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Main determinants of the grain size distribution of overbank deposits in Poland – an overview of literature on models of sedimentation

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The article describes the most important features of the grain size distribution of overbank deposits (madas) of Polish rivers. The most important characteristics of their deposition and the factors determining the variability of the grain size distribution of overbank deposits are indicated. Almost all grain fractions distinguished in nature, i.e. cobbles, gravels, sands, silts, and clays, occur in the overbank deposits of Polish rivers. The sandy fraction dominates in overbank sediments, which contradicts their widespread recognition as silty-clayey (mud) sediments. The change in the proportion of these fractions (the formation of different types of lithological overbank deposits) is caused by a change in the conditions of sediment transport dependent on six factors: (1) decrease in water flow velocity over a floodplain along with an increase in the distance from the river channel, (2) change in water flow velocity during a single flood (stages of a flood), (3) the diversity of the floodplain relief, (4) changes in the forest cover of the river basin (catchment), (5) change in the longitudinal slope and (6) width of floodplains.

Key words: sedimentology, overbank deposits, grain size distribution, models of deposition.

INTRODUCTION

In this publication the phrase "overbank deposits" will be used interchangeably with the term "mada", as according to Polish pedologists and geomorphologists this means a synsedimentary type of soil. Overbank deposits are found on the channel deposits of meandering (Allen, 1965a) and anastomosing rivers (Smith and Smith, 1980; Nanson and Knighton, 1996). The issue of the lithology of overbank sediments and the factors determining it in the river systems of Poland has been repeatedly examined by authors including Pożaryski (1955), Klimek (1974), Teisseyre (1985, 1986, 1988a, b), Zwoliński (1986, 1992), Kalicki (2006) and Szmańda (2011).

Madas are usually referred to as vertical accretion deposits, as opposed to channel deposits which occur as a result of the lateral accretion of channels and so also termed lateral accretion deposits. Teisseyre (1985) proposed that naming overbank deposits "vertical accretion deposits" is incorrect because they are formed as a result of five types of accretion: vertical, frontal, lateral, backward, and compound. Subsequent study (Szmańda, 2011), involving lithodynamic interpretation of overbank deposits, showed that the dominant process by which madas form is saltation, or intermittent suspension. On this basis, one can assume that overbank sediments form as a result of frontal accretion, down the river valley, consistent with the general direction of water flow over a floodplain.

Due to the complexity and discontinuous nature of sedimentation processes on the river floodplains, the study of sedimentation patterns is difficult. Nevertheless, this paper reviews ideas on the main trends and factors determining the grain size distribution of the overbank sediments of Polish rivers and the construction of the overbank deposit sedimentation models in Poland.

THE GRAIN SIZE DISTRIBUTION OF OVERBANK DEPOSITS

Studies of the grain size distribution of overbank deposits indicate their considerable diversity depending on the time and place of deposition on the floodplain (Mycielska-Dowgiałło, 1978; Myślińska, 1980; Myślińska et al., 1982; Turkowska, 1988; Florek, 1991; Andrzejewski, 1994; Kalicki, 2000; Ludwikowska-Kędzia, 2000; Kordowski, 2001, 2003; Kaczmarzyk et al., 2008; Kalicki and Szmańda 2009; Szmańda, 2011; Lisek and Petera-Zganiacz, 2017).

This diversity is well illustrated by the distribution of 2250 overbank sediment samples of Polish gravel-bed and sand-bed rivers as regards mean grain size *versus* sorting (Fig. 1). The samples come from fossil Holocene overbank (Kalicki, 1996, 2000, 2006; Szmańda et al., 2004; Chruścińska et al., 2012)

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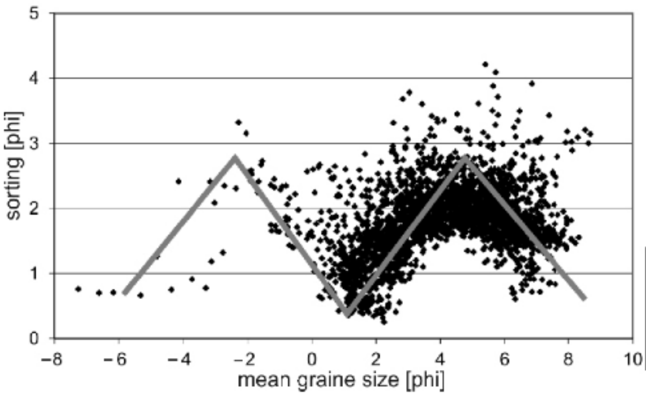

