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VARIABILITY OF CHANNEL-BELT DIMENSIONS AND THE CONSEQUENCES FOR ALLUVIAL ARCHITECTURE: OBSERVATIONS FROM THE HOLOCENE RHINE–MEUSE DELTA (THE NETHERLANDS) AND LOWER MISSISSIPPI VALLEY (U.S.A.)

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ABSTRACT: **Over the past decades, many studies have focused on the dimensions of channel-belt sand bodies (referred to as "channel belts") in fluvial deposits because of their relevance for hydrocarbon exploration and production. Some field studies have revealed a significant downstream decrease of channel-belt width and width/thickness ratio along the length of the channel belt. To verify whether this is a common feature in fluviodeltaic settings, eight Holocene channel belts in the Rhine–Meuse delta (The Netherlands) were selected and one in the Lower Mississippi Valley (U.S.A.). We determined channel-belt geometry (width or width/thickness ratio) using geological–geomorphological maps and detailed cross sections based on borings. It was found that the width of channel belts encased in cohesive deposits decreases by a factor of 4 to 6.5 in a downstream direction along the length of the channel belts. The width/thickness ratio decreases by a factor of 2.5 to 5. On the other hand, the width of a channel belt incised in a noncohesive substrate remains constant along its entire course. These observations are related to longitudinal changes in bank erodibility and stream power. It is suggested that bank erodibility is the dominating factor determining the geometric properties of channel belts, and the variability therein, at least in the Rhine–Meuse delta. The currently available alluvial-architecture models most likely overestimate sand quantities and connectedness in alluvial successions, because channel-belt dimensions are held constant in all models. We therefore propose that the factors "bank erodibility" and "stream power," which influence width and width/thickness ratio of channel belts, should be incorporated in future alluvial-architecture models in order to make more realistic estimates of sand quantities in river deltas.**

INTRODUCTION

Ancient fluvial channel-belt sand bodies (henceforth referred to as "channel belts") commonly act as reservoirs for natural resources, such as oil and gas, water, and metals. In view of this fact, many field studies (e.g., Shanley and McCabe 1993; Zaleha 1997; Ryseth et al. 1998; Tye et al. 1999; Holbrook et al. 2006) and modeling studies (Leeder 1978; Allen 1978, 1979; Bridge and Leeder 1979; Bridge and Mackey 1993a, 1993b; Mackey and Bridge 1995; Bryant et al. 1995; Heller and Paola 1996; Karssenberg and Bridge 2005) have focused on understanding the relative proportion, geometry, and spatial distribution of channel belts and overbank deposits in fluvial successions ("alluvial architecture" cf. Allen 1978). These studies made clear that, given a constant floodplain width and aggradation rate, the proportion of channel-belt deposits in an alluvial succession is positively correlated to the width and thickness of the channel belts (e.g., Leeder 1978; Bridge and Leeder 1979). Furthermore, the degree to which channel belts are connected ("connectedness" cf. Allen 1978; Leeder 1978) increases with rising channel-deposit proportions (e.g., Bridge and Mackey 1993b; Zaleha 1997). The dimensions of channel belts thus greatly influence alluvial architecture. Therefore, gaining insight into the (downstream) variation of channel-belt dimensions leads to a better understanding of the architecture of fluviodeltaic successions. This eventually could improve alluvial-architecture models and lead to better predictions of hydrocarbon reserves.

Although the geometry of channel belts has received much attention (for an overview, see Gibling 2006), data on the longitudinal variation of channel-belt geometry is relatively scarce. Törnqvist et al. (1993) and Makaske et al. (2007, this issue) reported significant downstream changes in the dimensions of two Holocene channel belts in the Rhine–Meuse delta (central Netherlands) (Fig. 1). They found a downstream decrease of channel-belt width (w) by a factor of 4.3 and 6.7, respectively, whereas thickness (t) increases by a factor of 1.2 and 2.6. The reported channel-belt width/thickness ratios (w/t) decrease by a factor of 4.7 and 8.2 in the downstream direction. According to Törnqvist et al. (1993) and Makaske et al. (2007), variations in the ability of the channel to migrate laterally, variations in substrate erodibility, and discharge changes explain the observed downstream variations in channel-belt dimensions. The channel belts studied by Törnqvist et al. (1993) and Makaske et al. (2007) were two small, partly anastomosing Rhine distributaries (Schaik and Schoonrewoerd channel belts) of middle Holocene age. It is not clear if their observations are applicable to other channel belts in the Rhine–Meuse delta as well. Furthermore, studies in other fluvial settings (e.g., Schumm et al. 1994; Bridge 1999) suggest that the above-mentioned trends probably are common to many fluvial systems, but this needs to be verified. To address to these issues, we extended the existing datasets of Törnqvist et al. (1993) and Makaske et al. (2007) with geometric data of channel belts with varying size, age, and channel planform, and which are located in two different fluvial settings.

Characterization of the architecture of fluvial successions requires extensive datasets (outcrops, seismic data, and/or a high quantity of cores, and age control; Bridge 2003). The Holocene Rhine–Meuse delta

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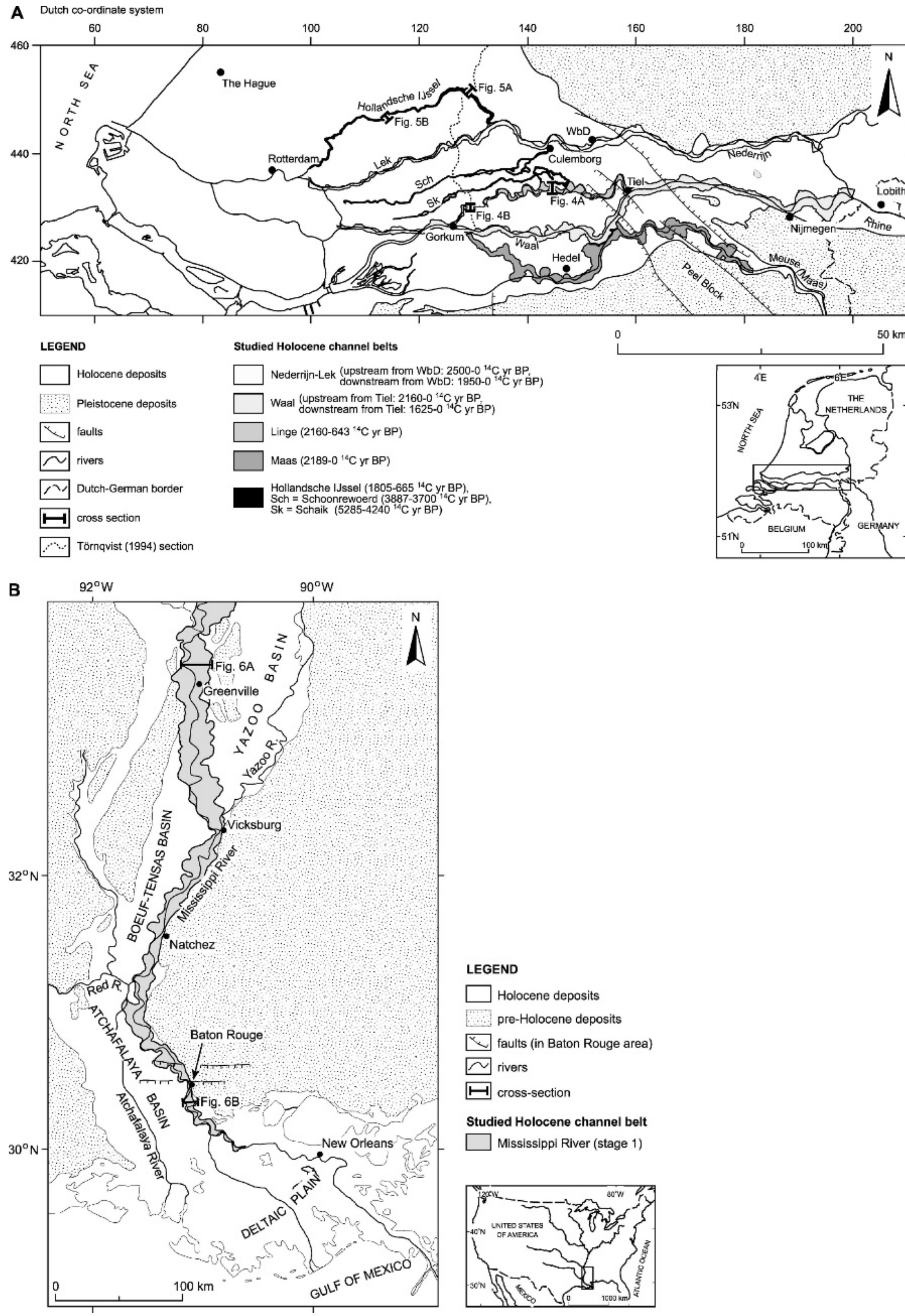


FIG. 1.— **A)** The Rhine–Meuse delta, The Netherlands, and **B)** the Lower Mississippi Valley downstream from Greenville, U.S.A. The studied channel belts are indicated as well as the locations of the cross sections in Figures 4–6. Age of the Rhine–Meuse channel belts is according to Berendsen and Stouthamer (2001), Berendsen (2005), and Berendsen and Hoek (2005). Sch = Schoonrewoerd channel belt; Sk = Schaik channel belt, WbD = Wijk bij Duurstede.

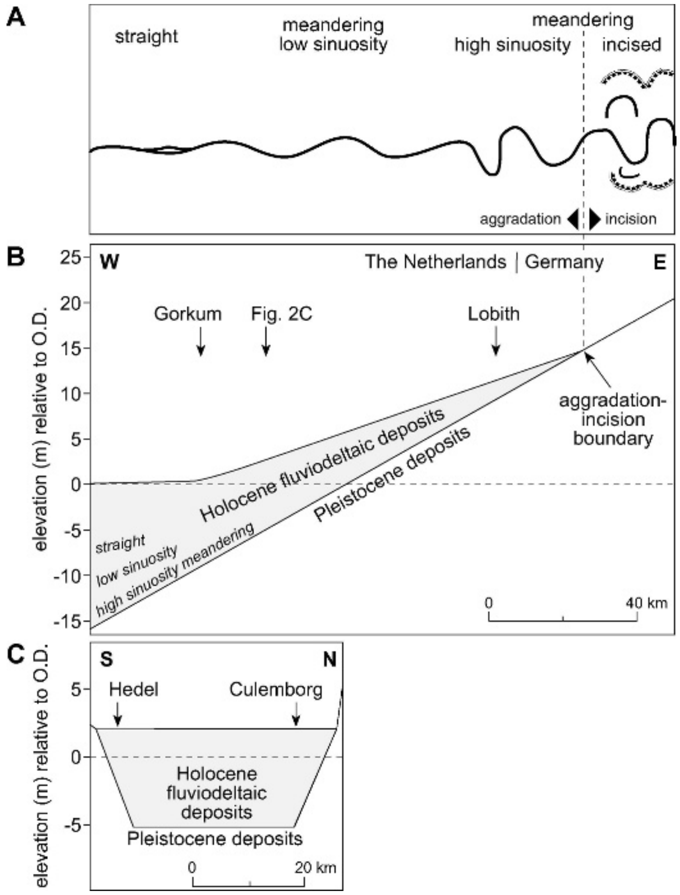


FIG. 2.—**A)** Longitudinal change in river planform in the modern Rhine–Meuse delta (Wolfert 2001), and schematic transects **B)** parallel and **C)** perpendicular to the general flow direction. The longitudinal pattern of change in river planform shifted upstream towards its present location during the Holocene along with the aggradation–incision boundary. In the western part of the delta, a vertical succession of channel belts is formed by high-sinuosity, low-sinuosity, and straight channels. O.D. = Dutch Ordnance Datum (~ mean sea level).

