Human-caused avulsion in the Rhine-Meuse delta before historic embankment (The Netherlands)

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ABSTRACT

Although the shifting of deltaic river branches (avulsion) is a natural process that has become increasingly influenced by humans, the impact of early human activities as a driver of avulsion success has remained poorly explored. This study demonstrates how two important avulsions in the downstream part of the Rhine-Meuse delta, The Netherlands, were stimulated by human activities in the first millennium CE, before historic embankment constrained the river courses. Peatland reclamation induced land subsidence in the lower delta. This effect, together with a human-induced increase in suspended fluvial sediments and tidal backwater effects, allowed for a gradual ingression of tidal creek channels and progradation of fluvial crevasse channels into human-occupied and drained peatlands, where they eventually connected. We reconstructed the initial situation and identified the feedback loops among overbank sedimentation, tidal incursion, and land drainage subsidence that led to avulsion success. The processes and feedbacks resulting from human activities are generic and hence relevant to many other deltas today where human-induced subsidence results in tidal ingression, potentially connecting to rivers and causing unexpected avulsions.

INTRODUCTION

Avulsion, the shift of a river course, takes place in multiple phases. The preconditioning phase occurs before the river shifts its course; during this phase, factors such as sediment supply and sea-level rise create the necessary conditions for eventual flow diversion (e.g., Makaske et al., 2012). Many modern fluvio-deltaic environments where avulsion takes place have been increasingly affected by humans over the last millennia. Humans are known to have deliberately triggered avulsion directly, by constructing canals and dams (e.g., Heyvaert and Walstra, 2016), but less is known about unintended avulsion resulting from human impacts in the delta plain and in the hinterland before the avulsion is actually triggered. This is despite the potential importance and impact of avulsion on densely populated deltas worldwide. These areas have low topographical gradients, and, during the preconditioning phase, small human-induced changes in sedimentation or subsidence may already lead to critical shifts in the topographically favorable pathway through a delta.

Here, we present a case of two avulsions in the lower Rhine delta in the first millennium CE, a period during which population density increased, and the natural delta environment became more affected by human impact (Pierik and van Lanen, 2017). The new Lek and Hollandse IJssel (HIJ) Rhine branches formed during this period, crossing 30 km of freshwater peatland to connect to the tidal channels of the Old Meuse estuary. This caused the abandonment of the Old Rhine course (Fig. 1). These avulsions are excellent cases to study human impact on avulsion because they occurred in a data-dense area, and they allow the different stages of the avulsion process to be studied. Their record is well preserved because early in the second millennium, the new rivers were embanked, limiting lateral reworking. The boundary conditions—climate, sediment supply, and flooding regime, as well as human presence—are well known.

Remarkably, the Lek and HIJ were the first channels in 3000 yr that managed to cross an extensive alder peat swamp. While Rhine floodwaters had fed these swamps, older crevasse splays ran dead into the swamp, implying that vegetation and substrate reduced floodwater flow velocities, inhibiting the crevasse channels to develop into avulsion belts (Makaske et al., 2007). This situation changed from the Late Iron Age onward (250 BCE), when suspended sediment delivery from the upstream river basin increased as a result of hinterland deforestation (Erkens et al., 2011), while at the same time tidal ingression from the downstream direction occurred due to peatland drainage and reclamation (Pierik et al., 2017a; de Haas et al., 2018). These human-induced developments have been studied separately, but the ways in which they interacted, and the degree to which they led to lower delta avulsion are not known.

Here, we show for the first time how human-induced upstream and downstream factors interacted to set the stage for successful avulsion in a low-gradient unembanked delta. We mapped and dated the stages of downstream tidal ingressions, upstream crevasse splay progradation, and peatland reclamation. Furthermore, we identified the drivers and feedbacks that eventually led to the successful avulsion. Our case shows the effects of human impact on avulsion and serves to illuminate potential future avulsion in other populated deltas that would have substantial socioeconomic impacts.