Fig. 1. Sample distribution tendency of selected Polish river overbank deposits on a mean grain size *versus* sorting diagram, on the basis of samples taken from floodplains the locations of which are shown in Figure 2

and modern deposits (Teisseyre, 1980, 1986; Szmańda, 2011; Gierszewski and Szmańda, 2012) collected from floodplains of the Vistula River (in the section from Krakow Gate to the Toruń Basin), the Drwęca, the Tążyna and the Złotna rivers (Fig. 2). These deposits represent all forms of the proximal and distal zones of floodplain (Kalicki, 1996, 2006; Szmańda, 2011). They were taken from segments of the river valley bottoms (1) with different floodplain width, (2) of meandering and anabranching channel patterns, and (3) of varied channel sinuosity.

The samples analysed are located within the M-shaped trend determined by Folk and Ward (Szmańda, 2004, 2011; Fig. 1). This is not consistent with the proposal of the genetic classification of river deposits adopted by Mycielska-Dowgiałło and Ludwikowska-Kędzia (2011) and their division into river bed lag deposits, channel deposits, overbank deposits, and overbank-pool deposits, based on the distribution of sediment samples in the diagram of the mean grain size *versus* sorting diagram. The M-shaped distribution of samples in this diagram depends on the characteristics of the material found in nature (Pettijohn, 1957) and the mixing of the grain size fractions relative to change in water flow velocity (Folk and Ward, 1957; Szmańda, 2004, 2011).

Studies on patterns of grain size distribution of overbank alluvia (Szmańda, 2004, 2011) showed that four basic fractions can be distinguished in their grain size distribution (Fig. 3): (1) coarse and medium gravels, from –5 to –3 phi, (2) coarse sands, from 0 to 1 phi, and fine sands, from 2 to 3 phi, (3) coarse and medium-grain silts, from 5 to 6 phi, (4) medium clays, from 11 to 12 phi (Szmańda, 2011). Gaps called Tanner Gaps (Tanner, 1958) occur between them, where there is a paucity of certain

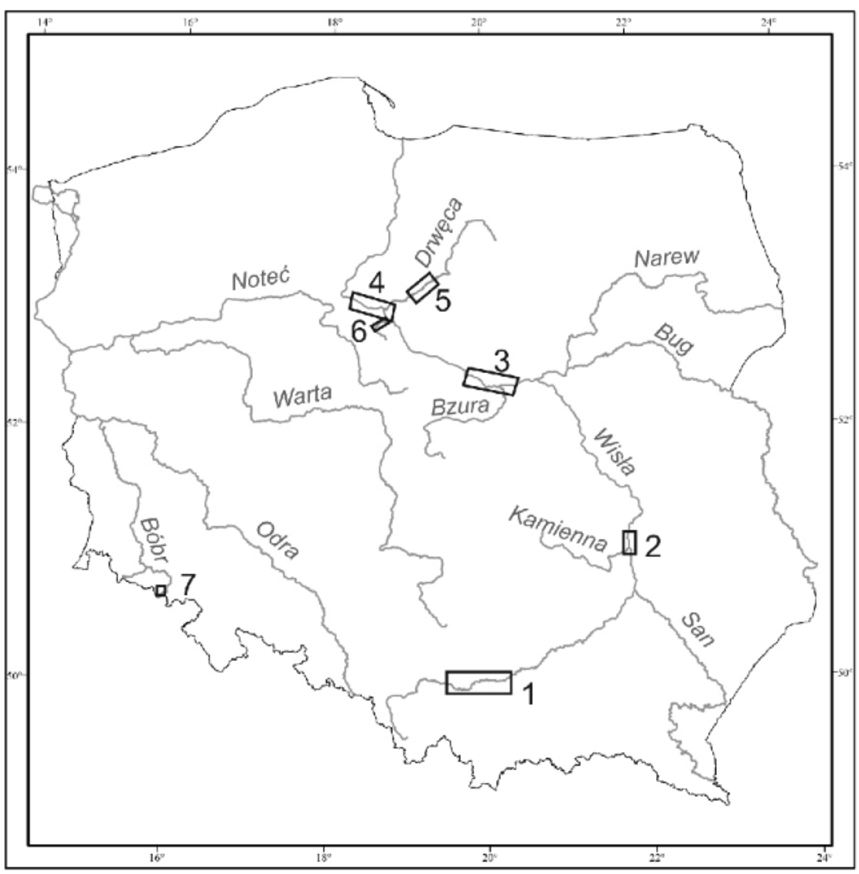

Fig. 2. Location of sampling areas of: 1–6 (Szmańda, 2011); 1 (Sandomierz Basin, Kalicki, 1996, 2006); 7 (Teisseyre, 1980)

