finally settlement persistency and settlement elevation shifts throughout the first millennium were analysed.

2.1. Archaeological source materials

Archaeological data on settlements in the research area were extracted from the Archaeological Information System of the Netherlands (ARCHIS). This system contains a national overview of reported archaeological finds (Roorda and Wiemer, 1992; Wiemer, 2002). For the study area this dataset was expanded and enhanced with archaeological data published in regional overview studies, which in general contain more detailed (meta)data on the settlements: Bechert and Willems (1995), Verwers (1998), and LGL World Heritage Database (2010). Both the ARCHIS and external data were integrated into a single dataset to obtain maximal chronological resolution and spatial accuracy of all available settlement data in the study area. Duplicate records were selected, compared and removed based on the appliance of a 100 m buffer around each settlement (for a more detailed description of this method see: Van Lanen et al., 2015a; Van Lanen and Pierik, in this issue). Next overviews of active settlements were created per archaeological period (Roman Period, Early Middle Ages) and subperiod (e.g. early-Roman period, middle-Roman period) as specified by the Archaeological Basic Register (ABR, Table 1).

Settlement data were compiled for seven ABR-defined subperiods which each roughly cover 100–200 years (see section 2.2. and Table 1). We chose these short time intervals to match changing settlement patterns to developments in the landscape with a high-chronological resolution. Settlements dating to an unidentifiable part of the period, i.e. broadly classified as RP or EMP only, were excluded from the analysis since their chronological resolution is too low to yield significant results when comparing settlement patterns to landscape changes on the considered time scale.

2.2. Geomorphological and palaeo-surface reconstructions

To assign elevation values to settlements and to assess their geomorphological setting across the delta landscape, two types of recently developed geomorphological reconstructions were used, which both cover the whole of the Rhine-Meuse delta: i)

Table 2

New river branches in the Rhine-Meuse delta between in the first millennium CE, compiled after overviews in Berendsen and Stouthamer (2001), Cohen et al. (2012, 2016), more specific references are given in the table. The initiation and mature phase are inferred from radiocarbon dates and relative dating. The location of the rivers is indicated in Fig. 1.

New river branch	Initiation	Mature phase
Hollandse IJssel	ca. 0 – 100 CE ^a	before 800 CE ^a
Lek	ca. 40 – 300 CE ^a	around 700 CE ^a
Waal	ca. 220 – 450 CE ^b	after 450 CE ^b
Maas (Meuse)	after 270 CE ^b	after 270 CE ^b
Gelderse IJssel	ca. 550–650 CE ^c	after 735 CE ^c

^a Based on Berendsen (1982).

^b Based on Törnqvist (1993); Weerts and Berendsen (1995).

^c Based on Makaske et al. (2008); Cohen et al. (2009).

palaeogeographical maps (geomorphological reconstruction maps) for the time slices 100, 500 and 900 CE; and ii) two DEMs (Digital Elevation Models) representing the surface topography for 100 and 900 CE. These time steps equally divide the first millennium and the phasing of these developments. The first time step comprises the initial stage of a series of avulsions in the delta (Table 2); the second time step fits with the stage of ongoing avulsions and increased flooding frequencies; the last interval represents the last natural state before embankment with matured new channel belts of a more-or-less completed avulsion. Their compilation method is explained in Pierik et al. (2017) and summarised below.

The maps show the extent and distribution of the alluvial ridges present in the past landscape, which consist of natural levees and crevasse splays either on top of or flanking channel belts (Fig. 2). The maps also include residual channels, zones of younger reworking by river activity, and dike-breach splays that cover the old landscape (Fig. 2). The landscape elements were mapped based on the lithological and geomorphological criteria following methods of Berendsen and Stouthamer (2000), Berendsen et al. (2007), Van Dinter (2013), and Pierik et al. (2016). The lithological information was obtained from an extensive borehole database maintained by Utrecht University, whereas LiDAR images provided modern elevation of the landscape (Berendsen and Volleberg, 2007). The age of the mapped landscape elements was assessed from ^{14}C dates, archaeology and relative dating (Berendsen and Stouthamer, 2000; Gouw and Erkens, 2007; Cohen et al., 2012; Van Dinter et al., 2017; Pierik et al., 2017).

To determine alluvial ridge and settlement elevation we used reconstructions of the palaeo surface on a 100×100 m resolution for 100 CE and 900 CE, which both represent the situation just

before large-scale embankment of the rivers around 1100 CE (Hesseling et al., 2003). The 100 CE surface level, derived from borehole data, was buried by flood sedimentation afterwards. The 900 CE surface level was mapped from current surface expression in LiDAR datasets (for details see Pierik et al., 2017). Absolute elevation (meters above O.D.) was converted to relative elevation (meters above a reference plain with a floodplain gradient) in order to facilitate comparison of changing settlement elevation on alluvial ridges throughout the delta. As a reference plain we used an interpolated palaeo-groundwater level reconstruction (Cohen, 2005; Koster et al., 2016), selecting the reconstructions for 2000 BP and 1000 BP (i.e. early-Roman period and Early Middle Ages) (Figs. 3–5).

The total vertical error of the surface reconstruction is estimated to be ca. 15 cm per individual grid cell (Pierik et al., 2017). Its main components are the core sampling error and the maximum error of the groundwater reconstruction. The palaeo-surface reconstruction is most accurate on the higher parts of the alluvial ridges where most settlements were situated. Data density in general is somewhat lower for built-up areas. Given the amount of data points used for the interpolation ($n = 80,000$), these errors are cancelled out when considering larger areas.

After 100 CE only limited sedimentation of clay took place in the research area (some cm on the inherited natural levees to max 30 cm in the lower flood basins), which in general did not significantly affect the distribution of high and low areas throughout the landscape (Gouw and Erkens, 2007). Close to the active rivers, however, post-Roman sedimentation rate was significantly higher, with active levees and dike breach deposits reaching a height of some tens of cm to max. 2 m (Hesseling et al., 2003; Gouw and Erkens, 2007). Because of the uncertainty in sedimentation rate