(The Netherlands) and the Lower Mississippi Valley (U.S.A.) (Fig. 1) are two of the most extensively studied fluvial areas in the world. The datasets of the two areas include borehole logs, geological–geomorphological maps, detailed geological–lithological cross sections, and ^{14}C and OSL dates (Berendsen and Stouthamer 2001; Saucier 1994). Therefore, we chose the Rhine–Meuse delta and the Lower Mississippi Valley to: (1) quantify the downstream geometric variability of channel belts; (2) test the hypothesis that alongstream geometric variations of channel belts are common in aggrading fluviodeltaic settings; and (3) find out how these variations influence alluvial architecture.

GEOLOGICAL SETTING

Rhine–Meuse Delta (The Netherlands)

The central Holocene Rhine–Meuse delta (Fig. 1A) is underlain by Late Weichselian (Oxygen Isotope Stage 2) fluvial sediments. These sediments consist predominantly of coarse sand and gravel deposited by braided rivers in the Rhine–Meuse paleo-valley. Relative sea-level rise after the Last Glacial Maximum resulted in onlap, and the boundary between Holocene aggradation and incision, i.e., the inland limit of Holocene onlap (see Fig. 2), shifted upstream (Pons 1957; Stouthamer and Berendsen 2001). This resulted in the formation of a fluviodeltaic wedge (Fig. 2B, C) of Holocene fluvial clastic deposits and organics. Holocene aggradation started approximately 8000 ^{14}C yr BP in the western part of the present delta (Van Dijk et al. 1991). Presently, the aggradation–incision boundary between the Holocene and Weichselian deposits is located near the Dutch–German border (Stouthamer and Berendsen 2001) (Fig. 2B).

Wolfert (2001) recognized longitudinal change in channel planform in the modern Rhine–Meuse delta (Fig. 2A). Upstream of the aggradation–incision boundary, a terraced landscape exists with incised, high-sinuosity meandering channels. Aggrading, high-sinuosity meandering channels occur just downstream of the aggradation–incision boundary. Farther downstream, the channel pattern changes to low-sinuosity meandering and ultimately to straight (Fig. 2A). This longitudinal change in channel planform shifted upstream during the Holocene, along with the aggradation–incision boundary (Berendsen and Stouthamer 2001). The result is that a vertical succession of high-sinuosity meandering, low-sinuosity meandering, and straight (paleo-) channels is found in the western part of the delta (Fig. 2B) (Törnqvist 1993b). Furthermore, the *rate* of sea-level rise during the Holocene influenced river planform in the downstream part of the Rhine–Meuse delta (Törnqvist 1993b; Berendsen and Stouthamer 2001). During rapid sea-level rise in the middle Holocene, an anastomosing (Törnqvist 1993b) or straight (Makaske 1998) channel pattern existed in the west-central part of the delta. When sea-level rise decelerated, the low-sinuosity meandering pattern shifted slightly downstream, probably as a result of increased discharge and within-channel sedimentation (Berendsen and Stouthamer 2001). At the margins of the delta, a high-sinuosity meandering planform was maintained throughout the Holocene due to the presence of easily erodible Late Weichselian sands in the shallow subsurface (Törnqvist 1993b). Channel-belt width/thickness ratios in the Rhine–Meuse delta are typically less than 15 for straight channels (Törnqvist et al. 1993; Makaske 1998) and more than 50 for fully meandering channels (Weerts 1996; Makaske 1998).

Southern Lower Mississippi Valley (U.S.A.)

The base of the Holocene in the southern Lower Mississippi Valley between Greenville and Baton Rouge (Fig. 1B) is formed by late Pleistocene sands and gravels deposited by braided Mississippi River precursors. Pleistocene and Tertiary uplands border the alluvial valley to the west and the east (Fisk 1944, 1947; Autin et al. 1991; Saucier 1994).

Although the paleogeographic evolution of the Lower Mississippi Valley is still under debate, its Holocene fluvial evolution seems to be similar to that of the Rhine–Meuse delta. New data on Holocene sea-level rise in the Gulf of Mexico (Törnqvist et al. 2004a; Törnqvist et al. 2004b) suggest that Holocene aggradation in the northern Mississippi delta plain started approximately 8000 ^{14}C yr BP. Prior to 5000 ^{14}C yr BP, sea level in the Gulf of Mexico rose rapidly. This led to high aggradation rates and the development of a multichannel, possibly anastomosing, river planform in the southern Lower Mississippi Valley. The multichannel river system created isolated, narrow channel belts encased in fine-grained overbank deposits (Aslan and Autin 1996, 1999). Width/thickness ratios of these early to middle Holocene channel belts are typically less than 125 (Aslan and Autin 1996). After 5000 ^{14}C yr BP, sea-level rise and aggradation rates decreased, which is reflected in the fluvial succession by an abundance of channel-belt deposits formed by laterally migrating meandering channels. The width/thickness ratios of these relatively wide channel belts range up to 500 (Aslan and Autin 1996, 1999).

Schumm et al. (1994) reported significant variations in planform and dimensions of the modern Lower Mississippi River channel. They postulated two factors responsible for this variability: valley slope (affecting sinuosity and stability of the channel) and bank erodibility. Channel-belt width and channel width/depth ratio of the modern Mississippi River decrease in a downstream direction (Bridge 1999;

TABLE 1.— *Present discharge of the Mississippi River, Rhine, and Maas (Berendsen and Stouthamer 2001; U.S. Geological Survey 2002) and a paleo-discharge estimate of the Schoonrewoerd channel belt (Makaske et al. 2007). The Waal and Nederrijn–Lek channels are distributaries of the modern Rhine system (see Fig. 1A). Although present-day bankfull discharge is strongly human-regulated, the figures give a notion of the relative magnitude of discharge (see Makaske et al. 2007).*

	Mean annual discharge (m^3/s)	Maximum bankfull discharge (m^3/s)
Mississippi River	17,110	56,000
Rhine	2200	13,000
Waal	1470	8700
Nederrijn-Lek	490	2900
Maas	250	3000
Schoonrewoerd	unknown	100–400[a]

[a] Paleo-discharge, estimate.

Schumm et al. 1994). The Mississippi River channel belt is 15–25 km wide in the Yazoo Basin and 10–15 km wide in the Atchafalaya Basin and the deltaic plain (Fisk 1944; Bridge 1999). Maximum bankfull channel depth increases from 20 m near Cairo (~ 400 km upstream from Greenville) to 50 m near New Orleans. The thickness of the Holocene floodbasin succession in the southern Lower Mississippi Valley ranges from approximately 15 m near Vicksburg to approximately 30 m near Baton Rouge (Fig. 1B) (Fisk 1944; Saucier 1969; Autin et al. 1991; Saucier 1994).

METHODS

Nine Holocene channel belts were selected for this study: eight in the Rhine–Meuse delta and one in the Lower Mississippi Valley (Fig. 1). These particular channel belts were chosen because (1) they are accurately mapped and sufficient in length to study the geometry and the variation therein; (2) the channel-belt reaches do not include major bifurcations or confluences of other channel belts, which excludes large discharge variations within the reaches; (3) the channel belts represent a broad range of discharge magnitudes (Table 1); and (4) the age and period of activity of the studied channel belts is known.

Channel-belt geometry (width or width/thickness ratio) was determined at several locations along the course of the channel belt under consideration. To identify the geometric variability of the channel belts in a downstream direction, the geometric parameters of each channel belt were plotted against distance along the channel-belt axis (Fig. 3).

Channel-Belt Width

Digital geological–geomorphological maps of both study areas were used to measure channel-belt width of the selected channel belts. In case of the Rhine–Meuse channel belts, the geological–geomorphological map of the Rhine–Meuse delta (scale 1:100,000; Berendsen and Stouthamer 2001) was used. This map is based mainly on detailed geological and geomorphological maps (scale 1:10,000). The channel width of the modern Rhine and Meuse branches is derived from historical topographic maps that date back to the period 1836–1859 AD, i.e., before the river channels were fixed by the construction of groins. For the selected Mississippi river channel belt, the geological–geomorphological map of the Lower Mississippi Valley (Saucier 1994) was used. This map is basically a compilation of maps originally at a scale of 1:62,500, which were reduced to a scale of 1:250,000. To determine the variability of channel-belt width for the Rhine–Meuse channel belts, we determined the width every 1 km, and for the Mississippi channel belt every 10 km. The measuring distance is chosen on the basis of morphometric variation of the channel belts. Cutoff channels were considered to be part of the channel belt. The methods and principles described by, e.g., Törnqvist (1993a, p. 135–137), Weerts (1996, p. 30–56), and Saucier (1994, p. 187–198), were followed to separate the channel belts from other fluvial landforms with a similar lithology, such as crevasse channels and sandy natural levees.