1 – Vistula River valley, Kraków Gate and Sandomierz Basin, 2 – Vistula River valley, the Lesser Poland Gorge, 3 – Vistula River valley, Płock Basin, 4 – Vistula River valley, Toruń Basin, 5 – Drwęca River valley, 6 – Tążyna River valley, 7 – Złotna River valley

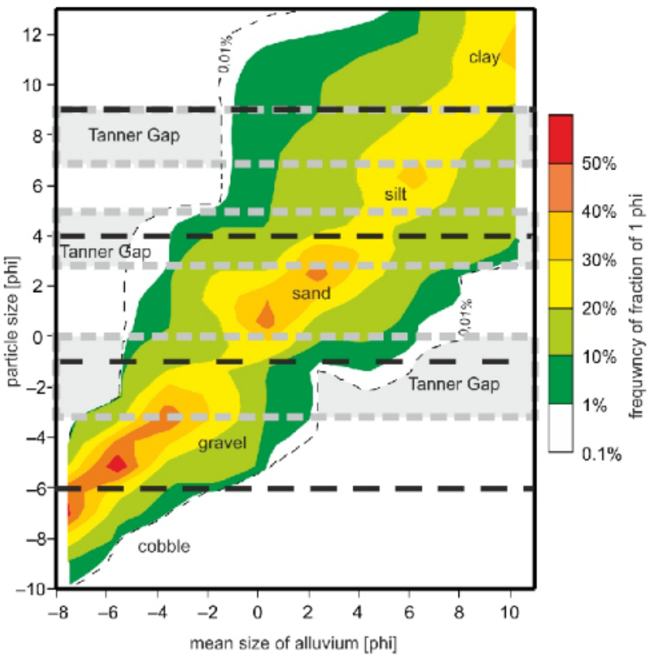

Fig. 3. Spectral diagram of grain size distribution of overbank deposits, on the basis of samples taken from floodplains the locations of which are shown in Figure 2

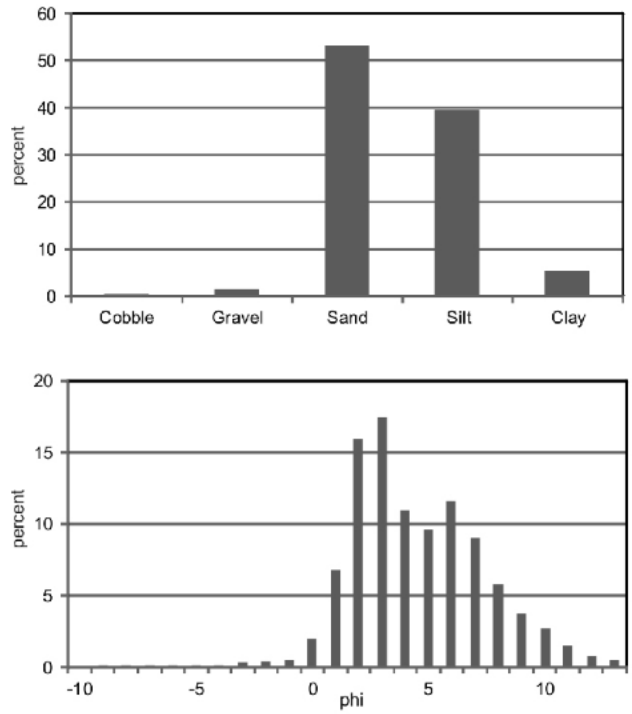

Fig. 4. Average frequency of overbank deposit fractions, based on results of grain size samples from floodplains indicated in Figure 2

grain sizes: (1) from –3 to 0 phi, (2) from 3 to 5 phi, (3) from 7 to 9 phi (Fig. 3). The change in the share of the gravel, sand, silt and clay fraction, reflecting changes in current velocity, determines the lithological characteristics of the sediments in the various sedimentary environments (Spencer, 1963; Tanner, 1964), including in madas (Szmańda, 2004, 2011). Features of the grain size distribution of overbank sediments cannot be a determinant of its own genesis and are similar to the features of glacial, glaciofluvial, eolian, and lacustrine sediments (compare with e.g., Wysota et al., 1996; Podgórski and Szmańda, 2002). The dominant fraction in the overbank deposits studied is the sand fraction (53% on average) and, within this, the fine-grained sand fraction (2–3 phi – on average 17.5%; Fig. 4).