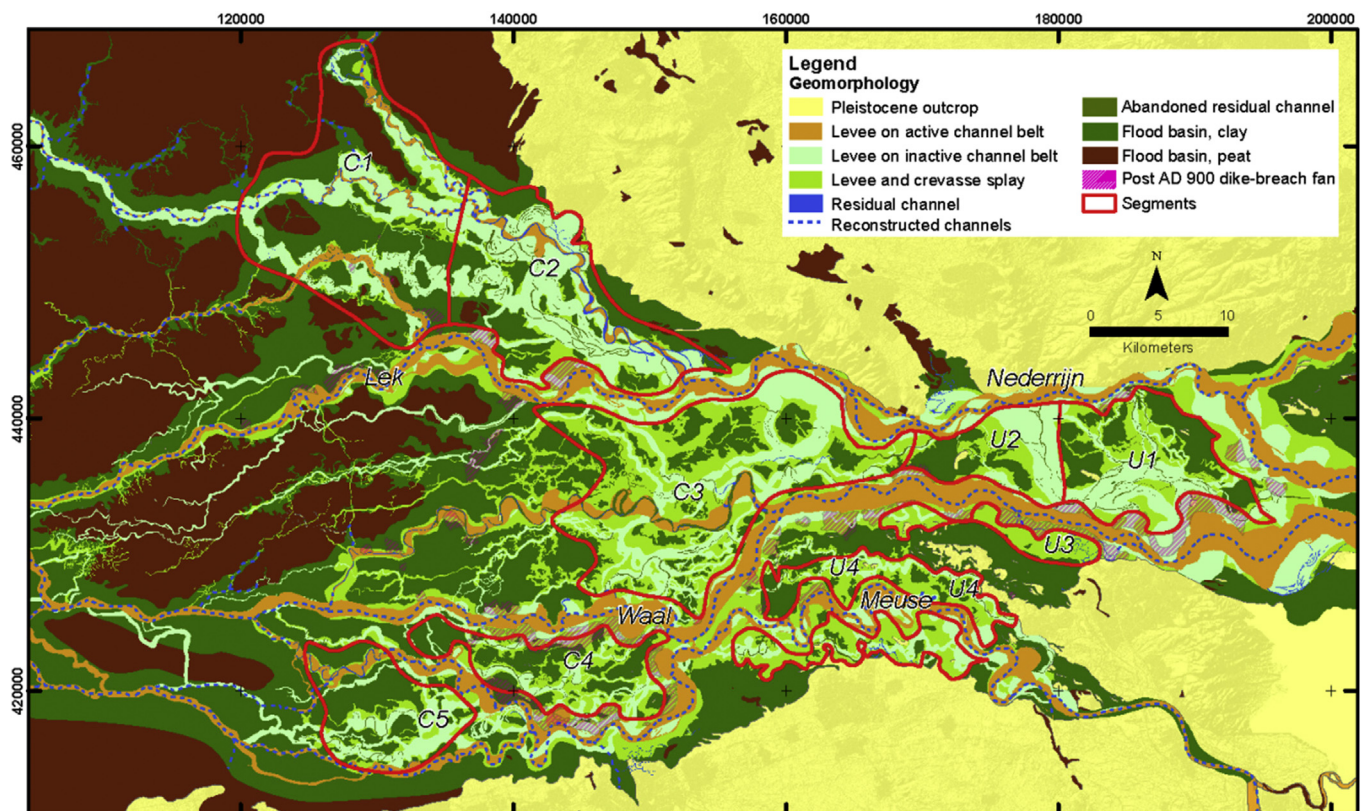


Fig. 2. Geomorphological reconstruction for 900 CE (Pierik et al., 2017). Segments C1–C5, D, and U1–U4 are based on geomorphological criteria (Table 4).

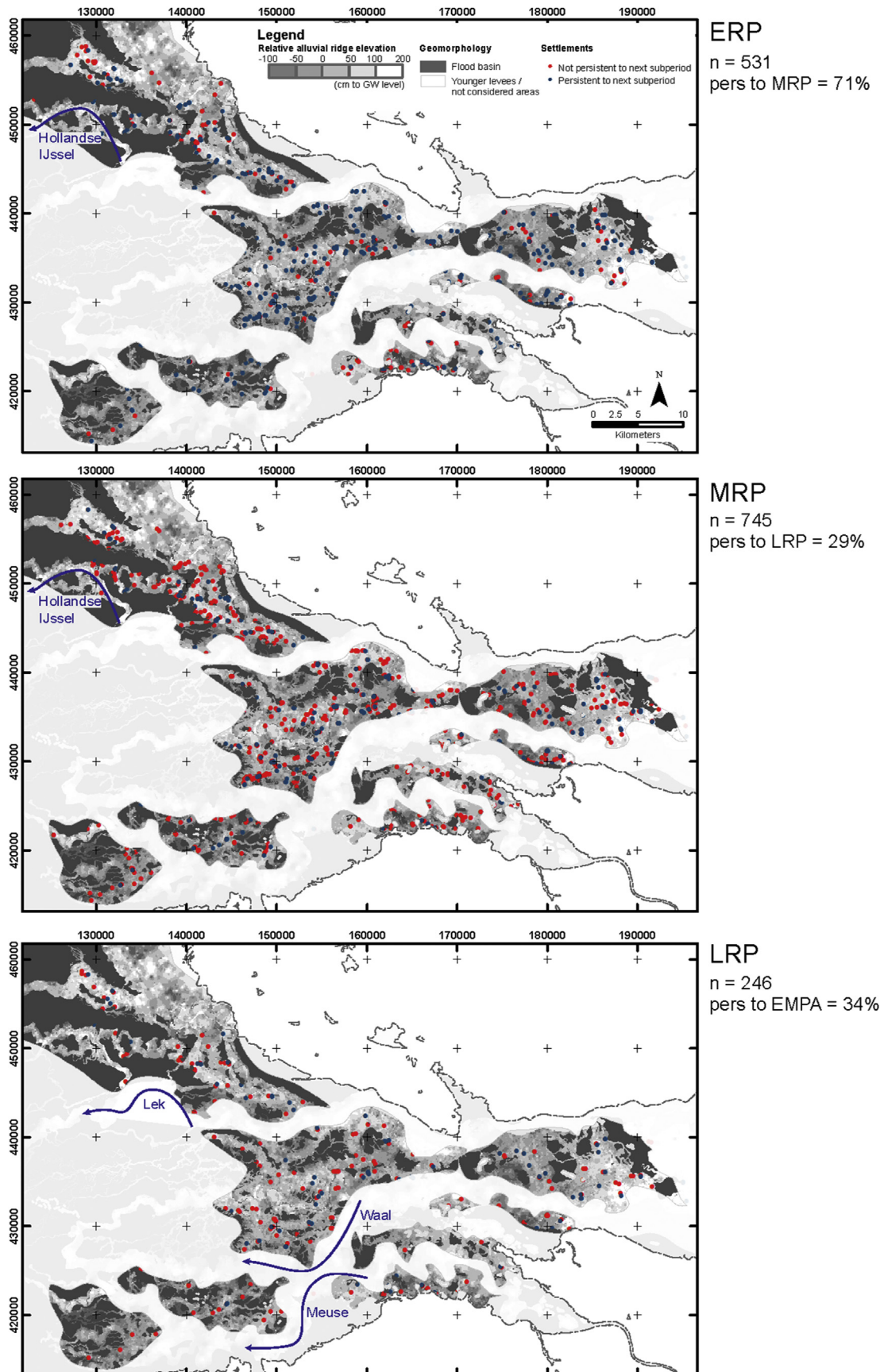


Fig. 3. Persistent (abbreviated as *pers*) and non-persistent settlements for the Roman period plotted on the palaeo-surface reconstruction of 100 CE (for colour version see Fig. 5), with the settlements per time slice. Masked areas are not included in the analysis. The most important avulsions are indicated, for the segment codes see Fig. 2.

