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Effect of Emergency Water Discharges from the Dam in Włocławek on the Sedimentary Structures of Channel Bars in the Lower Flow Regime of the River Vistula

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Abstract: Changes in the stream flow contribute to transformation of the river channel due to erosion and accumulation. Channel bars move as a result of water flow. This article presents the results of studies carried out on two channel bars formed in the River Vistula that were transformed during emergency discharges of water from the Włocławek reservoir. In order to present changes in structure and texture, pits were dug in the channel bars and samples were taken for grain-size analysis. The rate of migration of channel bars caused by emergency discharges was determined. Sedimentary structures were recorded as groups of strata indicating a variability in flow conditions (2D and 3D dunes, parasitic ripple marks, reactivation surfaces). It was observed that changes in the level of water and flow are reflected in sedimentary structures. The emergent channel bars are affected by aeolian processes that wear the flow marks off.

Keywords: discharge; sedimentary structures; channel bar; dam; Włocławek reservoir

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1. Introduction

Rivers are an element of the natural environment affected by continuing natural and anthropogenic changes.

Natural changes include, for instance, lateral and vertical fluvial erosion and bed load transport. A special example of natural changes in the river channel is ice jam. The disintegration of the winter ice cover on the river can give rise to ice jam, raising the water level and causing ice jam floods [1,2]. The flow in rivers can also be blocked by landslides and landslide tongues, which leads to the formation of seasonal ice-dammed lakes [3,4]. Rivers constituting natural habitats for various species of mammals are also transformed as a result of their activity. On small rivers and streams, water dams are built by beavers—*Castor fiber* [5,6]. By raising the water level in streams, beavers also contribute to improvement in the local storage of water [5,7].

Riverbeds can be transformed due to human activity through the construction of transverse weirs such as groynes or dams. Dams on rivers are built as floodgates and as impoundments for power generation purposes [8,9]. Water reservoirs formed by river damming are often used for recreation purposes [10]. Dams erected on small rivers have an additional function; that is, they raise the water level for farming purposes, e.g., River Noteć [11].

The construction of dams leads to changes in river flow before and after the dam [12]. Dissolved load and bed load transported by the river is deposited in storage reservoirs, gradually decreasing their capacity [13–15]. The Włocławek reservoir retains 100% of bedload sediments and from 42% [16] to 50% [17] of suspended sediments [18]. Simultaneously, load-free water from storage reservoirs is used for powering turbines and generating electricity. The operation of a hydroelectric power plant when the water level is low can lead to negative changes in the river ecosystem [19]. The operation of a hydroelectric power plant determines changes in the volume of water flowing through the dam. Erosion downstream of the dam is a significant geomorphological factor in the case of discharges of water from the reservoirs. Erosion is exacerbated by the fact that the river must be replenished with sediment load again—the so-called “hungry water” effect [20–23]. Erosion cuts down into the riverbed, making it deeper, and wears away the banks of the river channel [24–26]. Szatten et al. [18] determined that in 2016, the erosion zone was located on a stretch 720–740 km along the Vistula. The sediment accumulation zone is right behind the erosion zone [18]. Due to the presence of this zone, the effects of geomorphological processes downstream of the dam can also be seen in various accumulation forms, such as channel bars [9]. Following a decrease in water level on the surface of channel bars, newly formed bedforms (dunes, ripple marks) created at specific water flow rates can be observed [27]. Previous studies regarding channel bars in the River Vistula mainly covered the rate of their migration, the volume of transported sediment [9,13], and their texture and mineral composition [9,13,28–31]. Our study presents the sedimentary structures of channel bars in the Vistula. Worldwide studies of sedimentary structures were carried out on channel bars formed in natural flow conditions, e.g., [32,33]. Our study also presents records of emergency discharges of water from the dam in Włocławek visible in the sedimentary structures of channel bars of the Vistula (flow modified by anthropogenic intervention).