THE INFLUENCE OF THE SLOPE AND WIDTH OF THE VALLEY BOTTOM ON THE GRAIN SIZE DISTRIBUTION OF OVERBANK DEPOSITS

The change in the longitudinal valley bottom slope, which contributes to the change in water flow velocity over a floodplain, has a significant effect on the type of deposits that accumulate in river valleys (Schumm, 1977; Teisseyre, 1991). This is due to Lane's (1955) general principle that $QrD \sim QS$. It assumes that at a constant flow rate (Q) and a constant sediment transport rate (Qr), along with the decrease of the longitudinal valley bottom slope (S), the size of the grain deposited on its bottom (D) decreases. This relationship is supported by the increase in the share of silty deposits relative to sandy deposits in the Vistula overbank sediments, along with the declining floodplain slope between the Toruń Basin and the Unisław Basin (Kordowski, 2001, 2003). The share of fine clastic sediments in the deposits of the Vistula River between the upper gravel-bed section of the meandering river (between Kraków Gate and the Sandomierz Basin) and the middle and lower section of the sand-bed anastomosing Vistula River increases in a similar way (Szmańda, 2011).

The greater share of fine-clastic sediments on the bottom of a valley with a gentle slope than in a valley with a steeper slope is also visible in the comparison of the grain size distribution of the overbank deposits from the floodplains of the Tążyna and the Drwęca rivers (Szmańda, 2003). Sandy madas are deposited on the bottom of the Tążyna valley, where the average slope of the floodplain amounts to 2.3‰, while mainly mud deposits accumulate on the bottom of the Drwęca valley where the average slope of the floodplain is 0.4‰.

The effect of the change in valley bottom width on the accumulation of overbank sediments depends on the relation between the water flow velocity in the channel (Vk), and on the floodplain (Vp) during floods (Wyżga, 1999). The deposition of mineral material on the floodplain occurs when the difference between the water flow velocity in the channel and on the floodplain is expressed in the relation $Vk > Vp$. Along with a decrease of this velocity in the distal direction of the floodplain, selective deposition of overbank deposits occurs due to the falling out of finer grains from the bed load and suspended load (Teisseyre, 1985, 1988a, b; Wyżga, 1999). In fixed water flow conditions, the water flow velocity in flood areas (where the relief allows the free flow of water down the valley) will change depending on the wet cross-section of the river. As a consequence, as the width of the valley bottom increases, increasingly finer sediment will be accumulated on the floodplain. This type of accumulation, referred to as upwardly controlled aggradation (Mackin, 1937), makes the size of the accumulated grains and the thickness of the deposits decrease along with the course of the river and with the increase in the distance from the channel (Fig. 5). In the inlet to the basin-like extensions of river valleys, along with the flooding under subaerial conditions, mainly sandy piping fans are formed (Teisseyre, 1980, 1988b). Within them, the flow in the channel is divided into several courses. Then, along with the deposition of fine clastic sediments on central bars causing their consolidation, separate

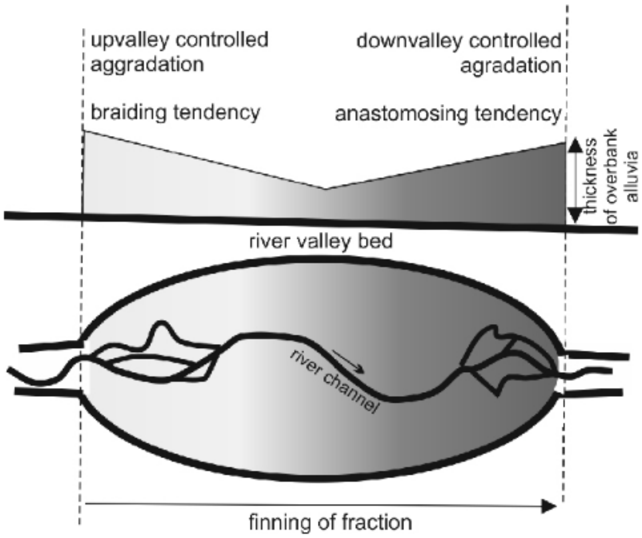

Fig. 5. Scheme of overbank deposits accumulation in basins based on Mackin (1937), Teisseyre (1985), Szmańda (2011)