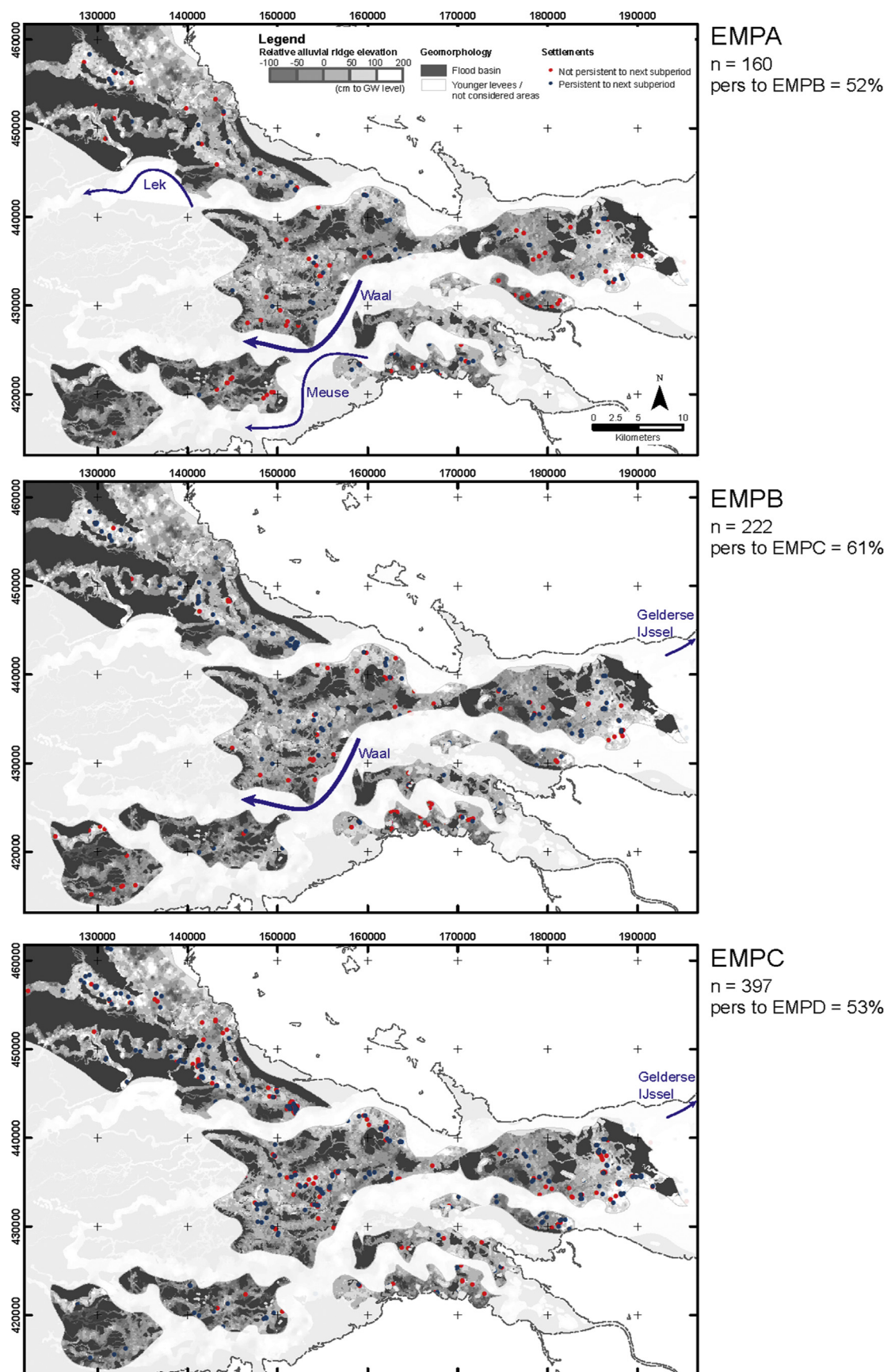


Fig. 4. Persistent (abbreviated as pers) and non-persistent settlements for the Early Middle Ages plotted on the palaeo-surface reconstruction of 100 CE (for colour version see Fig. 5), with the settlements per time slice. Masked areas are not included in the analysis. The most important avulsions are indicated, for the segment codes see Fig. 2.