Apart from the discharge of water in connection with the operation of a hydroelectric power plant, an emergency discharge of water (transport, overhauls) provides an additional impulse to erosion. Large fluctuations in water level and flow rates, occurring over a short time, lead to considerable changes in kinetic energy. In turn, changes in the kinetic energy of flowing water contribute to intensive erosion in the river channel [9,13]. They activate fine, medium, and coarse-grained sediments deposited in the river channel [33] and, episodically, silt [34]. Such sediments can be contaminated with heavy metals [35]. Contamination with heavy metals can also be redeposited during floods and derives from sediments accumulated in the past on flood plains [36,37]. For rivers transporting sandy sediments, increased concentrations of heavy metals can be observed near the banks, as well as for rivers with gravel-filled beds in channel bars [35,38–40].

Valuable information about the effect of natural channel processes and emergency discharge of water on bed load transport is provided by sedimentary structures that can be observed in pits made in channel bars [32,34]. The elements analysed in sandy bars are structure and texture [34,41].

The studies aimed to determine if and how emergency discharge of water from the dam in Włocławek is reflected by the sedimentary structures of channel bars. Grain size distribution and Folk and Ward [42] parameters were also determined for the analysed sediments.

2. Materials and Methods

2.1. Study Area

The Vistula is the longest river in Poland and consists of three sections: upstream, from the springs to the confluence with the River San, midstream, from the confluence with the River San to the confluence with the River Narew, and the downstream section (Lower Vistula Valley), extending from the confluence with the River Narew until the point at which the River Vistula issues into the Baltic Sea (Figures 1 and 2). The Vistula basin in Poland extends over an area of 174,202 km^2, of which 45,874 km^2 is the Upper Vistula, 88,765 km^2 is the Middle Vistula and 39,565 km^2 is the Lower Vistula with Żuławy Wiślane [10]. The discharge of the Vistula is 1046 m^3 s^{-1} at its confluence into the sea, while the discharge from the dam in Włocławek was 905.7 m^3·s^{-1} in 1971–2015 [22].

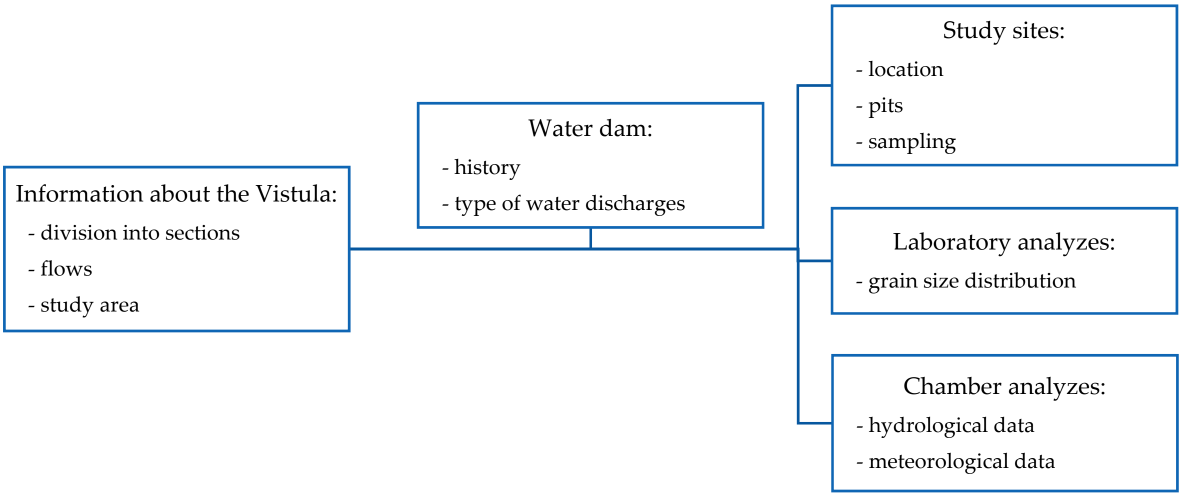

Figure 1. The flowchart describes the methodological approach applied in this study.