channels are formed (Teisseyre, 1991, 1992). The river evolves from a braided to an anastomosing one. In the case of high water levels (floods), the accumulation of deposits on floodplains takes place under subaqueous conditions (Teisseyre, 1988b). Often such conditions occur at the outlets of basin-like segments of river valleys as a result of damming the flow that causes the backwater effect. In this case, so-called downvalley controlled aggradation occurs (Fig. 5; Mackin, 1937). Because coarse-grained material was usually deposited in the river valley in the upper part of the basin, more and more fine-grained material is accumulated in the lower part of the basin, as its width decreases. In the case of downvalley controlled aggradation, accumulation of increasingly finer material, with an increasing thickness of deposits, occurs as the width of the valley bottom decreases (Teisseyre, 1988b). Under these conditions, the flow is often divided into several channels separated by areas built of cohesive sediments. Therefore, the river has a tendency to be anastomosed.

FINING AND COARSENING UPWARDS SEQUENCES IN OVERBANK DEPOSITS

The fining upwards sequence, observed by Allen (1965b) as a diagnostic feature of alluvial sediments of meandering rivers described as "fining-upwards cycles in alluvial successions", is usually continued in the structure of overbank deposits.

It consists of the fining of grain fractions towards the surface and is a consequence of the change in water flow velocity along with the increase in the distance from the active river channel, described in the 1940s by Fisk (1947). The tendency towards the fining of overbank sediments as the distance from the river channel increases, caused by the slow decrease in water flow velocity, is also supported by the results of tests of madas (overbank deposits) in the proximal and distal zones of the floodplains of Polish rivers (i.a. Teisseyre, 1988a, b; Kalicki, 1996; Wyżga, 1999; Szmańda, 2011; Kordowski et al., 2014). The phenomenon of grain fining along with the increase in the distance from the river channel occurs not only between the proximal and distal zones of floodplains, but also in the development of natural levees themselves (Teisseyre, 1988b; Kurowski, 1999; Szponar, 2000). The fining upwards sequence observed in the profiles of deposits attests to the moving away of the river channel from the place of deposition. On the other hand, a coarsening upwards sequence is the effect of the channel approaching the place of deposition.

The coarsening upwards sequence often found in the structure of overbank deposits in the valleys of Polish rivers may be caused not only by the channel approaching the place of accumulation, but also by two other factors: (1) the accretion of sediments on floodplains and, consequently, the change in the relative height on the floodplain; (2) changes in the land cover in the bottom of a river valley and its catchment.

The accretion of the thickness of the deposits deposited on floodplains results in the fact that coarser sediments are deposited in a given place on the floodplain, with flows of ever higher energy (Tomczak, 1971). Particularly rapid accretion of sediments occurs in the natural levee zone (Teisseyre, 1985). This phenomenon is accompanied by a decrease in the thickness of accumulated layers of sediments towards the surface of floodplains (Tomczak, 1971; Kalicki, 2000; Szmańda, 2003; Czajka, 2007). Based on the results of these authors' research, it should be noted that the accretion of overbank deposits decreases along with the flood size, and increasingly larger floods are observed in the increasingly higher areas of floodplains near the river channel.

The influence of the relative height of the floodplain on the grain size of deposited sediments was emphasized by Teisseyre (1985), Zwoliński (1985), Tomczak (1987), Florek (1991), Kordowski (2001, 2003), Szmańda (2003, 2006) Kalicki (2006) and Kordowski et al. (2014). Based on the results of their research, it can be concluded that sandy sediments are deposited on the higher-lying areas of floodplains and silty sediments are deposited on lower-lying floodplains and in post-flood basins. The type of deposited sediment is influenced by the height of the water column (Teisseyre, 1988a) which, at the time of particular water levels, is the smallest over natural levees, and the largest over post-flood basins. As a consequence, high flow regime conditions, under which the accumulation of coarse deposits takes place, occur over natural levees, and low flow regime conditions and the accumulation of fine deposits occur in flood basins.

Changes in land cover are also seen as a cause of the coarsening upwards sequences in overbank deposits. Changes in the land cover in river catchments are mainly related to the change in the amount and size of the material supplied to river channels. The causes of these changes can be natural or anthropogenic. Some authors assume that the reason for the accumulation of overbank sediments and their lithological diversity in the profiles is the changes in land use associated with deforestation, which began in the Neolithic (clayey madas) and was particularly intense in the early Middle Ages (sandy madas; Biernacki, 1968; Klimek, 1988, 1999; Alexandrowicz, 1996; Klimek et al., 2003; Szmańda et al., 2004; Szmańda, 2005; Kaczmarzyk et al., 2008). The results of studies, for instance those conducted by Pożaryski (1955), Starkel (1960, 2001), Myślińska (1980), Rutkowski (1987), Kalicki (1996, 2006) and Kukulak (2004), show that the accumulation of overbank sediments took place at different intensities in all the periods of the Late Glacial and Holocene, as well as in the Pleni-Vistulian (Gębica, 2004). These authors associate the accumulation of overbank deposits with changes in land cover caused not only by human activity, but also by climate change.