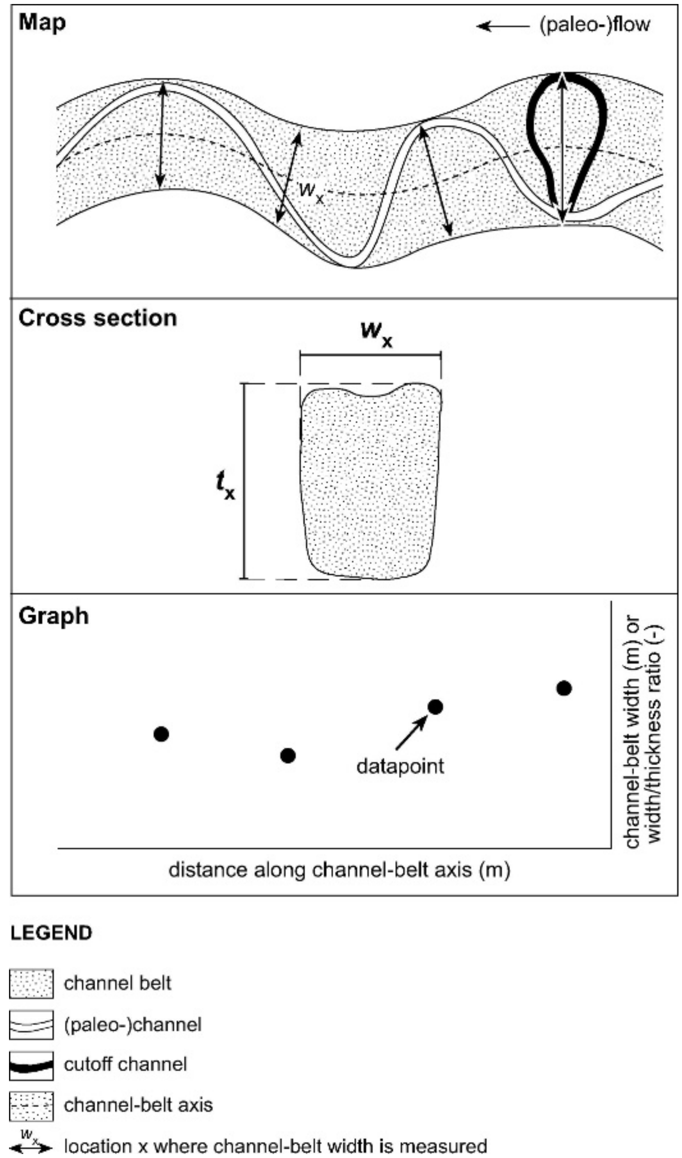


FIG. 3.— Method used in the present study to determine the width and width/thickness ratio of channel belts. The width (w) is measured at regular distances (Rhine–Meuse channel belts: 1 km; Mississippi River channel belt: 10 km) along the length of the channel belt. Thickness (t) and width/thickness ratio (w/t) are determined using cross sections. The data obtained are plotted against downstream distance along the channel-belt axis.

Channel-Belt Width/Thickness Ratio

New field data were gathered from two late Holocene Rhine channel belts (Linge and Hollandsche IJssel; Fig. 1A) to gain insight into the downstream variability of the channel-belt thickness and the width/thickness ratio. We compiled a total of seventeen cross sections. The cross

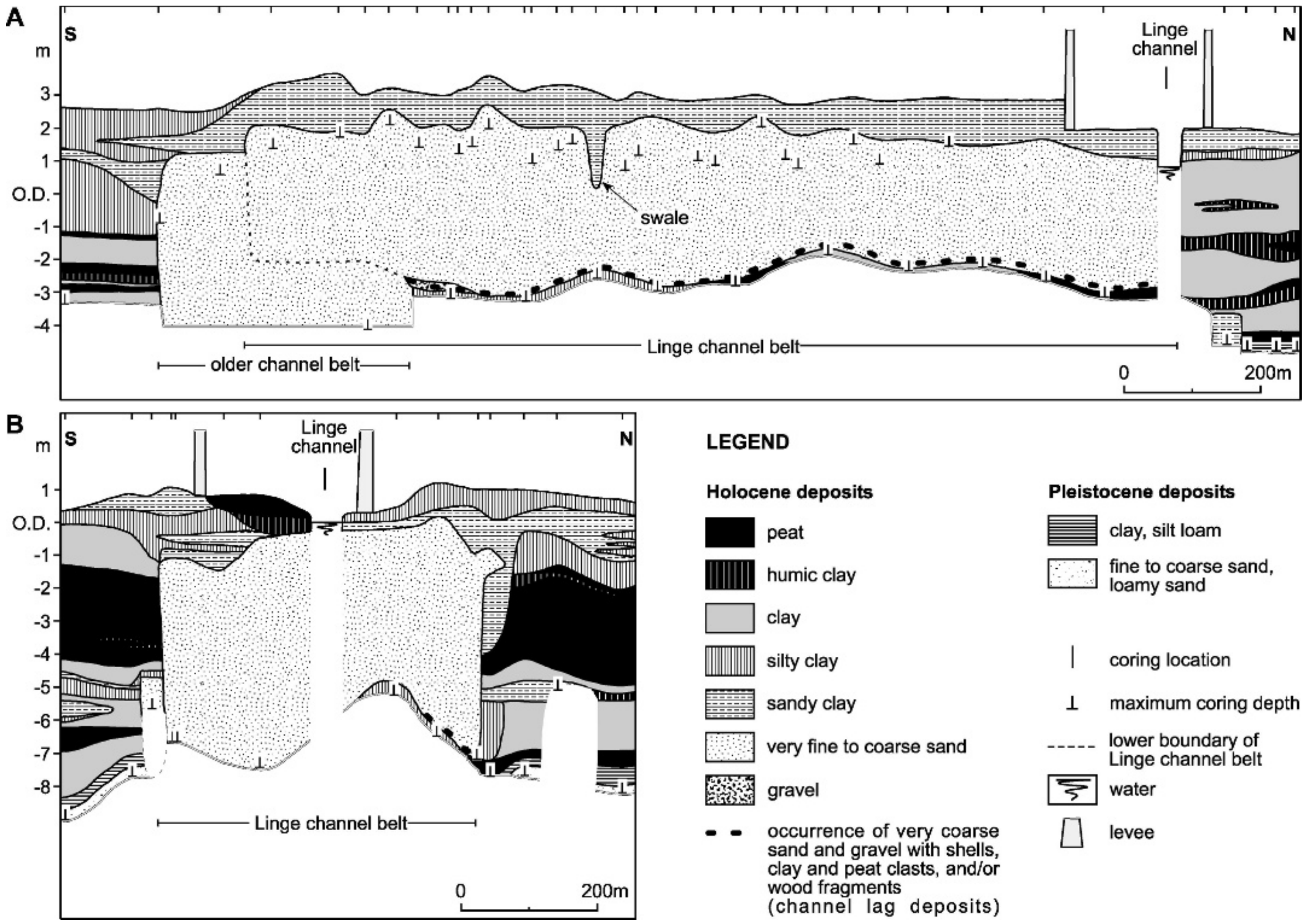


FIG. 4.—Lithological sections across the Linge channel belt. **A)** upstream, **B)** downstream. For location, see Figure 1A.

sections are oriented perpendicular to the channel-belt axis to exclude overestimation of its width. A total of 268 borings were used to construct the cross sections, of which 130 were retrieved from the database of the Department of Physical Geography at Utrecht University (Berendsen 2005). An additional 138 borings were carried out to complete the dataset. The hand-operated drilling equipment consisted of an Edelman auger and a gouge (diameter 3 cm) for floodbasin deposits and the Van der Staay suction corer to penetrate channel deposits below the groundwater table (see Oele et al. 1983). The cores were logged with regard to sediment texture, organic matter content, color, plant remains, iron and calcium-carbonate content, elevation of groundwater level, and other relevant characteristics (e.g., occurrence of shells, concretions). When sandy deposits were encountered, the median grain size, gravel content, sorting, and roundness were described. Distance between the boreholes ranged from 10 to 100 m, depending on the dimensions and complexity of the channel belt and the surrounding floodbasin deposits. In every cross section, we measured the width and maximum thickness of the channel belt to calculate width/thickness ratios (Fig. 3). When the base of the channel belt could not be identified (e.g., in case the channel belt was incised into the Pleistocene substrate), the difference between the top of the channel belt and the top of the Pleistocene substrate was measured. This is the minimum channel-belt thickness, which results in a maximum width/thickness ratio. The edges of the channel belt were assumed to be located halfway between two bounding borings. The accuracy of the measured channel-belt width typically is 25 m for the Schaik and Schoonrewoerd channel belts, 40 m for the Hollandsche IJssel channel belt, and 70 m for the Linge channel belt.

Width/thickness ratios for the modern ("stage 1" cf. Autin et al. 1991) Mississippi River channel belt were derived from cross sections published by Saucier (1967, 1969) and Kolb et al. (1968). These cross sections are based on borehole data provided mainly by the U.S. Army Corps of Engineers and the former Louisiana State Highway Department. Available borehole data from Fisk (1947) were added to the cross sections. The accuracy of the measured channel-belt width, based on the distance between bounding borings alone, ranges from 350 m to 1250 m. The actual accuracy is likely to be better, however, because the location of the channel-belt edges on the maps used is derived from aerial photographs as well (Saucier 1967, 1969; Kolb et al. 1968; Saucier 1994). Since the thickness of the Mississippi River channel belt is not explicitly depicted in the available cross sections, it was assumed to equal the depth of the deepest part of the channel following the classical concept of Allen (1964, his figure 4) for meandering rivers; possible vertical accretion of the channel belt is ignored. Vertical aggradation is expected to have been of minor importance for the formation of the modern Mississippi River channel belt, since late Holocene channel belts in the Lower Mississippi Valley are formed predominantly by lateral migration of the channel instead of vertical aggradation (Aslan and Autin 1996). Therefore, the derived thickness of the Mississippi River channel belt is estimated to be accurate within a few meters, but it should be taken as a minimum value leading to a maximum width/thickness ratio.