MATERIALS AND METHODS

The HIJ and Lek avulsion cases were traced by using an extensive data set containing the age and position of channel belts and their natural levees, crevasse splays, and tidal creek landforms in the Rhine-Meuse delta (e.g., Berendsen and Stouthamer, 2000). We expanded this rich data set by sampling and ^{14}C dating the top of peat directly below overbank deposits at multiple locations along the HIJ and Lek branches (see the
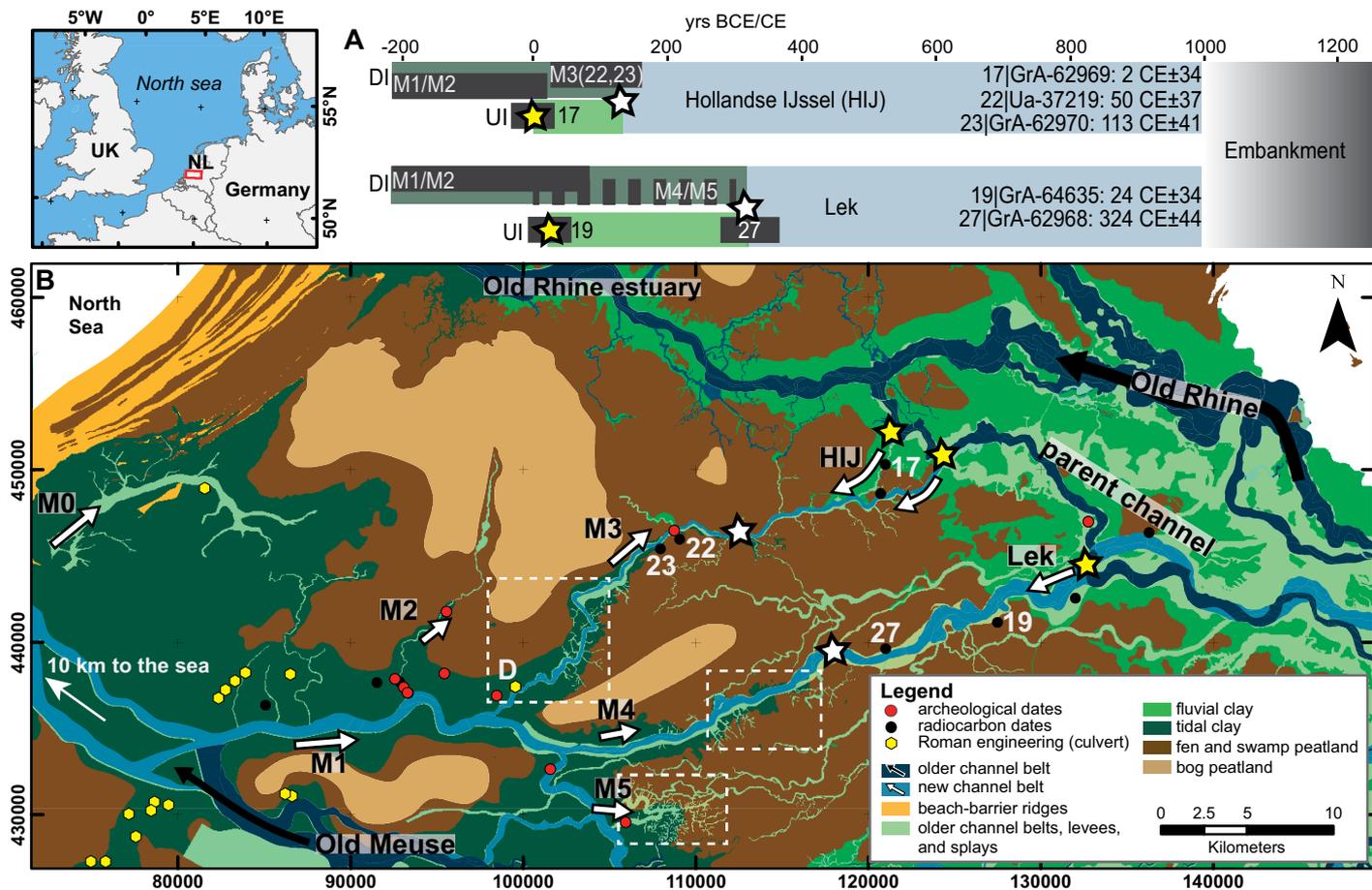
Figure 1. A: Time line of stage development of Hollandse IJssel (HIJ) and Lek avulsions, highlighting initiation phases at downstream (DI) and upstream (UI) locations. Main supporting ^{14}C dates (±1σ) for samples from top of peat below river clay are indicated with black bars. M0–M5 indicate different tidal creeks from Old Meuse estuary; white rectangles indicate occurrence of rectangular creek networks. White stars indicate presumed tidal-fluvial connection moments and locations based on orientation and intersection of adjacent crevasse splays. Yellow stars indicate UI crevasse-avulsion initiation and position. B: Surficial geological map of study area showing old river courses (dark blue) and new courses (light blue; Cohen et al., 2012), flood-basin extent (green), and raised peat bogs (light brown; Van Dinter et al., 2014). Anthropogenic features of youngest 1000 yr were removed from map. Selected dates, relevant archaeological sites mentioned in text, and inferred stages of avulsion are indicated. See Data Repository (text footnote 1) for a full description of age control. UK—United Kingdom; NL—Netherlands. Map in RD projection, EPSG: 28992.