A CYCLOTHEM AND A RYTHMITE AS A DIAGNOSTIC STRUCTURAL FEATURE OF OVERBANK DEPOSITS

Changes in water flow conditions and the resulting erosion processes and transport and accumulation of sediments on floodplains were described by Zwoliński (1992). He distinguished 6 stages of floods, in 5 of which changes in water flow velocity were observed on the floodplain during a flood: (1) the rising of water stage and bank modification, (2) flood inundation and initial deposition, (3) flood peaks and widespread transport and deposition, (4) falling of water stage, and high intensity deposition, (5) cessation of overbank flow and final deposition.

The record of changes in flow velocity occurring during these 5 stages of a single flood event is expressed in the form of a flood cyclothem (Klimek, 1974; Teysseyre, 1988b; Szmańda, 2011). This cyclothem is characterized by a pensimetric graded sequence (Mansfield, 1938) consisting of three layers:

– lower – silt of a massive structure, containing plant detritus (mainly organic matter in the form of grass and leaves);
– middle – sand, locally in inversely graded sequence with gravels;
– upper – silt and/or massive clay.

The lower layer of silt with the content of plant organic matter is formed in the first stage of the flood, corresponding to the rapid increase in the water flow and level. At this stage, considerable flow resistance associated with grassy vegetation contributes to the accumulation of a lower series of silts on and among this vegetation. Its thickness decreases with distance from the edge of the channel. The lower silts usually have a thickness of a few millimetres. The accumulation of silts on grassy vegetation contributes to the reduction of resistance and, within the natural levees, to the change from low flow regime to high flow regime (Teisseyre, 1988b). As a result, a gradual change in accumulation from silts to sands takes place. At the second stage of the flood, mainly sands are deposited. Grain sizes increase consistently as flow velocity increases, to reach the largest diameters at the culmination of the flood wave (stage 3), or to be transformed into gravel fractions and create an inversely graded sequence (Teisseyre, 1988b). The thickness of the sand and gravel layer may reach up to several centimetres. Subsequently, at stages 4 and 5, along with the gradual waning and cessation of the flood flow, a layer of upper silts is formed. Its thickness gradually increases in the distal direction of floodplains, reaching a maximum locally in post-flood basins. The cyclical record of the flood course in the textural and structural features of sediments is also a reflection of changes in the concentration of material transported during floods. These changes have the characteristics of hysteresis (Froehlich, 1982; Młynarczyk, 1996) and mainly affect the thickness of deposited layers. A flood cyclothem occurs mainly in the natural levee zone and on the flat floodplain. It is also found in the structure of flood silts of the so-called series of clayey overbank deposits or in post-flood basins (Teisseyre, 1985; Szmańda, 2003, 2011). During the inundation and initial depositional stages, vertically-stacked laminae are formed in post-flood basins, thus forming a lower plane bed (being the equivalent of the lower silts). Then, at the stage of flood peaks and widespread transport and deposition with high velocity flows, ripple marks are formed from the silt fraction subject to deposition from the saltation load (Rees, 1966). Small-scale ripple mark lamination develops. This corresponds to the layer of sands with reverse grading formed at this stage. As transient forms, however, ripple marks disappear very quickly during the stage of water level fall and rapid deposition, and during cessation of the overbank flow and final deposition. Then, with a large proportion of the material being deposited from the suspended load, lower plane bed lamination and a layer of upper silts are formed again.