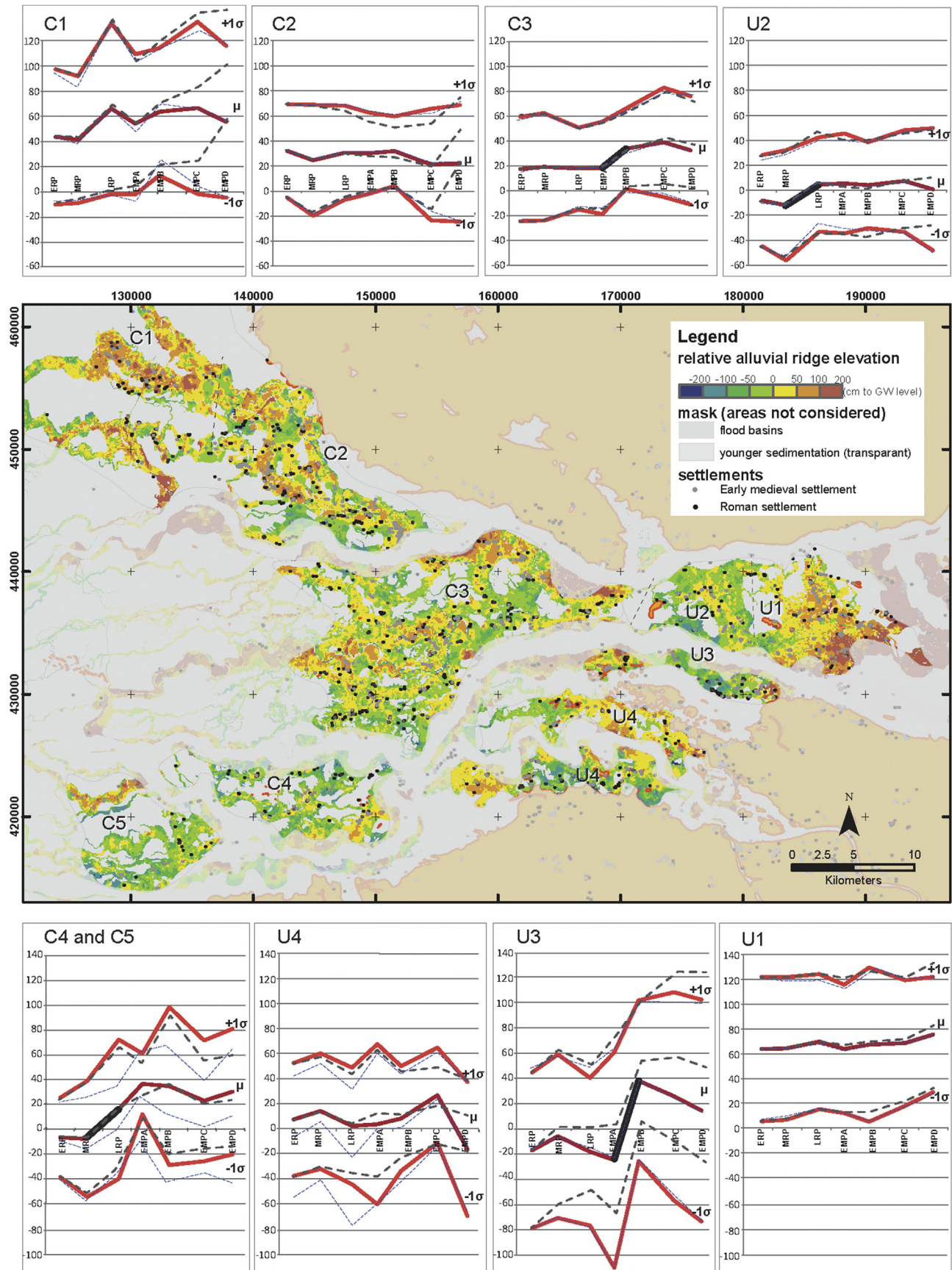


Fig. 5. Average settlement elevation (μ) and 1σ (68% of settlements) for the segments per subperiod on the 100 CE DEM. Areas not included in the analysis are masked transparent. Red lines: average settlement elevation (scenario 1); blue dashed lines: average and standard deviations of scenario 2 (section 2.3); grey dashed lines: average and standard deviations of scenario 3 (section 2.3); black lines: significant average differences for $p \leq 0.05$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in these areas, they were excluded from the analyses, which implies that a small number of settlements located in these areas were not taken into account. We used the delineations of these younger geomorphological elements from Pierik et al. (2017) as boundaries for our analyses (Fig. 2).

2.3. Assigning elevation to settlements

For each time slice we assigned the reconstructed landscape elevation to the settlements and subsequently determined the changes in settlement elevation observed between the time slices. Per DEM grid cell in the palaeo-surface reconstructions the maximal error dx is 15 cm (see section 2.2). The mean elevation error of a selection of cells (i.e. those with settlements), $d\bar{x}$, depends on the number of cells (i.e. settlements) considered N , and was estimated as:

$$d\bar{x} = \frac{dx}{\sqrt{N}}$$

For the case with the smallest number of samples ($N = 11$ samples in EMPA in section C4 and C5), the uncertainty of the mean equals 4.5 cm, which we assume the most conservative case.

To account for possible errors in the source datasets we developed three scenarios (Table 3). By comparing these scenarios we tested the accuracy of the two DEMs and the settlement-shift trends. Scenario 1 and 2 use two input datasets (GW2000 and DEM100 (OD)), whereas scenario 3 additionally uses groundwater and surface-level reconstructions of 900 CE. For scenario 1 we used the reconstructed 100 CE DEM for the settlement elevation of all time slices. This assumed that the elevation differences between higher and lower areas remained constant after 100 CE. Scenario 2 was performed to test the influence of local errors which either originate from location administration errors in the archaeological database or from administrative outliers in individual boreholes. These types of error were compensated for by taking the average value of the 9 grid cells within 100 m surrounding the cells on which the settlement was positioned. In scenario 3 we assume a linear floodplain-sedimentation rate on the alluvial ridges between 100 CE and embankment around 1100 CE, by assigning the interpolated value between the 100 CE and the 900 CE DEM to the settlements per time slice. From the results we subtracted the interpolated value of groundwater-level reconstructions between 1000 and 2000 BP. In this scenario a thicker layer of overbank clay is deposited on the lower ridges than on the higher ridges (Pierik et al., 2017).

Some settlements were positioned on dwelling mounds (e.g. Edelman et al., 1950) that were not mapped on the DEMs. Therefore, settlements located on known dwelling mounds were selected manually and their elevation was corrected using the mounds' present surface elevation as the RP and EMP elevation. A two sample t -test (with unequal variances) was performed to assess the significance of the differences between average settlement elevation in the subsequent periods.

2.4. Calculating settlement persistence

Other important aspects of settlement dynamics are persistence, abandonment, and settling in new areas. In this context persistence is defined as the degree of spatial correlation in settlement locations between two successive subperiods. We regard settlement locations in use during two successive subperiods (e.g. the early-Roman period and middle-Roman period) within the same 100 m area as persistent (cf. Schlanger, 1992). The term refers to the long-term use of a specific area, i.e. not necessarily continuous use by the same inhabitants.

To analyse these aspects we spatially buffered the settlement locations for all periods using a 100 m buffer. For each subperiod, we evaluated whether the point settlement overlaps with the 100 m buffer area around the point settlement from the preceding subperiod. This buffer reflects the minimum surface area of a settlement, i.e. settled area (cf. Van Lanen et al., 2015b) of the ARCHIS settlement point data. In addition this buffer compensates for possible administration inconsistencies in location coordinates that are present in the original datasets.