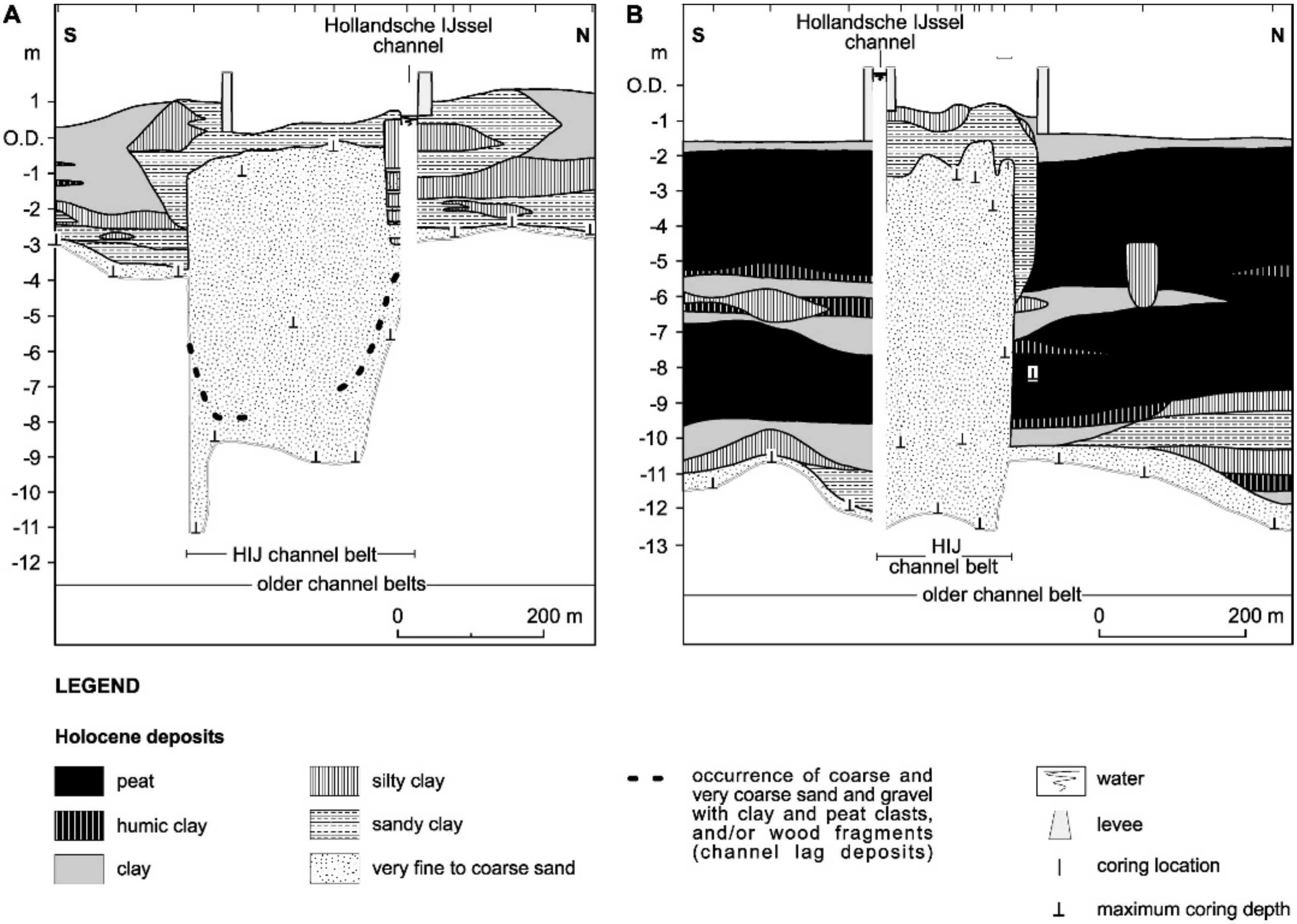


FIG. 5.—Lithological sections across the Hollandsche IJssel channel belt. **A)** Upstream, **B)** downstream. HIJ = Hollandsche IJssel. For location, see Figure 1A.

RESULTS

Cross Sections

To illustrate the geometrical properties of the studied channel belts, and the nature of the deposits in which the channel belts are encased, a total of six cross sections of two late Holocene Rhine channel belts (Linge and Hollandsche IJssel) and the stage 1 Mississippi River are shown (Figs. 4–6).

The Linge channel belt (Fig. 4A), located in the central part of the Rhine–Meuse delta (Fig. 1A), is 1250 m wide and ~ 6 m thick, resulting in a width/thickness ratio of 208. The section crosses a large meander of the Linge, which explains its relatively wide channel belt here. The channel belt is flanked by a more than 4.5-m-thick clay and peat succession (floodbasin deposits) to the north and is incised into an older channel belt in the south (Fig. 4A). The latter represents a small Rhine distributary, which was active before the Linge came into existence (Berendsen and Stouthamer 2001). Very coarse sand of up to 2000 μm, gravel, shells, clay pebbles, wood fragments, and peat clasts occur at the base of the Linge channel belt, and is interpreted as the channel lag. Farther downstream (Fig. 4B), the Linge channel belt is much narrower (480 m). Here, the channel belt is encased in a succession of Holocene clay and peat up to 7 m thick. The base of the channel belt could not always be identified in the cores, but a minimum thickness of 7 m could be determined on the basis of the elevation of the top of the Pleistocene deposits (Fig. 4B). The width/thickness ratio of the downstream part of the Linge channel belt is 69 at the most, i.e., three times smaller than the width/thickness ratio of its upstream part.

The upstream part of the Hollandsche IJssel channel belt (Fig. 1A) has a width of 315 m and a maximum thickness of 7.5 m (Fig. 5A), resulting in a width/thickness ratio of 42. The base of the channel belt consists of coarse to very coarse sand (420–1400 μm) and gravel mixed with lumps of (humic) clay, and peat and wood fragments (channel lag deposits). The channel belt is incised in two older Holocene channel belts (Fig. 5A). In the downstream part, the Hollandsche IJssel channel belt is much narrower (180 m; Fig. 5B) than further upstream. The downstream part of the channel belt is encased in a Holocene succession up to 10 m thick, consisting mainly of peat with intercalated clay layers (floodbasin and crevasse-splay deposits). The base of the channel belt could not be identified here due to the absence of recognizable channel lag deposits in the cores. However, the minimum thickness is 8 m, on the basis of the depth of an underlying sand layer at approximately 10 m below O.D. (Fig. 5B). This results in a maximum width/thickness ratio of 23 for the downstream part of the Hollandsche IJssel channel belt.

The studied reach of the stage 1 Mississippi River stretches from Greenville to Baton Rouge, and flows through parts of the Yazoo Basin, the Tensas Basin, and the Atchafalaya Basin (Fig. 1B). Figure 6A shows the channel belt of the Mississippi River just north of Greenville. The channel belt is 23,300 m wide and is flanked on both sides by a succession up to 10 m thick, consisting mainly of silts, (silty and sandy) clays, and fine sands grading downward into gravelly sands (Fisk 1947; Kolb et al.

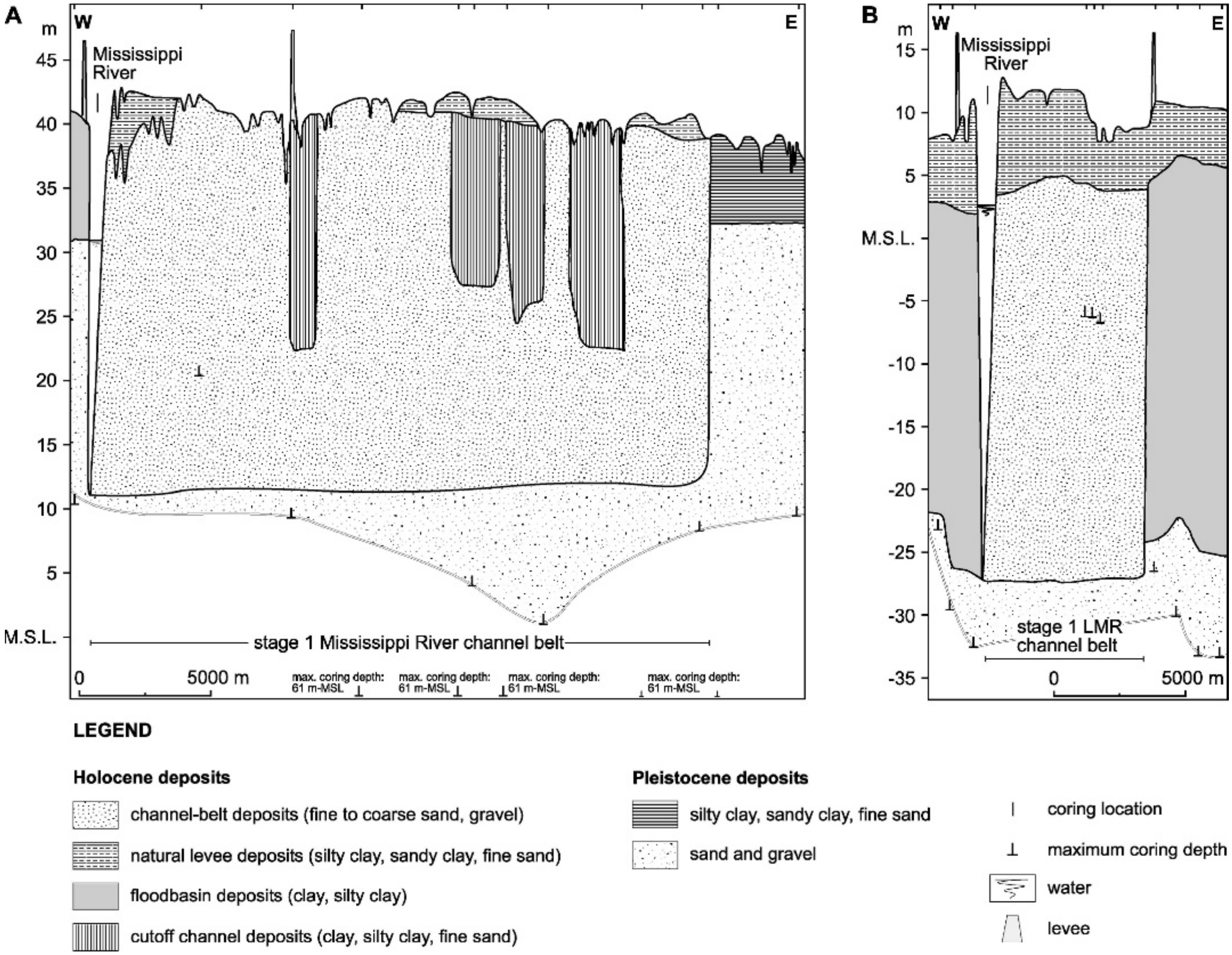


FIG. 6.—Sections across the stage 1 Mississippi River channel belt. **A)** Upstream (Fisk 1947; Kolb et al. 1968, modified), **B)** downstream (Saucier 1969, modified). LMR = Lower Mississippi River. For location, see Figure 1B.

1968; Saucier 1994). The main part of these sediments is interpreted as pre-Holocene braided-river deposits (Fisk 1944), although they may have been partly deposited by Holocene Mississippi River precursors (Saucier 1994). The thickness of the Mississippi River channel belt is ~ 31 m, which results in a width/thickness ratio of *ca.* 750. The channel belt near Baton Rouge (Fig. 6B) is encased in a Holocene succession, more than 30 m thick, of clays and silty clays (floodbasin deposits; Saucier 1969). Here, channel-belt width is ~ 6200 m, and its thickness is more than 30 m, resulting in a width/thickness ratio of ~ 200. This value is about four times smaller than the width/thickness ratio determined for the upstream part of Mississippi River channel belt. The distance between the two cross sections is approximately 400 km.