GSA Data Repository[1]). All dates are reported in standard calibrated form in yr BCE/CE with a 1σ range. Based on these dates, we identified the stages of channel initiation at either end of the branches and the maturation stages after the channels connected (Fig. 1). We correlated these events to human activity using archaeological artifacts that were found on the natural levees and on top of the peat. Peatland-surface elevation before avulsion was reconstructed for each ^{14}C sampled site (including compaction correction—Koster et al., 2016, 2018; see the Data Repository) to assess the gradient advantage along the new course through the pristine peatlands over the abandoned course.

UPSTREAM AND DOWNSTREAM ANTHROPOGENIC CONTROLS

In the last millennium BCE, two upstream-induced processes determined the geomorphological setting for our study. In the central Rhine delta, avulsions toward the Meuse estuary developed along the eastern margin of the peatlands (Fig. 2A). Additionally, human deforestation of the upstream Rhine catchment resulted in increased supply (30%–60%) of fine-grained sediment toward the delta after ca. 500 BCE (Erkens et al., 2011), affecting the delta plain and its estuarine outlets. Along the

peatlands, this caused the Rhine branches to raise their levees by ~1 m between 1000 and 1 BCE (Fig. 2C) and caused the crevasse splays to grow larger and faster than their precursors. This accelerated the initial stages of avulsion and thus increased the probability that the crevasse splays could develop into an avulsion. The increased sediment load and enhanced connection of Rhine channels along the peatlands toward the Meuse outlet resulted in larger sediment transport toward this estuary (Berendsen and Stouthamer, 2000). Furthermore, increased freshwater input triggered floods, which led to the first stage of tidal area expansion close to the mouth of the estuary around 230 BCE (M0 in Fig. 1; Vos, 2015).

Upstream Initiation of Crevassing (UI)

The parent channel belt for the HIJ and Lek avulsion was the secondary Rhine branch that ran along the northern edge of the peatland that had developed in prior times (Figs. 1B and 2A). Around settlements on these channel belts, as well as in the adjacent flood basins, riparian deforestation for wood use had become widespread during the Roman age (notably between 1 and 200 CE; Van Dinter et al., 2014). This decreased overbank flow roughness and resulted in reduced stream-power gradients laterally from the channel to the flood basin (e.g., Pierik et al., 2017b). Combined with the increased suspended sediment supply, this made crevasse systems penetrate farther into the peatland flood basin. Avulsion-belt formation by crevassing along the HIJ and Lek branches began around 2 CE and 24 CE, respectively (dates 17 and 19; Fig. 1; Table DR1).
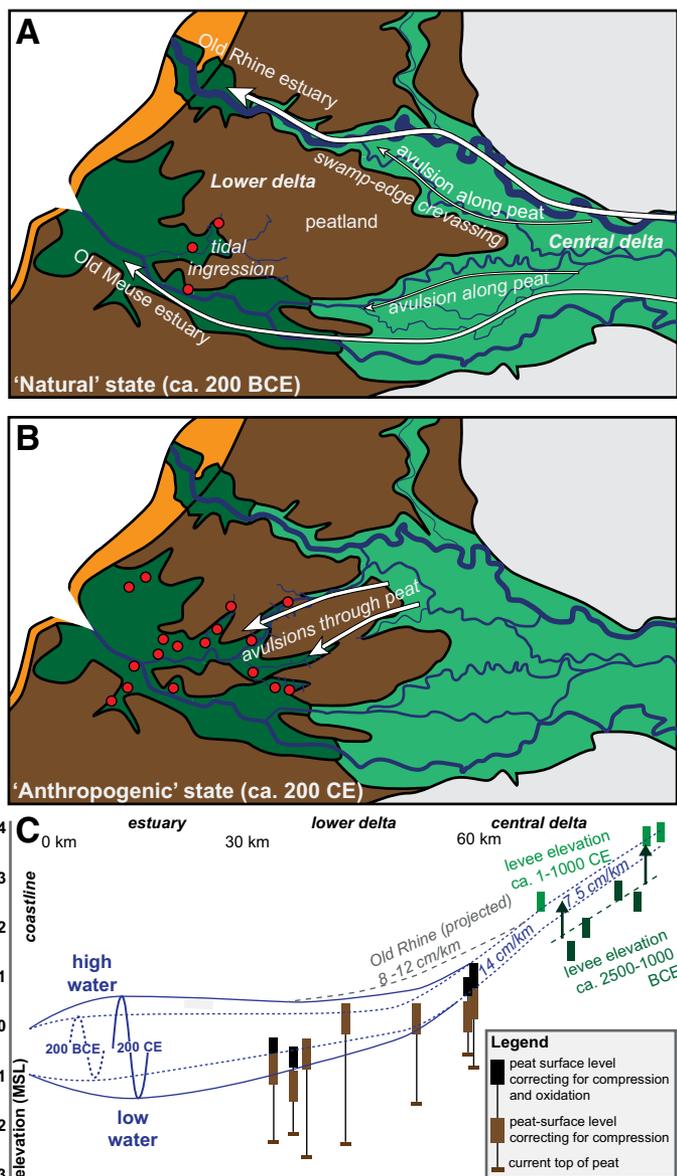
Figure 2. A: Simplified map of delta network in its last natural state around 200 BCE. B: Simplified map of delta network in first anthropogenic state around 200 CE. Colors are as in Figure 1; red dots indicate settlement locations. C: Reconstruction of pre-avulsion surface elevation along HIJ and Lek paths. Upstream—mapped levee elevation for two generations of natural levees (green and dark green from Pierik et al., 2017b); central—top of peat (see Data Repository); downstream—tentative tidal incursion, increasing with tidal creek progradation from 200 BCE to 200 CE (Vos, 2015). MSL—mean sea level (in m). Projected Old Rhine gradient was measured along its residual channels, after Cohen et al. (2012).