The next step was to evaluate the elevation difference between abandoned and persistent settlements. We performed the comparison for all subperiods on the 100 CE DEM under the assumption that the relative elevation in the landscape did not change after 100 CE (section 2.1). A t -test (with unequal variances) was used to test the significance of the results.

2.5. Selecting delta segments

To test the influence of landscape settings (e.g. delta plain width, alluvial ridge configuration, or position of river branches) on settlement dynamics we divided the delta plain into 10 segments. We followed the existing segments of Pierik et al. (2017), which are based on distinct landscape settings. Regarding delta-plain width we distinguished three major segments: the upper delta (U: confined delta plain), the central delta (C: widening delta plain), and the lower downstream part of the delta (D: wide delta plain, large flood basins) (Fig. 2). The central delta was divided further into five spatial segments, based on areal percentages of the alluvial ridges and the avulsion history of the major rivers (Table 4). Settlements within these segments that were situated on post-Roman embanked floodplains, levees, and dike-breach deposits were excluded from the analysis (also see 2.1). The lower delta plain, which is characterized by extensive peat areas and narrow alluvial ridges, does not contain sufficient archaeological data for the studied periods. Therefore this segment was excluded from the analysis.

3. Results

Settlements in both the RP and EMP generally were located on the higher parts in the landscape, 99% being located on top of natural levees or crevasse splays, of which 60% was situated on top

Table 3
Scenarios used to assigning elevation to the settlements.

	Scenario 1	Scenario 2	Scenario 3
Input datasets	DEM100 (OD) GW2000 ^a	DEM100 (OD) GW2000 ^a	DEM100 (OD) GW2000 DEM900 (OD) GW1000 ^b
Spatial varying overbank sedimentation and groundwater level rise?	—	—	v
100 m smoothing	—	v	—

^a GW2000 was subtracted from DEM with elevation relative to OD.

^b The interpolated value of groundwater-level reconstructions between 1000 and 2000 BP was subtracted from the interpolated value between DEM100 (OD) and DEM900 (OD) per time slice.

Table 4

Delta segments and their geomorphological criteria (also see Fig. 2).

Main segment	Delta width	Segment code	Geographical name	Alluvial ridge elevation relative to delta plain gradient	Alluvial ridge area ^a (areal % of the segment)	Flood-basin area ^b (areal % of the segment)	Remarks
Upper	~10 km	U1	Overbetuwe	High	60	35	
		U2	Nederbetuwe (east)	Low	68	29	
		U3	Southern bank Waal	Average	86	9	
		U4	Upper Meuse	Average	77	19	
Central	10 - 40 km	C1	Utrecht	Average	40	59	Large river silts up
		C2	Kromme Rijn	Average	61	33	
		C3	Nederbetuwe west/ Tielerwaard east	Average	74	22	Large river forms
		C4	Bommelerwaard	Low	52	46	
		C5	Land van Heusden Altena	Low	52	46	
Lower	>40 km	D	Alblasserwaard, Krimpenerwaard	Low	—	—	Not considered

^a Alluvial ridges include natural levees, crevasse splays and levees on channel belts in Fig. 2.^b Flood-basin area includes lower clayey and peaty flood basins in Fig. 2.

of channel belt sand bodies (Figs. 6A and 7D). Within these landscape units some shifts in settlement location and therefore also settlement elevation from the RP to the EMP can be observed (Figs. 5 and 7). The changes in settlement elevation through time are described below and linked to the most important landscape developments. The deviations in scenarios are indicated in Fig. 5, indicating the robustness of the analysis.

ERP - MRP: Compared to the ERP, during the MRP settlement numbers increased by 40% throughout the study area (Figs. 6A and

B and 7A). No significant difference in settlement elevation can be observed between the ERP and MRP (Fig. 7E). In terms of large floods and river avulsion both periods were relatively quiet (Fig. 7B, C - Toonen et al., 2013).

MRP - LRP: From the MRP to LRP the number of settlements dramatically decreased by 66%, coinciding with the abandonment of the *limes* around 270 CE (e.g. Alföldi, 1967; Heeren, 2015; Verhagen et al., 2016) (Fig. 6A and B). Only 33% of the MRP settlement persisted to the LRP (Fig. 6C). Throughout the entire delta