Channel-Belt Width

All Rhine channel belts (Waal, Nederrijn-Lek, Linge, Hollandsche IJssel, Schaik, and Schoonrewoerd) show an overall trend of decreasing maximum width in a downstream direction (Fig. 7). The factor of decrease ranges from 4 to 6.5: for instance, the maximum width of the Waal channel belt decreases from ~ 3200 m to ~ 800 m in the downstream direction (Fig. 7A). Superimposed on this trend, a local narrowing of the channel belt occurs where it crosses the upthrown Peel Block (see also Fig. 7B, G). The channel-belt width of the Maas does not clearly decrease, which is in contrast to the Rhine channel belts. Width values of the Maas channel belt vary between 350 and 1800 m (Fig. 7G), with an average of ~ 1000 m. The constant width of the Maas channel belt is due to the fact that the river is incised into a sandy substrate over almost its entire length (Törnqvist 1993b; Berendsen and Stouthamer 2001). The channel-belt width of the modern Mississippi River decreases by a factor of 6 over its 480-km-long studied course (Fig. 7H). Minimum width values of 5–6 km are found near Baton Rouge, where the river encounters the active Baton Rouge fault zone (Autin et al. 1991; Saucier 1994).

Channel-Belt Width Versus Channel Width

Both modern Rhine distributaries (Waal and Nederrijn-Lek) show an increase in the ratio between channel width and channel-belt width in a downstream direction (Fig. 8). In the downstream part of these channel belts, channel-belt width equals channel width, which implies that the channel did not migrate laterally.

The Maas also shows a downstream-increasing ratio of channel width to channel-belt width, despite the absence of a significant downstream

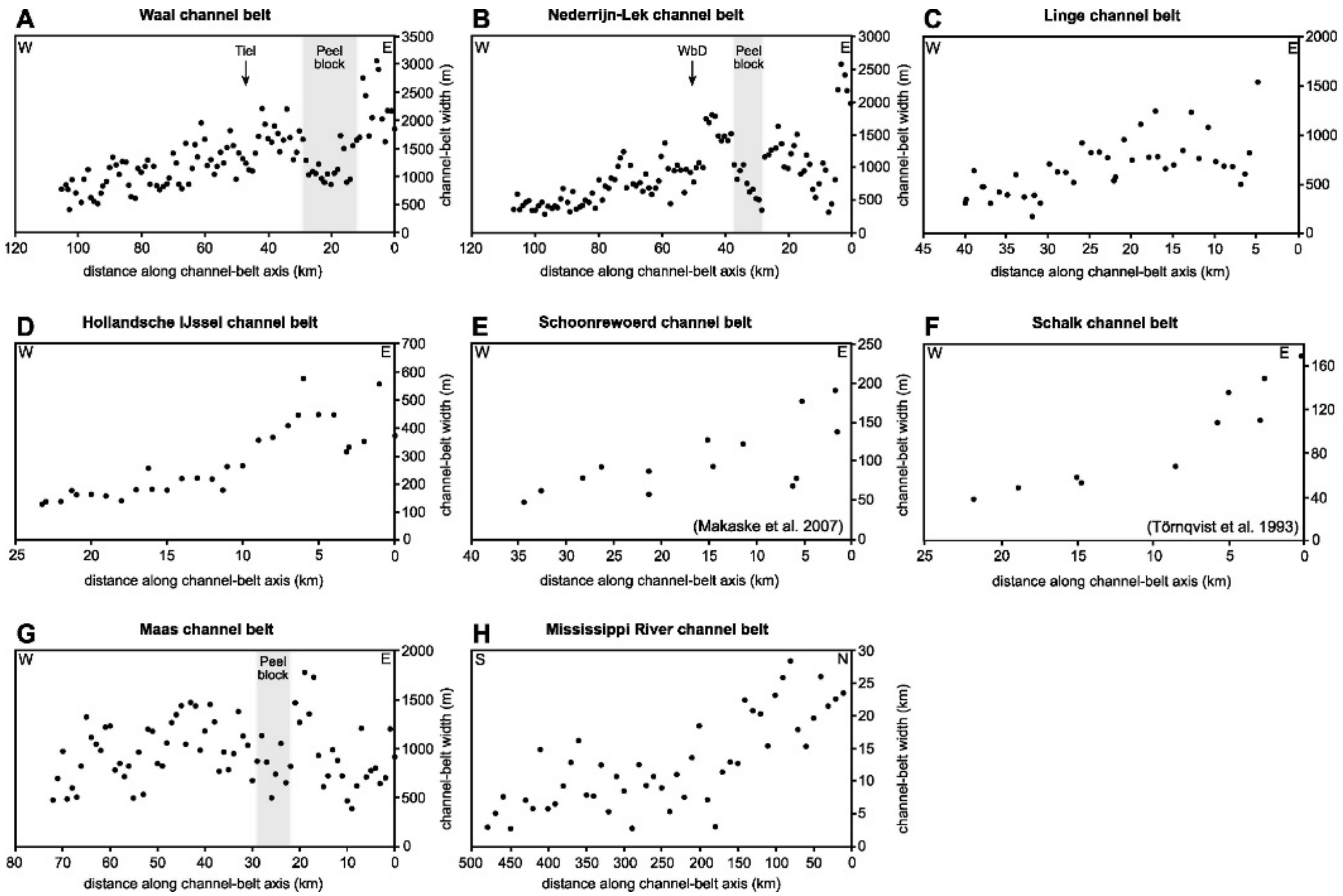


FIG. 7.— Width of the studied channel belts plotted against downstream distance (downstream direction is to the left). **A–F)** The Rhine channel belts and **H)** the Mississippi River channel belt show width decreasing by a factor of 4 to 6.5 in the downstream direction. However, **G)** the Maas channel belt has a more or less constant width.

trend of decreasing channel-belt width. However, the width of the Maas channel nearly doubles from 130 m (upstream) to more than 250 m (downstream).

Channel-Belt Thickness and Width/Thickness Ratio

The thickness of the studied Rhine channel belts, as deduced from the cross sections, ranges from 3.6 to 10.5 m with an average of 6.7 m (Fig. 9; Table 2). Channel-belt thickness increases by a factor of ~ 1.2 to 2.5 in the downstream direction. Combined with the data of Törnqvist et al. (1993) and Makaske et al. (2007), a general downstream decrease of the width/thickness ratios by a factor of 2.5 to 5 is obtained for the studied Rhine channel belts (Fig. 10; Table 2).

For the Mississippi River channel belt, a maximum width/thickness ratio of ~ 750 is found in the upstream part of the studied reach (Table 2), which is due to the fact that the channel belt is relatively wide (up to 30 km) here. Given a downstream value of ~ 200, a decrease of the width/thickness ratio by a factor of about four seems to be valid for the stage 1 Mississippi River channel belt.

DISCUSSION

The results indicate that the width of a channel belt is 5 to 750 times larger than its thickness. Furthermore, the decrease of channel-belt width in the downstream direction is significantly larger than the increase in thickness (Table 2). Channel-belt width is consequently the most important variable determining the width/thickness ratio of channel belts. The discussion therefore focuses on channel-belt width, specifically (1) the reasons for the observed downstream changes in channel-belt width, (2) a conceptual model explaining the observed trends in channel-belt width, and (3) the implications of this study for alluvial architecture.

Explanation of the Observed Downstream Changes in Channel-Belt Geometry

Makaske et al. (2007) proposed two factors to explain downstream changing dimensions of the Schoonrewoerd channel belt: stream power and substrate erodibility. The ability of the river channel to migrate laterally decreases with decreasing stream power and/or bank erodibility, and vice versa. Stream power is the product of specific gravity, river gradient, and channel-forming discharge. If specific gravity and discharge are constant, stream power increases linearly with the gradient of the river. There are some minor discharge variations involved in our study, despite the intention to select channel belts with a constant discharge along their reaches. Within the studied reach of the Mississippi River, the Yazoo River contributes to the Mississippi River, increasing its discharge by 3% (U.S. Geological Survey 2002), whereas the Atchafalaya River (Fig. 1B) diverts approximately 30% of the discharge (Aslan et al. 2005). Furthermore, Törnqvist et al. (1993) and Makaske et al. (2007) hypothesized that some discharge may also be lost through crevasse systems connected to the trunk channels of the anastomosing Rhine distributaries. This does not apply to the other studied Rhine–Meuse

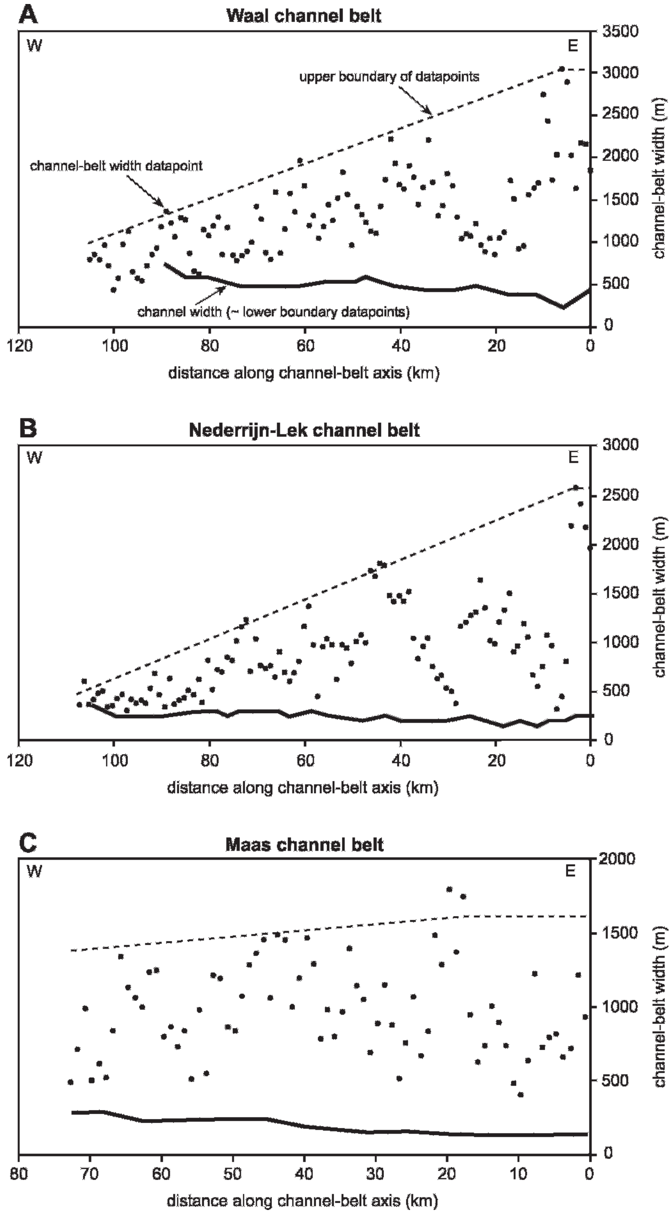


FIG. 8.—Channel-belt width and channel width of **A)** the Waal, **B)** Nederrijn-Lek, and **C)** Maas. The channel width forms the lower boundary of the envelope of the channel-belt data points. In case of the Waal and Nederrijn-Lek, the envelope tends to narrow in the downstream direction, indicating decreasing variability of channel-belt width. Downstream is to the left.