The diagram of sedimentation of the overbank sediments deposited during a single flood event (Fig. 6) represents the theoretical distribution of the variability of deposition of flood cyclothems on a floodplain. This diagram is patterned on the models of sedimentation in valleys of gravel-bed (Teisseyre, 1988b) and sand-bed rivers (Zwoliński, 1985; Szmańda, 2011). The following sets are an effect of deposition in the proximal zone of a natural levee (Fig. 6): Fm-Smi-GDm-Sm-(Fm), Fm-Sh-Sr-(Fm) – lithofacial coding according to Miall (1977), and Zieliński and Pisarska-Jamroży (2012). Near the edge of the river channel, no layer of upper silts is formed. The reason for this is the flow of water over the natural levee connected with

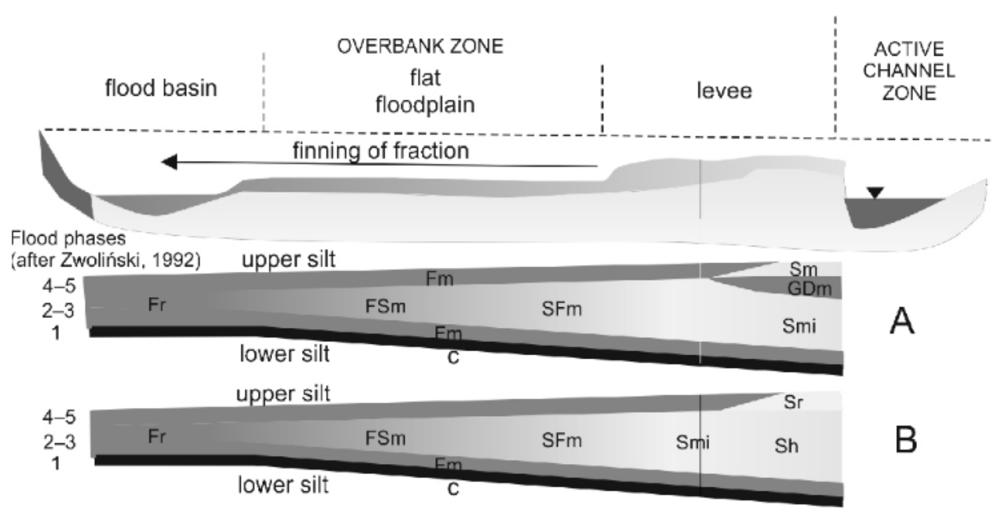

Fig. 6. Model of cyclothemal units in overbank deposits based on Teisseyre (1988b) and Szmańda (2011), modified

A – on gravel-bed meandering river; **B** – on sand-bed meandering and anastomosing rivers; lithofacial units: GDm – massive diamictic gravel, Smi – inversely graded sand, Sm – massive sand, Sh – horizontally laminated sand, Sr – ripple cross-laminated sand, SFm – massive silty sand, FSm – massive sandy silt, Fm – massive silt or mud, Fr – ripple cross-laminated silt, C – organic matter; flood phases after Zwoliński (1992) – (1) the rising water stage and bank modification, (2) flood inundation and initial deposition, (3) flood peaks and widespread transport and deposition, (4) falling of water stage, and rapid deposition, (5) cessation of overbank flow and final deposition its return to the active channel during the retreat of water from the floodplain. Sedimentation on this part of the natural levee may not occur at all, as levees may be raised above the water level. In the distal zone of the natural levee, the record of individual stages of the flood is the set Fm-Smi-Fm. In the floodplain zone, a cyclothem may consist of the set of layers Fm-SFm(FSm)-Fm, with a tendency towards fining in the middle layer, from massive silty sands to massive sandy silts. Sets of the silty layers Fm-Fr-Fm are formed in flood basins. A layer of plant detritus (C) is typically located at the floor of all sets.

Flood rhythmites are laminated sediments consisting of laminasets of pairs of layers differing in grain size distribution: (1) a lower layer of coarse-grained sands or sandy gravels, locally with an inverse graded sequence structure, and (2) an upper layer of massive silts/muds. Two flood stages are recorded in flood rhythmites in the upper layer: (2) flood inundation and initial deposition, and (3) flood peaks and widespread transport and deposition, and another two flood stages in the lower layer: (4) falling of water stage and rapid deposition, (5) cessation of overbank flow and final deposition (Antczak, 1985; Niedziałkowska, 1992; Czyżowska, 1997; Szmańda, 2006, 2011; Kaczmarzyk, et al., 2008).

The record of the course of the flood wave can be expressed not only in the lithofacies variation between the layers (laminae) of the flood rhythmite, but also in the differences in organic matter content (Szmańda, 2006). In the sandy deposits of natural levees of the Tążyna River, sets of pairs of layers were found based on differences in the colour of sand laminae. These differences result from the variable content of organic matter, in which the upper lamina of the set is enriched. Since peats occur in the substrate of the natural levee, it can be assumed that the greater admixture of organic matter in the upper laminae comes from the redeposition of peats at the stages of the falling water and during the cessation of overbank flow and final deposition.