The Vistula, between 1970 and 2005, had mean annual flow rates of 895 $m^3 s^{-1}$ and 1004 $m^3 s^{-1}$ in Włocławek and Toruń, respectively. In wet years (1971, 1974–1975, 1977–1982, 1998–2002) the flow rate ranged from 945 to 1342 $m^3 s^{-1}$ in Włocławek. In dry years (1972, 1984, 1987, 1990–1992, 2003–2004), the values reached from 580 to 790 $m^3 s^{-1}$. The minimum flow rate of the Vistula in Toruń was 158 $m^3 s^{-1}$ in September 1992 [43]. New studies regarding the flow of water in the Vistula [22] indicate that in the period 1970–2015, the inflow of water into the Włocławek reservoir was larger than the outflow. Changes in the flow rates are also determined by the use of the reservoir during floods and emergency discharges for improving navigability.

The Lower Vistula Valley is 380 km long and is made of alternating wider and narrower sections. The wider sections are up to 25 km wide [15]. They are wide potholes remodelled by lateral erosion. Narrower sections are old glacial valleys in which the present-day Vistula flows [44,45]. They are from 3 to 8 km wide [15].

The study area is situated on the lower Vistula, on the section between the dam in Włocławek (674.9 km along the Vistula) and a road bridge in Bydgoszcz Fordon (774.8 km along the Vistula) (Figure 2). The channel of the Vistula on the section from Włocławek to Silno (718 km along the Vistula) is partly regulated and is about 380–500 m wide. From Silno to Toruń, the channel is 330 m wide, and downstream of Toruń its width increases to 430 m [2].

2.2. Methods

Studies aiming to identify reflections of emergency water discharge in the sedimentary structures of channel bars were carried out on two test sites. At the first site (Byzie, 697 km), the studies were carried out on 19 October 2012. Sedimentary structures linked to emergency discharges in May and June 2012 were analysed. At the second site (Solec Kujawski, 764 km), the studies were carried out on 2 November 2012 and 20 November 2012. On 2 November 2012, sedimentary structures formed in May and June 2012 were analysed. On 20 November 2012, sedimentary structures formed in November 2012 were analysed. Study sites were selected based on the accessibility of channel bars. The channel bar at the Byzie site was accessible from the bank of the river, but to reach the channel bar at the Solec Kujawski site, we took an inflatable dinghy from the harbour in Solec Kujawski.

The reflection of emergency water discharge in the sedimentary structures of channel bars was verified on test sites using pits perpendicular to the bar head. The pits were 3 to 6 m long. At the second site (Solec Kujawski), a pit was also made at a distance of 21–24 m from the bar head. The thicknesses of respective strata and dip angles were determined in the pits. Boundaries were determined between respective sedimentary layers and bar heads reflected in sediments, and sedimentary structures were identified using lithofacies codes based on [46,47] after [48]. Some authors use their own description of sedimentary structures [32] resembling lithofacies codes based on [46]. A limitation to such studies is the water level. If the water level is raised, channel bars are flooded or their height above the water table is insufficient to make pits in them. In addition, the walls of pits made in summer dry out and thus impede the interpretation of sedimentary structures.