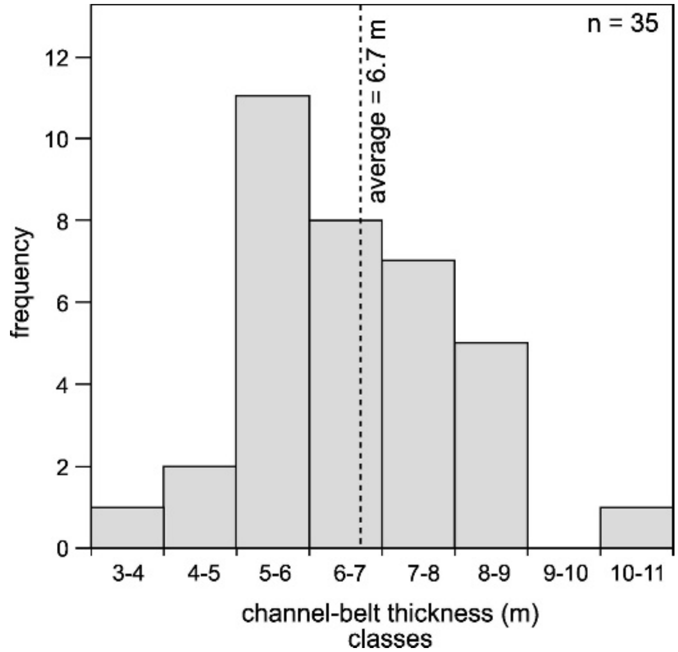


FIG. 9.—Histogram showing the distribution of values of channel-belt thickness for the studied channel belts in the Rhine–Meuse delta. Channel-belt thickness typically ranges from 5 to 9 m, and is 6.7 m on average.

channel belts, however, because large crevasse systems are absent in those reaches (Berendsen and Stouthamer 2001). Possible discharge variations therefore are likely to be marginal in our examples, at least for the studied Rhine–Meuse channel belts. Stream power consequently is proportional to the gradient of the river.

The gradient of deltaic rivers experiencing rising base level generally decreases in the downstream direction. The gradients of the Waal, Nederrijn-Lek, and Maas channel belts indeed seem to decrease downstream (Fig. 11). This implies downstream-decreasing stream power for these channel belts, which may explain the observed decreasing channel-belt width of the Waal and the Nederrijn-Lek. The gradients of the other studied Rhine channel belts, however, suggest that channel gradient, and thereby stream power, must have been (nearly) constant in the downstream direction (Fig. 11). Therefore, variations in stream power cannot always explain the observed trends in channel-belt geometry of the studied Rhine–Meuse channel belts.

Channel migration rate is also controlled by bank erodibility. The thickness of the cohesive floodbasin deposits (clay and peat) bounding the studied channel belts increases in the downstream direction (Fig. 11), which, in the Rhine–Meuse delta, is accompanied by an increase in the proportion of peat (see Figs. 4B, 5B). The cross sections through two Rhine distributaries and the modern Mississippi River (Figs. 4–6) show that, in the upstream reaches of these channel belts, easily erodible sands and gravels occur in the shallow subsurface, overlain by a relatively thin layer of cohesive clayey (floodbasin) deposits. The channel belts are relatively wide and thin here (high width/thickness ratios), pointing to a high rate of channel migration. This is contrary to the downstream reaches, where thick cohesive floodbasin deposits bound narrow channel belts with low width/thickness ratios, indicating a low channel migration rate. Thus, the downstream decrease in width, and width/thickness ratio, of these channel belts corresponds to an increase in thickness of cohesive river-bank material, i.e., a decrease in erodibility, whereas stream power may be constant (Fig. 11). Bank erodibility is more or less constant along the Maas channel belt, because Pleistocene and Holocene sandy deposits occur at shallow depth along almost the full length of the Maas (Fig. 11; Berendsen and Stouthamer 2001). This explains why the Maas channel belt has a virtually constant width along its course (Fig. 7G).

In conclusion, our observations suggest that width and width/thickness ratio of the studied channel belts in the Holocene Rhine–Meuse delta are controlled largely by bank erodibility; the downstream loss of stream power seems to be of less importance. This probably also applies to the studied Mississippi River channel belt (bank erodibility decreases in a downstream direction), but more data on stream power is needed to verify this.

Narrow channel belts may also be a result of a short period of activity of the formative channel. Channel belts with a long formation period tend to be wider, because the channel has had more time to migrate laterally. Differences in period of activity cannot explain the observed trends in

TABLE 2.—*Dimensions of the studied channel belts based on cross sections.*

Distance[a] (km)	Width w (m)	Thickness t^b (m)	w/t^c (-)	Cross section	Reference
Linge channel belt					
8.0	610	5.5	111		this paper
18.5	1250	6.0	208	Fig. 4A	this paper
22.8	540	5.4	100		this paper
26.5	940	8.0	118		this paper
33.5	400	5.4	74		this paper
38.5	480	≥ 7.0	69	Fig. 4B	this paper
40.5	340	≥ 7.0	≤ 49		this paper
Hollandsche IJssel channel belt					
3.1	315	7.5	42	Fig. 5A	this paper
6.3	450	8.0	56		this paper
11.3	180	8.0	23		this paper
16.2	320	≥ 9.0	≤ 36		this paper
21.3	180	≥ 8.0	23	Fig. 5B	this paper
23.2	150	≥ 6.2	≤ 24		this paper
Schoonrewoerd channel belt					
1.7	140	3.6	39		Makaske et al. (2007)
2.0	195	4.5	43		Makaske et al. (2007)
5.4	180	6.9	26		Makaske et al. (2007)
6.0	80	≥ 8.3	≤ 10		Makaske et al. (2007)
6.4	70	4.8	15		Makaske et al. (2007)
11.6	125	5.6	22		Makaske et al. (2007)
14.8	95	5.2	23		Makaske et al. (2007)
15.3	130	5.6	18		Makaske et al. (2007)
21.5	80	7.4	11		Makaske et al. (2007)
21.5	90	≥ 7.3	≤ 12		Makaske et al. (2007)
26.5	95	8.1	12		Makaske et al. (2007)
28.4	80	9.0	9		Makaske et al. (2007)
32.8	65	8.8	7		Makaske et al. (2007)
34.6	50	10.5	5		Makaske et al. (2007)
Schaik channel belt					
0.4	170	≥ 5.1	≤ 33		Törnqvist et al. (1993)
2.8	150	≥ 6.1	≤ 25		Törnqvist et al. (1993)
5.2	140	≥ 5.5	≤ 26		Törnqvist et al. (1993)
8.7	70	≥ 5.8	≤ 12		Törnqvist et al. (1993)
149	55	≥ 6.6	≤ 8		Törnqvist et al. (1993)
15.2	60	≥ 6.4	≤ 9		Törnqvist et al. (1993)
19.1	50	≥ 6.2	≤ 8		Törnqvist et al. (1993)
22.0	40	≥ 5.7	≤ 7		Törnqvist et al. (1993)
Stage 1 Mississippi River channel belt					
23.0	23310	31.0	752	Fig. 6A	this paper[d]
65.9	17680[g]	25.4	696		this paper[d]
287.9	3720	29.9	124		this paper[e]
348.3	4660	35.0	133		this paper[e]
447.4	1810[g]	28.6	63		this paper[f]
456.3	6210	31.6	197	Fig. 6B	this paper[f]

[a] Downstream distance measured along the axis of the channel belt from a fixed point in the upstream part of the channel belt.
[b] When the base of the channel belt could not be determined, a minimum thickness is given.
[c] Width/thickness ratio.
[d] Data deduced from cross section originally published by Kolb et al. (1968).
[e] Data deduced from cross section originally published by Saucier (1967).
[f] Data deduced from cross section originally published by Saucier (1969).
[g] Width is smaller than in published cross section (cross section is not located perpendicular to channel-belt orientation).

geometry of the individual channel belts, however. That is, the studied Rhine–Meuse channel-belt reaches have a constant period of activity along their length (Berendsen and Stouthamer 2001) and concurrently show a decrease in width. Exceptions are the Nederrijn-Lek, Waal, and Hollandsche IJssel channel belts (Fig. 1), of which the downstream reaches have a shorter period of activity (Berendsen and Stouthamer 2001). Channel-belt width of those reaches of the Nederrijn-Lek, Waal, and Hollandsche IJssel channel belts with a constant period of activity nonetheless decreases (Fig. 7A, B). Thus, the length of the period of activity may explain differences in width between several different channel belts, but not within a single channel belt.

The *variation* in channel-belt width also decreases in the downstream direction (Figs. 7, 8). In the upstream reaches of the channel belts, channel-belt width is highly variable as a result of lateral migration of a high-sinuosity channel and multiple meander-bend cutoffs. On the contrary, low-sinuosity channels with limited meander migration and few cutoffs form channel belts with a more or less constant width (see also Collinson 1978, his figure 1). Therefore, decreasing lateral migration rate of the channel in the downstream direction explains the observed decreasing maximum width and width/thickness ratios of the studied channel belts as well as the decrease in variation in channel-belt geometry.

Conceptual Model Explaining the Observed Trends in Channel-Belt Width

A conceptual model describing the downstream changes of channel-belt width in the Rhine–Meuse delta and Lower Mississippi Valley, as related to bank erodibility and stream power, is presented (Fig. 12). In upstream regions, bank erodibility and stream power are relatively high due to the occurrence of easily erodible material at or near the surface and relatively high gradients, respectively. Here, high-sinuosity channels with large lateral migration rates form channel belts having a large, and highly variable, width. Bank erodibility decreases in the downstream direction. In general, stream power also decreases downstream, driven by decreasing channel gradient, but this is noticeable only over large distances (Fig. 11). As a consequence, the lateral migration rate of the river channels decreases, leading to progressively narrower channel belts. This proceeds up to a point where lateral migration of the channel is almost completely restricted and channel-belt width approximately equals channel width.

This model applies only to channels and associated channel belts with longitudinally constant discharge. Furthermore, the presence of cohesive deposits of significant thickness is required. The latter is common to fluvial settings with a history of base-level rise caused by eustatic sea-level rise and/or subsidence.

Consequences for Alluvial Architecture

Given the positive correlation between channel-belt size and the proportion of channel deposits in cross section (CDP) as well as the connectedness between channel belts (CR) (e.g., Leeder 1978; Bridge and Leeder 1979), overestimates of channel-belt dimensions inevitably lead to overestimations of CDP and CR. In the currently available alluvial architecture models (e.g., Mackey and Bridge 1995), channel-belt width is determined in relation to bankfull channel depth and/or bankfull channel width (see Bridge and Mackey 1993b). Channel-belt dimensions in the models are defined when the channel belt originates after avulsion and remain constant along its entire course until the channel belt is abandoned (Mackey and Bridge 1995). This presumption is expected to lead to an overestimation of CDP and CR, because channel-belt width actually decreases, as shown in the present study. In order to assess the degree of the overestimation, we carried out a case study to compare real-world CDP and CR values with cases where a constant channel-belt width in a downstream direction is presumed.