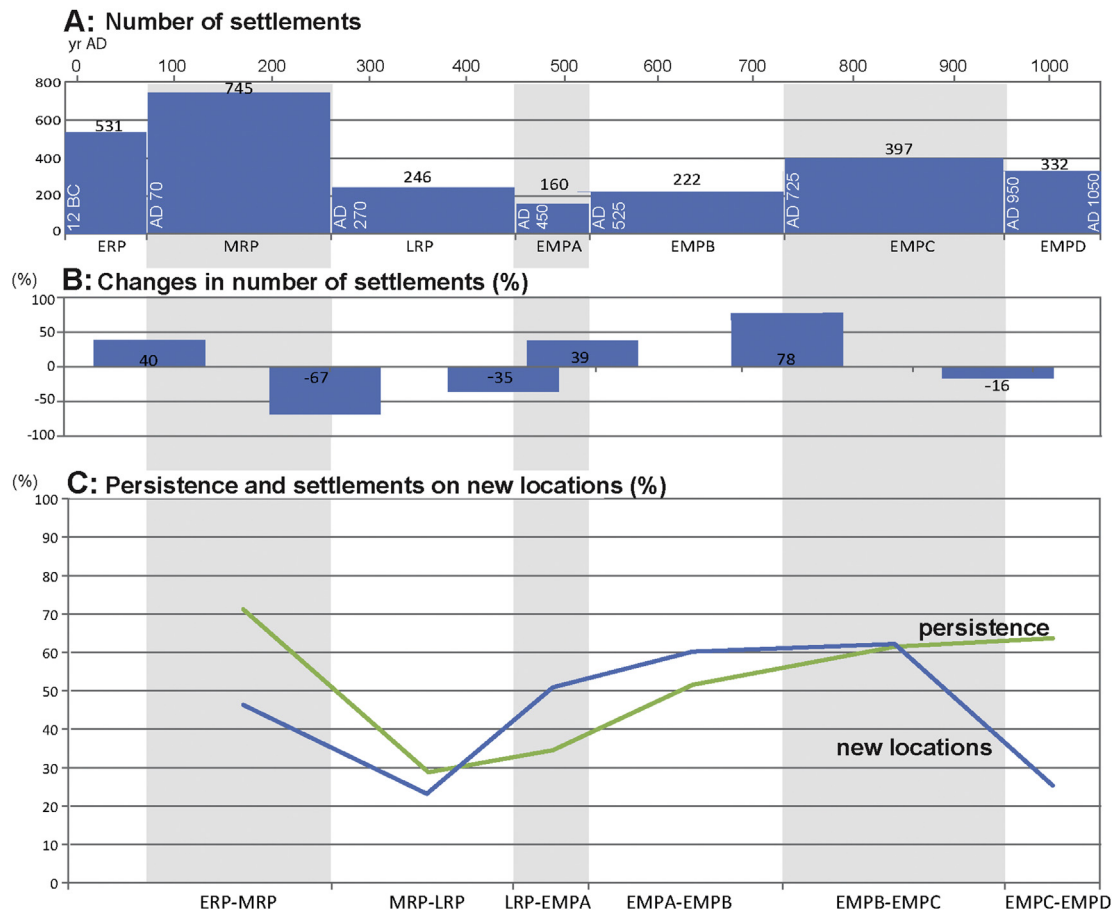


Fig. 6. A) Number of settlements in the research area; B) percentage difference in number of settlements between subsequent time slices; C) percentage of persistent settlements and settlements on new locations.

settlements shifted on average to 5–9 cm higher positions during the LRP (Fig. 7E). The MRP settlements that persisted to the LRP were situated ca. 8 cm higher than settlements that became abandoned, a trend that is statistically significant (Fig. 7F). This shift seems to have been strongest in the lowest segments (U2, C4, and C5 - Fig. 5). During the LRP it coincided with an increase in flooding frequency (50–100 yr recurrence time) and a large flood around 282 CE (Toonen et al., 2013). Locally this shift is also observed in the southern part of segment C1 (Fig. 5) where the river Hollandse IJssel and Lek were reactivated between 100 and 300 CE (Table 2; Fig. 7C - Cohen et al., 2012).

LRP - EMPA: Towards and during the EMPA the number of settlements decreased even further by 35% (Fig. 6A and B). Similar to the preceding period the persistence of settlements was still very low (Fig. 6C). No delta-wide rising trend in settlement elevation can be observed between the LRP-EMPA (Fig. 7E). However given the contrast between individual persistent and abandoned settlements, persistent settlements were located on average 13 cm higher than settlements that were abandoned (Fig. 7F). Combined with the absence of an average rise in settlements this implies that new settlements most likely were situated on similarly low elevations as settlements abandoned during the LRP.

EMPA - EMPB: After the EMPA the number of settlements increased by 39% (Fig. 6A, B). Throughout the research area the average EMPA-EMPB settlement elevation increased by 4–7 cm (Fig. 7E). About 50% of the EMPA settlements persisted into the EMPB. These persisting settlements were located on average about 27 cm higher than the abandoned settlements (Fig. 7F). One of the largest millennial floods in the research area occurred during the EMPA-EMPB (ca. 685 CE; Toonen et al., 2013). The most notable shifts towards higher grounds occurred in segments C3–C5 and U3 (Fig. 5). These trends correspond with the formation of the river Waal as the major Rhine branch. As segments C3 and U3 were located directly next to or just downstream of the Waal, they most likely were affected by higher and more frequent yearly floods conveyed through this new river branch. The effect of the formation of the Waal is further underlined by the abandonment of many existing settlements along this new river branch between the EMPA-EMPB. A similar trend is observed in the northern part of segment C3 corresponding with the increasing discharge of the river Lek (Figs. 3 and 4).

EMPB - EMPC: The number of settlements further increased during this period by 78%. The EMPB-EMPC settlement persistence is 60% (Fig. 6). Throughout the research area settlement elevation increased further (Fig. 7), with no clear spatial differences throughout the study area. Looking at persistent versus non-persistent settlements we observe a statistically significant 20 cm difference in settlement elevation. Presumably the large millennial flood of ca. 785 CE (Toonen et al., 2013) contributed to this rising settlement elevation.

EMPC - EMPD: In the EMPD the number of settlements decreased by 16% (Fig. 6B). This decline is best explained by 1) increased clustering of settlements and houses within these settlements (Numan, 2005) and 2) the lack of excavation data for this period. The trend of settlement movement to higher elevated areas stagnated and in some segments the average position of settlements even slightly decreased (C2, U2, U3, and U4). Persistent settlements were located 3 cm higher on average than non-persistent settlements (Fig. 7F). Newly-founded settlements appear to have been located on lower grounds. These observations are best explained by the combination of increased reclamation activities and water management during this period, enabling the colonisation of previously unsuitable areas (Lascaris and De Kraker, 2013), and the relatively small number of severe floods during this period (Fig. 7).

4. Discussion

4.1. Factors causing settlements shifts

The results show that from the RP to EMP settlements steadily shifted towards higher areas in the landscape. When comparing all subperiods except the ERP to MRP transition, persistent settlements on average were located higher than settlements that became abandoned. These shifts are most clear in the lowest segments in the MRP to LRP interval (U2, C4, and C5), and in the segments dating to the EMPA to EMPB transition close to a new river branch (C3 and U3). This suggests that during these periods water levels expressed by groundwater-level table, regular floods and extreme floods were important factors determining settlement location. The relative importance of these three factors is discussed below.

Influence of increased frequency of large floods – From the LRP onwards the study area experienced an increase in flooding frequency after centuries characterized by relatively few (large) floods (Fig. 7B). Trends in settlement elevation from the MRP to LRP are mainly observed in the lowest areas of the delta (U2, C4, and C5 in Fig. 5). From this we conclude that floods during the LRP must have affected the habitation conditions in the lowest areas in the study area, although they certainly will not have been the only cause of the depopulation. After the LRP, the lowest areas are much less populated and possible influences of major flooding events only are observed in the somewhat higher elevated segment C3, where a shift towards higher areas occurred until the EMPC (Fig. 5).

Segment U1 is the most confined delta segment, causing floodwater to be higher than in other segments. This suggests that settlements in this area must have flooded more frequently and that even during regular, less extreme floods the water levels were higher (Pierik et al., 2017). This area does not show significant trends in shifting patterns (Fig. 5), presumably because during the Roman period settlements in this region already were located on the highest possible positions (as can be observed in Figs. 3 and 4). Since segment U1 was never completely abandoned, its inhabitants probably were able to adapt relatively well to floods. Also in segment U4 no shift towards higher areas was observed for the MRP-LRP. This is best explained by the fact that this area was influenced by the regime of the river Meuse. Its flooding regime is yet unknown but as the river is smaller, floods can be expected to be less high compared to those of the river Rhine.