Downstream Creek Initiation (DI)

From 200 BCE onward, tidal deposition and multiple creeks of the Old Meuse estuary progressively expanded into the peatlands (M1–M5 in Fig. 1; Table DR1). Archaeological artifacts on top of this peat provide evidence for habitation and reclamation of this environment between 250 BCE and 250 CE (Fig. 1B; Table DR2). The intensified agricultural use of the artificially drained peatlands caused surface lowering. A Roman hollow-tree valve-culvert (Roman engineering work) found at site D (150–200 CE; Table DR2) along M3, and 16 other culverts found more downstream in the Meuse estuary (Ter Brugge, 2002; Fig. 1; Fig. DR1) provide evidence that the land was artificially drained during low tide. The valves allowed drainage during low tide and prevented a return flow during high tide, indicating that reclamations caused land-surface lowering to

below high tide water levels. In several places, Roman-aged small-scale creek ridges follow straight courses that are strikingly perpendicular to the larger natural channels, suggesting possible inheritance of human-dug ditch patterns. This pattern is present as sharp bends in the lower reaches of the HIJ and Lek branches, and also in the Alblas system (white dotted rectangles in M3–M5 in Fig. 1; Fig. DR3), an analogue to sites in the southwestern Netherlands, adjacent to our study area (Vos, 2015). As demonstrated in this coastal plain peatland, subsidence increased tidal volume and triggered tidal-creek expansion. Rates of subsidence were an order of magnitude larger than coeval sea-level rise and made the area increasingly sensitive to storm-surge flooding (e.g., Vos, 2015; Pierik et al., 2017a). The developing tidal ingressions transported sediments into the flood basins. At the distal front of the ingression, the weight of the sediment led to acceleration of the subsidence of the peatland. The total peat subsidence along the avulsion path from the beginning of the avulsion until today is ~2 m (Fig. 2C). We estimate that surface lowering due to sediment loading during the formation of the new river branch was around 1 m. The resulting expansion of the estuarine channel and creek network at the downstream side (M1–M5) shortened the distance that crevasse splays from upstream had to cross to connect downstream (Fig. 1B).

Connection and Beginning of Maturation

Ingressing creeks reached the central part of the peatlands around 50–150 CE, first along the path of branch HIJ (dates 22 and 23; Fig. 1; Table DR1). Not much later, crevasse-splay progradation reached this area from the east, and connection of tidal and fluvial subsystems occurred at the approximate location indicated by the white star in Figure 1B. Local subsidence and deforestation had removed the topographic and hydraulic roughness barrier that the swamps had been before, creating a slight hydraulic energy gradient advantage for the new course compared to the Old Rhine branch. By 300 CE, a second connection was established by the Lek branch (date 27; Fig. 1; Table DR1), which was shorter than the HIJ and had a wider channel belt. Its timing, length, and channel belt dimensions indicate that the Lek branch had a gradient advantage over the HIJ and became the dominant branch of the two.