In our case study, we used the section of Törnqvist (1994), which crosses a large part of the lower Rhine–Meuse delta (Fig. 1A). A relatively thick Holocene succession is present in this part of the delta, comprising numerous channel belts. It was presumed that all channel belts encased in cohesive floodbasin deposits experienced narrowing in a downstream direction by a factor of 4 to 6.5 (as shown in this study). We then calculated their upstream widths. The assumption in the

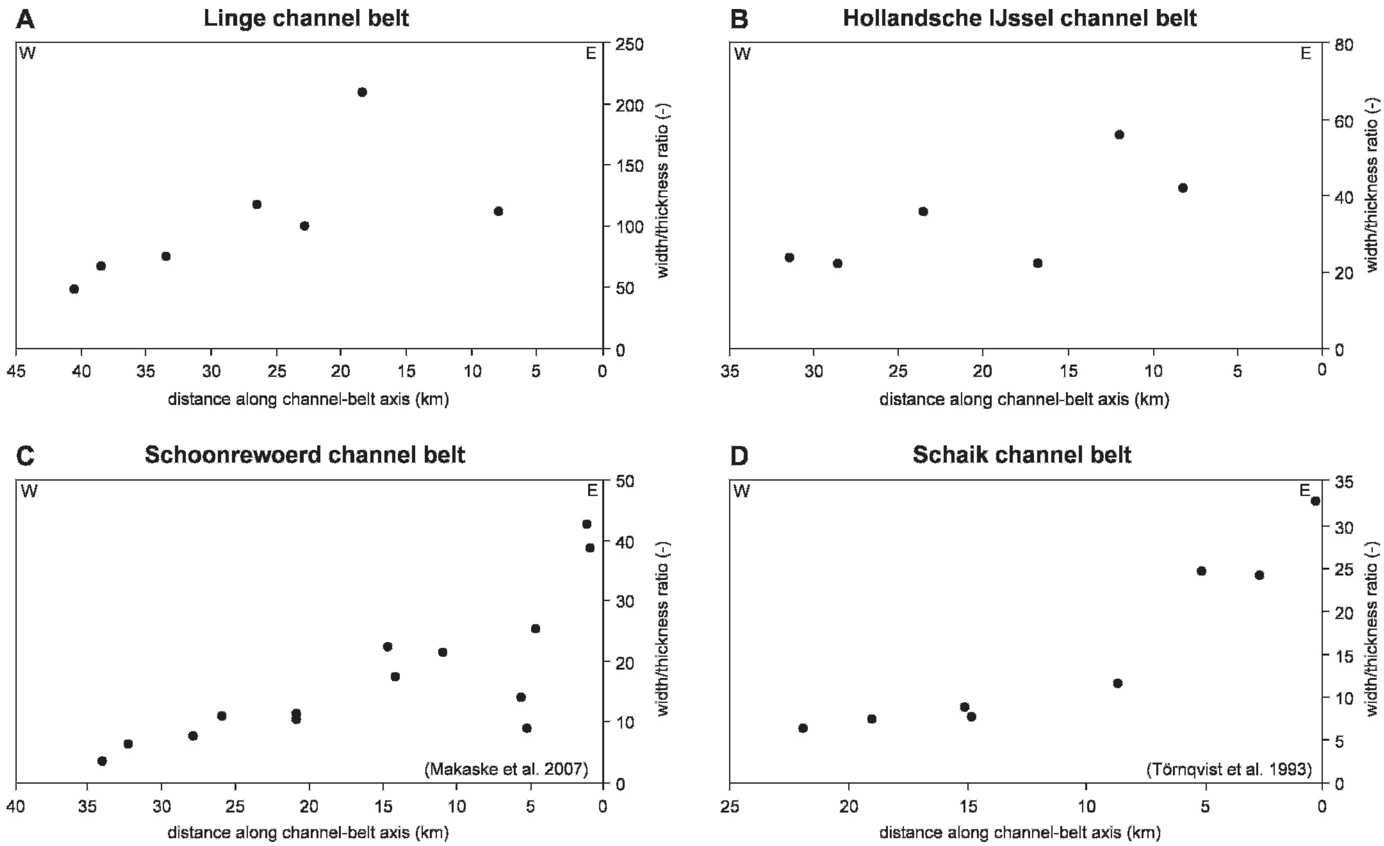


FIG. 10.—Width/thickness ratios of four Rhine distributaries (downstream is to the left). The width/thickness ratio of the channel belts decreases by a factor of 2.5 to 5 in the downstream direction.

presently available alluvial-architecture models that channel-belt width is constant along its entire course was artificially fulfilled by widening the channel belts in Törnqvist's (1994) cross section. Subsequently, we computed CDP and CR on the basis of two scenarios. In scenarios 1 and 2, the channel belts in the cross section were widened 4 and 6.5 times, respectively. Channel belts considerably (> 30% of their thickness) incised into a noncohesive substrate were presumed to have a constant width along their entire course. In other words, the width of these channel belts in the cross section was not increased in the case study. The thickness of the channel belts in the cross section, as derived from borehole data, was held constant. When channel-belt thickness was unknown, we presumed a value of 6.7 m, which is an average for Rhine–Meuse channel belts (Fig. 9). In the end, CDP and CR were calculated for the actual cross section and for both scenarios.

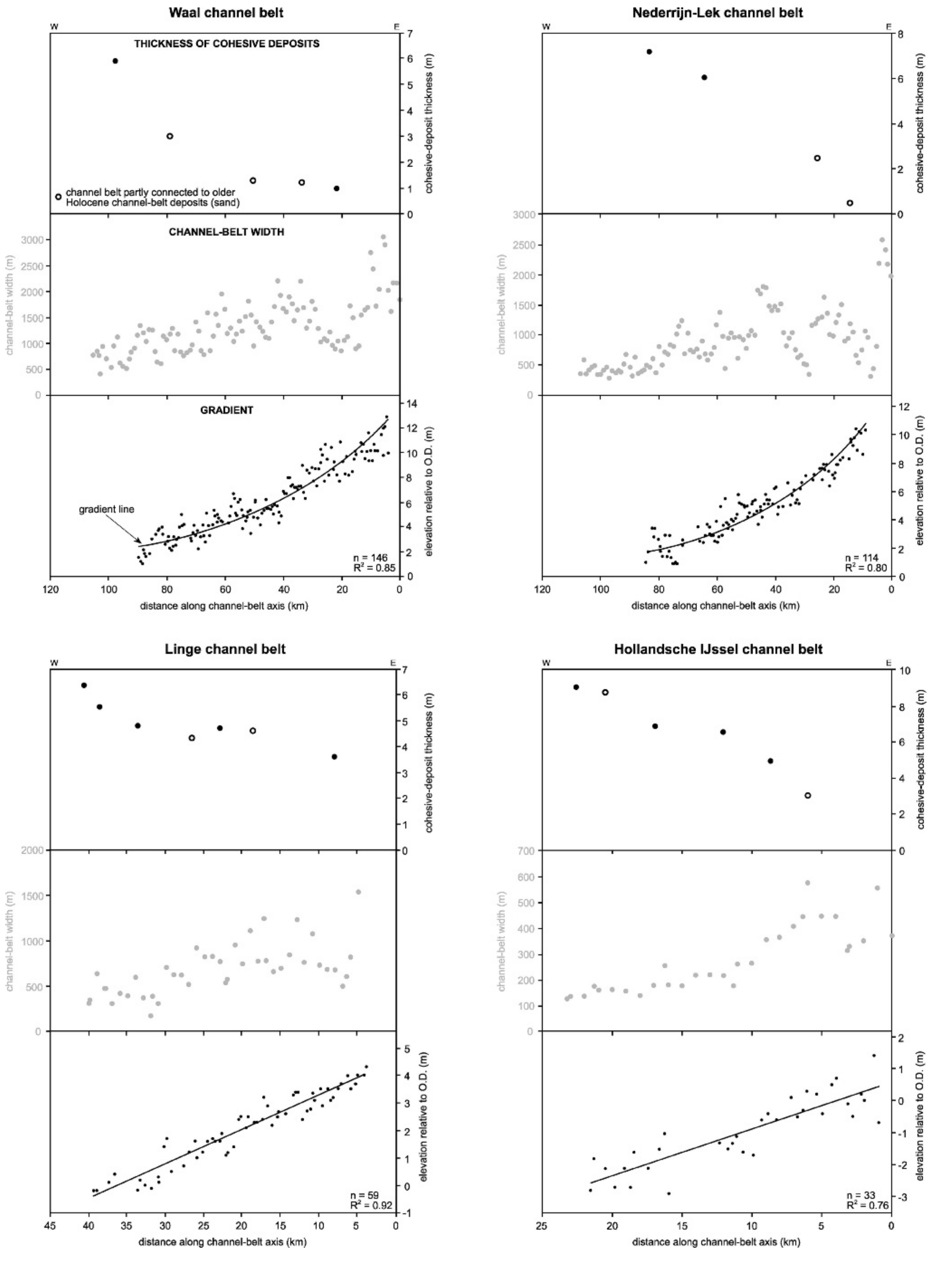
The results show a CDP of 0.29 and a CR of approximately 0.10 for Törnqvist's (1994) cross section (Table 3). In scenarios 1 and 2, CDP is 0.47 and 0.57, respectively. This means an overestimation (relative to the real-world value) ranging from 1.6 to 2.0. CR reaches values of 0.10 and 0.16 in the scenarios, which implies an increase of up to 1.6 times the determined value in the cross section. In conclusion, models ignoring decreasing channel-belt width in the downstream direction and assuming a constant width along the channel-belt length significantly overestimate predicted sand quantities in distal parts of river deltas. This means that potential fluvial reservoir volumes may be overvalued.