In summary, major floods caused settlements in the study area to shift upwards. These floods appear to have influenced settlement elevation shifts, but did not cause large areas to become permanently abandoned. The recorded floods are rare high-magnitude events and did not occur more frequently than once in several decades. Despite their possibly large impact, the relatively low frequency of these events probably made it possible for the delta inhabitants to return towards less elevated and therefore flooding-prone areas. This may explain why the settlements in the lowest areas in all cases were least persistent and why newly founded settlements often were located exactly here.

Position along a major river branch – The formation of the southern Waal course of the Rhine (Figs. 1, 3, and 4) and the subsequent silting up of the former main branch of the Rhine in the north around 450 CE (Weerts and Berendsen, 1995; Berendsen and Stouthamer, 2000; Van Dinter et al., 2017) caused the main discharge of the Rhine to flow through segments C4 and C5 instead of segments C1 and C2 (Figs. 3 and 4). This shift of the main channel from the northern part of the central delta towards the southern segment caused more frequent and higher floods in the southern areas and less severe flooding regimes in the northern part of the central delta. This is reflected in the trends of settlement shifting to

higher sites, as observed in segments C4, C5, and U3 and also in the southern part of C3 and C1 (Fig. 5, section 3). This is further underlined by the position of the settlements located in areas C4 and C5, which after the LRP mainly were confined to dwelling mounds. Although their absolute elevation through time (i.e., phases of dwelling mound elevation) is not known in detail, the trend of moving to higher areas is evident.

The configuration of large river branches affected settlement distribution by modulating both the distribution of flood water from large floods as well as from regular flooding events. Although the amplified effect of these events around rivers cannot be independently validated, as these lower-magnitude floods are not well recorded in the sedimentological record, they form the most likely explanation for the observed settlement shifts susceptibility close to major rivers compared to areas further away from rivers. The higher-frequency occurrence of these floods probably made them easier to be remembered by inhabitants of the delta. It is also possible that locally more permanent higher groundwater levels occurred as observed by Van Asselen et al. (2017) for flood basins where a new river branch formed in segments C3 and D between 6000 and 4000 cal BP. Despite the upward settlement shifts observed throughout the entire delta, no major areas seem to have become depopulated as a result of the environmental changes.

Gradually rising groundwater levels – Rising groundwater levels could have triggered the establishment of settlements on higher elevated locations. In the central and upper part of the delta groundwater-level rise was mainly forced by continuous sedimentation rather than by absolute sea-level rise during the first millennium BP (Cohen, 2005; Gouw and Erkens, 2007), i.e. while the surface area was being elevated by clay sedimentation, the groundwater-level also rose at a similar rate causing the groundwater level relative to the surface to remain more or less constant. Pierik et al. (2017) confirmed this by demonstrating that sedimentation on the alluvial ridges between 100 CE and river embankment around 1100 CE on average was 38 cm, which corresponds to the results of groundwater-level rise modelled by Cohen (2005). In this study, scenario 1 assumes equal pacing of groundwater and surface elevation, whereas scenario 3 actually tests this assumption using independent datasets on surface elevation and groundwater level reconstructions for 100 CE and 900 CE (see section 2.3; Table 3). When both scenarios are compared, it seems that sedimentation and groundwater level indeed kept the same pace, since both scenarios show comparable and consistent upward-shifting trends (Fig. 5). From this we conclude that at least on the location of the settlements, the groundwater level relative to the surface did not significantly rise. Locally, in the lowest parts of the alluvial ridges, gradual groundwater-level rise may have been a minor forcing. This mechanism, however, cannot fully explain the observed major settlement shifts in the study area and the differences between the segments.

Despite the dynamic nature and changing environmental conditions of the delta landscape, cultural patterns (e.g. route networks) seem to show signs of long-term persistence as can be seen in the connectivity patterns in the study area (also see Van Lanen and Pierik, in this issue).

4.2. Reflections on the scale and data resolution

The upward shift of settlements during the studied time interval are visible both on delta scale and in the individual segments of the delta. In addition for all three scenarios the differences in elevation between the subperiods are rather consistent (Figs. 5 and 7E). The introduction of 900 CE surface level and groundwater levels in scenario 3 in addition to the 100 CE surface level and groundwater

level used in scenarios 1 and 2 (Table 3) indicates that the latter input datasets are reliable. Administrative errors in settlement location appear to have a minor influence on the results (compare scenarios 1 and 2 in Figs. 5 and 7E). In segments C4, C5, and U4 some more deviation between scenarios 1 and 2 is observed, however the magnitude and timing of these changes remain similar.

The individual flood events generally have been dated with an accuracy of 30–150 years using ¹⁴C dating and correlation techniques (Cohen et al., 2016), which corresponds to the chronological precision of the archaeologically dated settlements, i.e. a 20–200 years resolution. Cohen et al. (2016, p.43) state that the occurrence of major flood events in the ERP and MRP are highly unlikely considering the sedimentological and archaeological evidence. The chronological recording of settlement data is most accurate for the Roman period. This is due to: 1) a shorter time interval per sub-period; and 2) the fact that typologies based on Roman material culture in our study area are well developed and allow precise dating. In addition large-scale analyses in our study area are bound to specific ABR chronological boundaries (i.e. on average 100–200 yr intervals, Table 1). Although locally more detailed dating is available, when performing large-scale analyses the least accurately dated sites are the bottleneck of the analysis. Methods by Verhagen et al. (2016) who explored a detailed and statistical approach for the Roman period, appear to be promising to increase chronological resolution of settlements and to better understand settlement abandonment, continuity and persistence for the first millennium AD.

4.3. Outlook

Since the LRP, settlements steadily shifted towards higher areas while the lower elevated settlements became abandoned. The observed elevation differences are small but appear to be robust. To further test the impact of floods on habitation conditions, hydraulic flood-modelling studies can be performed. These studies address flood-water dispersal through the delta assessing flooding frequency and intensity per gridcell. The palaeo-surface reconstructions can serve as input layer for such a study. Following the approach in this paper, segments in the delta can be compared and the role of delta plain width and avulsion in flooding frequencies can be further assessed.

The results of our study can be locally validated using information from studies characterized by a higher chronological and spatial resolution. When these studies focus on absolute settlement elevation and indications for wetter conditions (e.g. clay layer by flooding), the link between settlement dynamics (i.e. elevation trends and persistence) and floods can then be further evaluated.

The patterns observed in this paper can be compared to more detailed large-scale historical and archaeological studies regarding e.g. early-reclamation activities, land use, demography, political settings, and transport. This will further improve our understanding of past human-landscape interactions.