FINAL REMARKS

The indeterminate nature and unevenness of water flow as well as stream power during overbank flows and the resulting conditions of sediment transport are causes of the complex spatial distribution and discontinuity in the deposition of overbank deposits. Despite the complexity of these processes, based on the analysis of literature and on my own observations, several factors determining the accumulation of madas and the resulting patterns have been distinguished. These factors include (Fig. 7):

1. A decrease in water flow velocity over the floodplain along with an increase in the distance from the river channel results in the accumulation of increasingly finer clastic material as distance from the active river channel increases (Teisseyre, 1988b; Kalicki, 2006).

2. A change in flow velocity on floodplains during a single flood is recorded either in the sequence of a flood cyclothem (Klimek, 1974; Zwoliński, 1985; Teisseyre, 1988b), which is a record of the rise and fall of the flood wave, or in the sequence of a flood rhythmite, if the record includes the peak and fall stages of a flood (Antczak, 1985; Niedziałkowska, 1992; Szmańda, 2006).

3. The accumulation of more coarse deposits in the higher parts of floodplains located above the river channel is caused by the diversity of the floodplain relief and the increase of the overbank sediments thickness (Tomczak, 1971; Teisseyre, 1988b; Czajka, 2007).

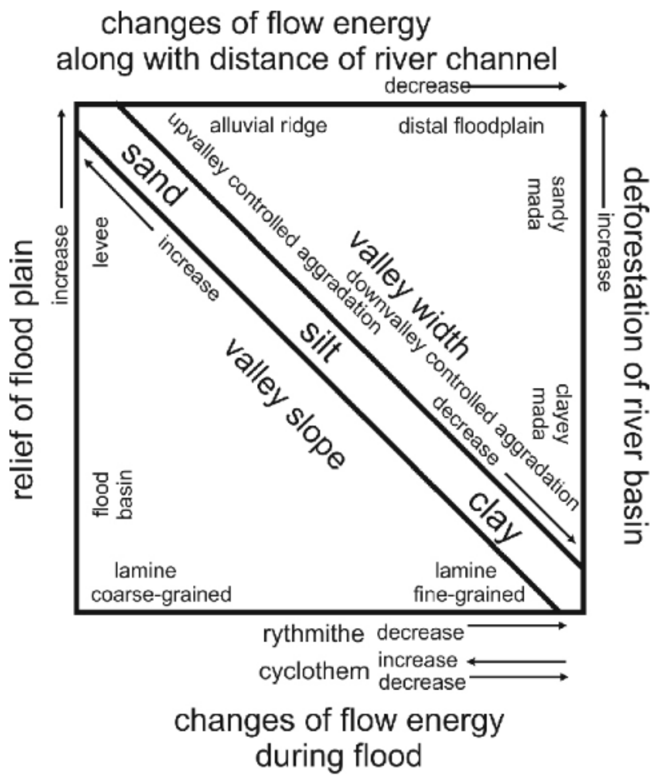

Fig. 7. Model of factors controlling the overbank deposit grain size composition of the Polish rivers after Szmańda (2011)

4. Changes in the proportion of forest areas in the basin result in the intensification or weakening of soil erosion. Afforestation contributes to a reduction in overall material supply to the river channel, and to a decrease in the proportion of coarse-grained material. As a result, the mainly fine-clastic suspended fraction that forms “clayey madas” is deposited on floodplains (Pożaryski, 1955; Kalicki, 1996, 2006). Deforestation contributes to an increase in the overall supply of material, including in particular suspended coarse-grained sediments, which are deposited on floodplains during floods, creating a “sandy madas” (Pożaryski, 1955; Biernacki, 1968; Kalicki, 1996, 2006).

5. Changes in the longitudinal slope of a floodplain depend on differences in the grain size composition of madas between sediments deposited on a floodplain of different slope. The proportion of sand fraction increases to the disadvantage of the silt fraction in the overbank deposits with an increase of the slope of a floodplain (Kordowski, 2001, 2003; Szmańda, 2003, 2011).

6. Changes in the width of floodplains mainly reflect an increase in the width of the floodplain into the basin of river valleys which results in a division of flow within coarse-grained overbank deposits (upvalley controlled aggradation), while a decrease in the width of the bottom of a valley results in the separation of channels in fine clastic deposits (downvalley controlled aggradation; Teisseyre, 1985).

Therefore, the change in the proportion of grain size fractions in overbank deposits takes place along with a change of depositional conditions, determined mainly by changes in the water flow conditions on floodplains. These conditions depend primarily on the six factors noted above.

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