CONCLUSIONS

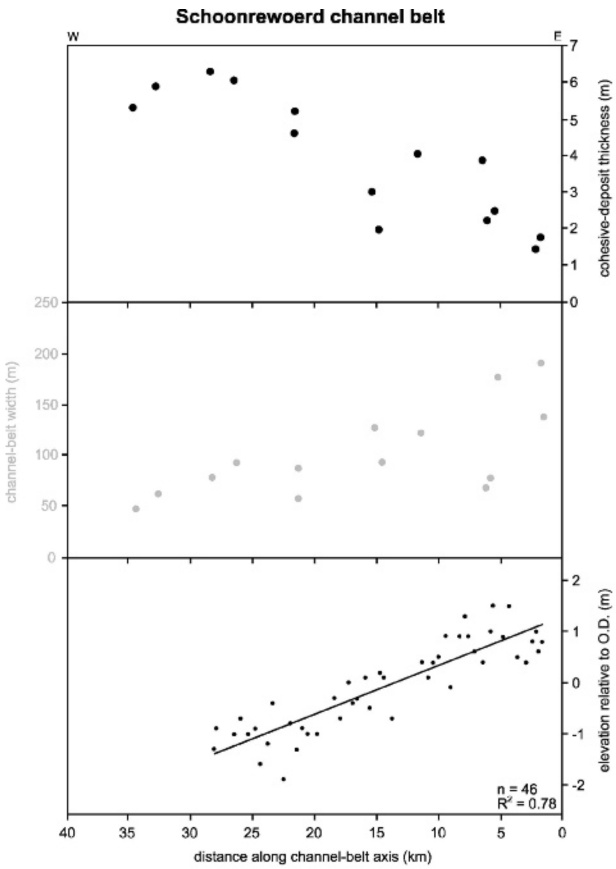
1. Downstream-decreasing width and width/thickness ratio of channel belts is a common feature in the Holocene Rhine–Meuse delta and the Lower Mississippi Valley. Channel belts encased in cohesive deposits show a width decrease by a factor of 4 to 6.5 in the downstream direction, and the width/thickness ratio decreases by a factor of 2.5 to 5.
2. Downstream-decreasing bank erodibility and stream power restrict lateral migration of the river channels, which leads to the formation of progressively narrower channel belts in the downstream direction. Channel-belt reaches with a longitudinally constant stream power and decreasing bank erodibility show the same trend, which suggests that the factor "bank erodibility" dominates over the factor "stream power" in determining channel-belt width, at least in the Holocene Rhine–Meuse delta.
3. The results of a case study in the Holocene Rhine–Meuse delta suggest that ignoring downstream-decreasing width and width/

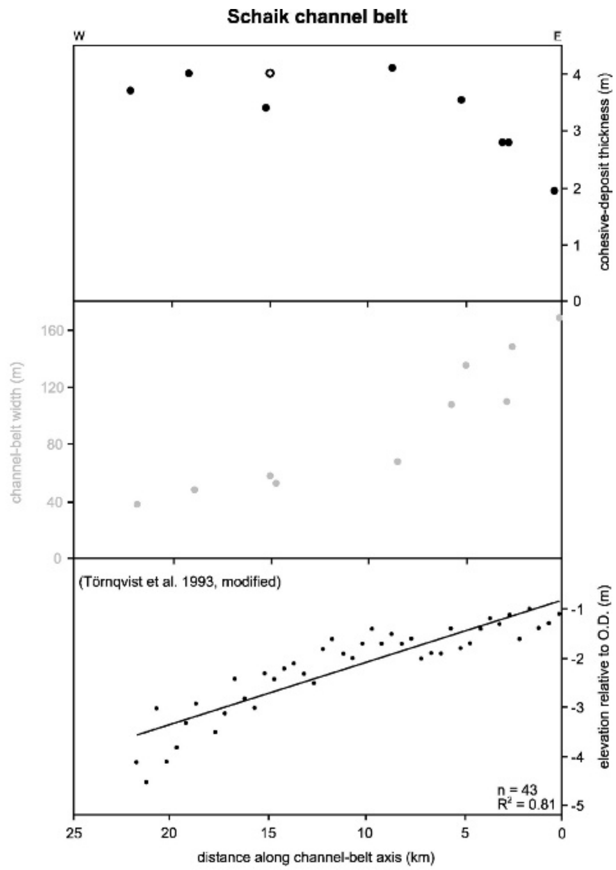
→

FIG. 11.—Relationships among gradient, thickness of cohesive deposits, and channel-belt width for the studied Rhine–Meuse channel belts (downstream is to the left). The gradient lines of the channel belts are constructed cf. Berendsen and Stouthamer (2000): the data points represent the highest elevation of sand in 0.5-km-long sections of the channel belt. The gradient line of a channel belt slightly overestimates the actual (paleo-) channel gradient, because sinuosity is disregarded. Data on the thickness of the Holocene cohesive deposits (clay, peat) bounding the channel belts are derived from cross sections constructed for the present study. For the Waal, Nederrijn-Lek, and Maas channel belts, the thickness of the bounding cohesive deposits is based on unpublished cross sections. See text for discussion.



Waal channel belt
W
E
THICKNESS OF COHESIVE DEPOSITS
cohesive-deposit thickness (m)
channel belt partly connected to older Holocene channel-belt deposits (sand)
CHANNEL-BELT WIDTH
channel-belt width (m)
GRADIENT
gradient line
elevation relative to O.D. (m)
n = 146
R² = 0.85
distance along channel-belt axis (km)
Nederrijn-Lek channel belt
n = 114
R² = 0.80
Linge channel belt
n = 59
R² = 0.92
Hollandsche IJssel channel belt
n = 33
R² = 0.76





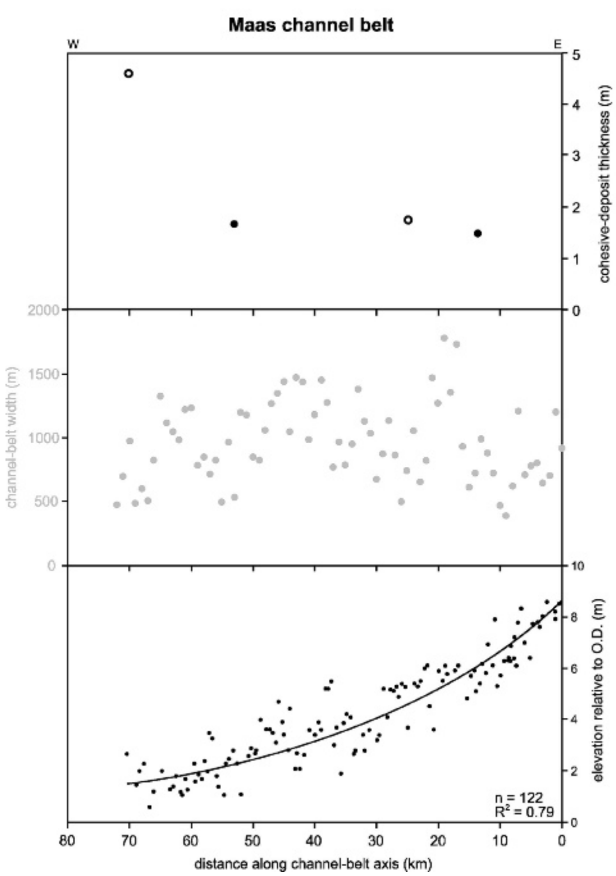


FIG. 11.—Continued.

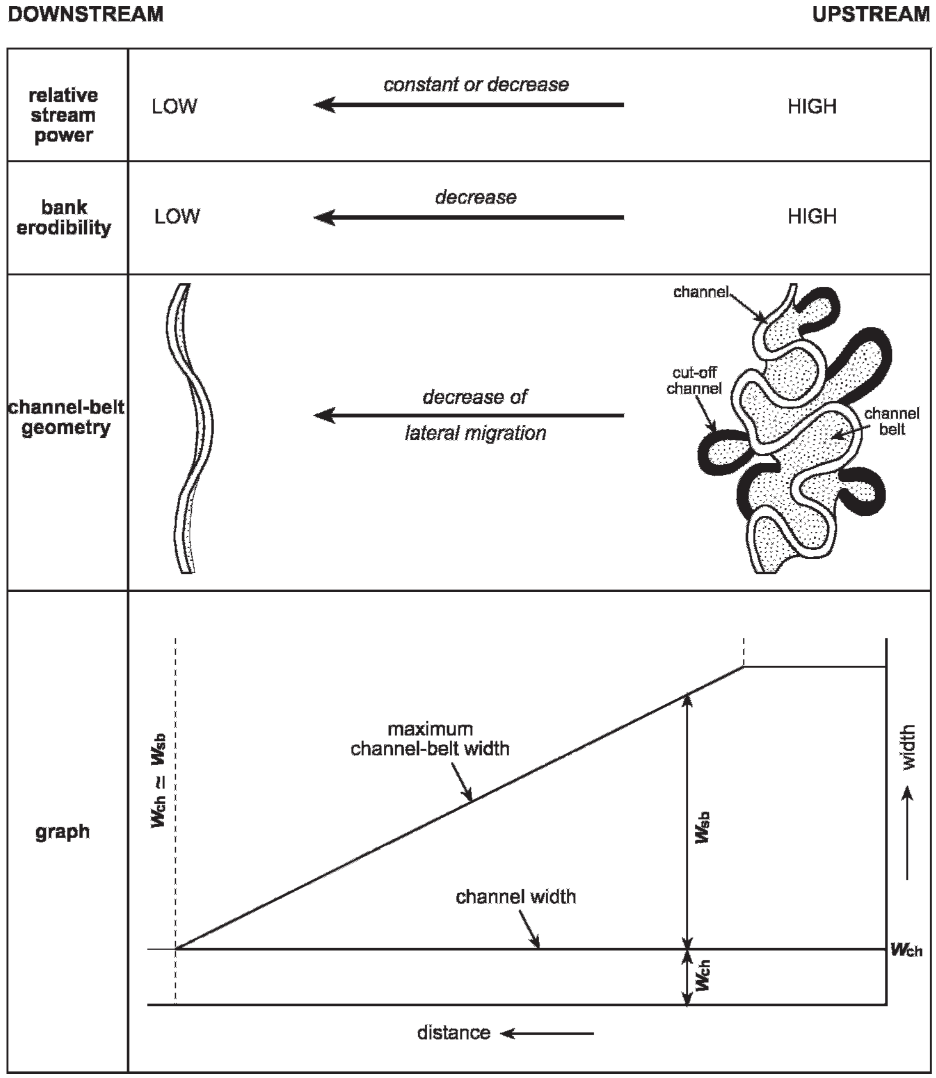


FIG. 12.—Downstream changes of channel-belt width as related to relative stream power and bank erodibility. Channel-belt width (w) can be divided into the width of the river channel (w_{ch}) and the lateral extent of the sandy deposits formed by lateral accretion of the channel (w_{sb}). See text for explanation.

thickness ratio of channel belts and assuming a constant channel-belt width in the downstream direction may lead to a significant overestimation of channel-deposit proportion and connectedness in the succession. We therefore propose that bank erodibility and stream power should be incorporated in future models simulating alluvial architecture in order to make more realistic estimates of total sand volume in fluviodeltaic areas.

TABLE 3.—*Calculated CDP and CR for the modified cross section of Törnqvist (1994) and for the scenarios discussed in the text.*

	CDP	CR
Törnqvist (1994) section	0.29	0.10
scenario 1	0.47	0.10
scenario 2	0.57	0.16

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