5. Conclusions

Settlement data from integrated archaeological databases were combined with geomorphological reconstructions and records of environmental changes in the Rhine-Meuse delta. This delta-wide approach demonstrates that:

- During the first millennium CE habitation mainly occurred on the higher parts of the alluvial ridges, with 40% of the settlements being situated on alluvial ridges without an underlying channel belt.

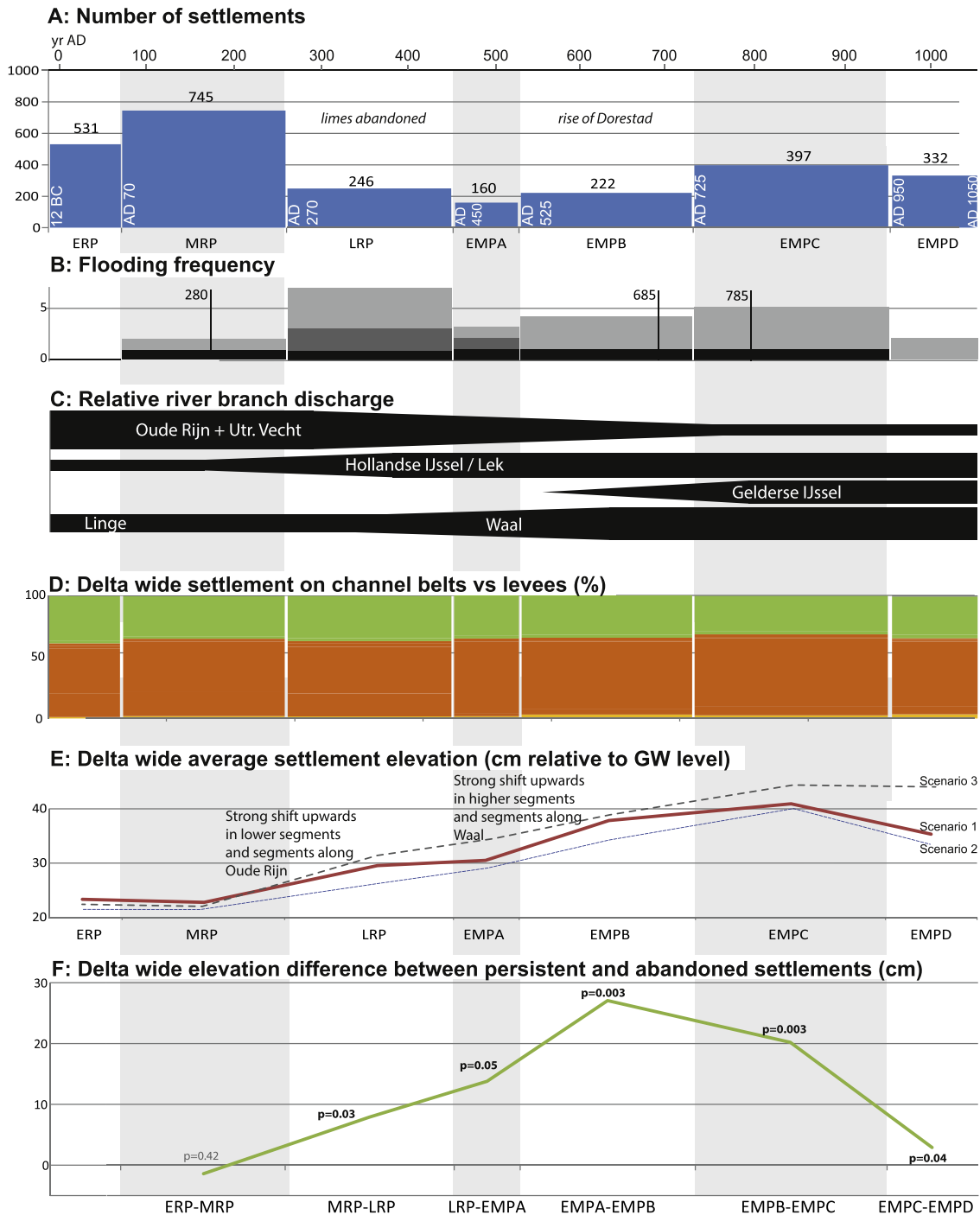


Fig. 7. **A)** Number of settlements in the research area; **B)** Holocene recurrence time of floods from black to light grey: 250 yr (very severe flood), 100 yr (severe flood), 50 yr (moderately severe flood), after: [Toonen et al. \(2013\)](#); [Cohen et al. \(2016\)](#); [Toonen \(personal communication\)](#); here the events are grouped per archaeological subperiod and the ages of the three largest floods are indicated; **C)** activity of major rivers in the research area after [Cohen et al. \(2012\)](#) and [Van Dinter et al. \(2017\)](#); **D)** percentage of settlements on geomorphological units on map of [Fig. 2](#). Orange: settlements on levees or crevasse plays on sandy channel belts, green: settlements on levees or crevasse plays outside sandy channel belts; **E)** delta-wide average settlement elevation; **F)** elevation difference between persistent and abandoned settlements for scenario 1, including p-values describing the significance of the results of the t-test, with values statistically significant at $p \leq 0.05$ accentuated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Between 270 and 750 CE settlements shifted towards higher locations. Between 270 and 450 CE this development mainly occurred in relatively low-elevated delta segments. From 450 CE onwards the somewhat higher-elevated central delta was affected as well. This settlement shift coincided with an increased frequency of severe floods.
- Areas close to newly-formed large river branches between 270 and 750 CE were characterized by a strong relocation trend of settlements towards higher-elevated positions or even by settlement abandonment. Close to rivers, settlements appear to be relatively more susceptible to low-magnitude floods (yearly to decadal) because here these floods occur more regularly and

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Online data sources: (accessed on 25-9-2016)

- Archaeological Basic Register (ABR): The Archaeological Basic Register is maintained by the Cultural Heritage Agency of the Netherlands and aims at the standardisation of archaeological terms used in the Netherlands. The Archaeological Basic Register is maintained by the Cultural Heritage Agency of the Netherlands and aims at the standardisation of archaeological terms used in the Netherlands. Website (in Dutch): http://cultureelerfgoed.nl/sites/default/files/downloads/dossiers/abr_website2.pdf.
- Archaeological Information System of the Netherlands (ARCHIS): The archaeological information system of the Netherlands is maintained by the Cultural Heritage Agency of the Netherlands and contains an overview of the archaeological finds excavated in the Netherlands. <https://archis.cultureelerfgoed.nl/#/login>.