FEEDBACKS LEADING TO AVULSION SUCCESS

The results show that human impacts—peatland subsidence and increased suspended sediment load—on the river, estuary, and peatlands made the lower delta more prone to avulsion. The sensitivity of the system in response to human impact can to a large extent be attributed to the compaction-prone nature of peat. The avulsions were successful due to interacting feedback loops in the preconditioning stage and after the connection, which are typical for this peatland environment (Fig. 3). In both the upstream and downstream realms, enhanced peat subsidence created more accommodation for floodwaters, leading to larger crevasse and creek channels. This facilitated additional sediment transport and deposition onto the peatlands, causing further subsidence. Upstream, this positive feedback loop was initiated by crevassing (sediment loading), whereas downstream, this loop was initiated by peatland subsidence (Fig. 3). As a result, the tidal channels expanded 15–25 km into the peatlands, bringing the point where the river connected to marine base level farther inland (Fig. 2C). Furthermore, a millennium of maturation with ever-increasing overbank sedimentation of the parent channel upstream had raised its levees by ~1 m (Fig. 2C). This increased the flood-basin gradient from ~4 cm/km to ~14 cm/km, yielding a slight gradient advantage to the parent channel slope (Old Rhine) of 8–12 cm/km upstream of Utrecht (Fig. 2C). This topographical gradient advantage, the enhanced landward penetration of the tides, and the decreased vegetation roughness together caused the effective energy gradient to increase significantly, especially during low tide in combination with high river discharge and water levels (Fig. 2C). Once a connection was established, channels matured, and natural levees formed that were resistant to lateral erosion. Additionally, the mass of the
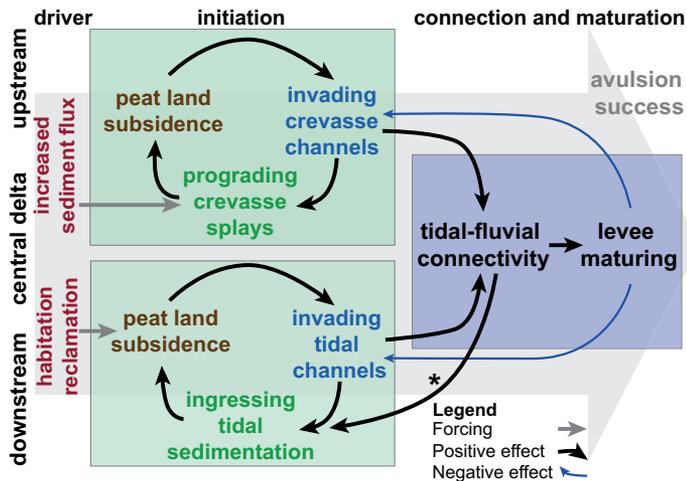
Figure 3. Progression of human-induced feedback mechanisms that lead to avulsion in compaction-prone deltas. Initially, human factors affected separate systems in areas upstream and downstream of peatlands, represented by two green boxes, which connect in central delta (blue box). Text in the boxes indicates processes; arrows indicate feedbacks. For explanation of asterisk, see main text.

levees caused further peat compression, thereby further hampering lateral channel development and moving the channel system to an equilibrium size (blue arrows in Fig. 3). A positive feedback in tidal-fluvial connectivity was the delivery of more sediment to the estuary, further accelerating peat subsidence and the ingression of creeks that were not yet connected to a river (labeled asterisk in Fig. 3). In this way, one avulsion could help the next avulsion to develop—starting before BCE (Fig. 2A) along the southern swamp edge, followed by the HIJ and finally the Lek.

IMPLICATIONS

Our historical case demonstrates how two sets of geographically separate anthropogenic landscape modifications—human-induced subsidence and sediment load increase—can change gradients in sensitive deltas, leading to tidal ingression and avulsion. We show that this human-induced preconditioning phase can take several centuries, but it has irreversible consequences once avulsion is triggered: It increases flooding risks and potentially leads to a rearranged delta landscape. Human-induced tidal ingression is generally not recognized as a major avulsion control, despite its potential impact in subsidence-prone, low-gradient deltas. Although the suite of events may be specific to the Rhine-Meuse delta, parts of the feedback loop recognized here may cause unexpected discharge redistribution in other currently densely populated deltas. Prime examples of deltas that experience ongoing human-induced subsidence are the Mekong River (Southeast Asia; Zoccarato et al., 2018), Yellow River (China; Zhang et al., 2015), and Mississippi Delta (USA; Törnqvist et al., 2008). These deltas are expected to face an increase in land-use intensity in the coming decades, combined with increased threats from cyclones and sea-level rise. Unembanked areas within these deltas that have a compaction-prone substrate, in particular, may be sensitive to freely occurring avulsion. The Rhine-Meuse delta case highlights the sensitivity of deltas to human impact and emphasizes the need for an integrated understanding of tidal, fluvial, and catchment processes for knowledge-based river and delta management.

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