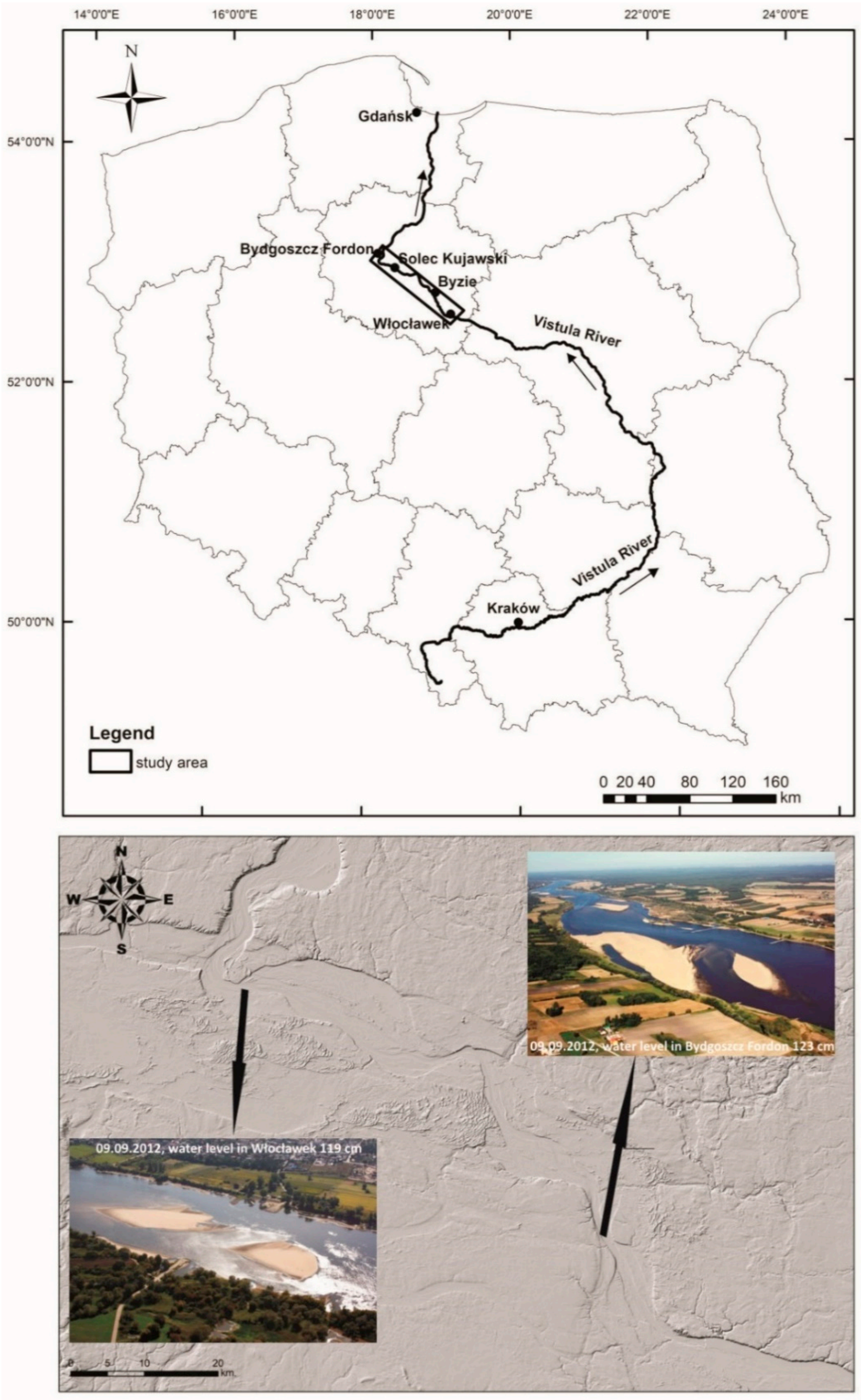

Figure 2. Location of the study area in Europe and in Poland.

Samples were taken from each pit in vertical profiles spaced at 1 m. If the sedimentary structures were varied, spacing between the profiles was reduced to 0.5 m or additional samples were taken from distinct sedimentary structures. At the site in Byzie, 55 samples were taken for grain-size analysis, and 105 samples were taken at the site in Solec Kujawski. Samples for analyses were also taken from granule ripples formed on the surface of the sand bar due to aeolian processes. All samples were sieved using a Retsch As200 (Retsch GMBH, Haan, Germany) shaker: −1 phi intervals for grains coarser than 1 mm, −0.5 phi intervals for grains finer than 1 mm. The results of grain-size analysis were used for calculating the average grain size (Mz) and sorting (∂_1) according to [42].

Data concerning water level and flow rate were provided by the Institute of Meteorology and Water Management (IMGW) and retrieved from the website www.pogodynka.pl.

2.3. The Dam and Its Operation

The dam in Włocławek was built at the 674.9 km point of the River Vistula. The construction of the dam started in 1963, while on 13 October 1968 the Vistula was dammed [8]. Damming up of water in the Włocławek reservoir commenced on 12 March 1969. This comprised four stages: water level rising rapidly due to the spring flood wave (12 March–8 April 1969), water level in the reservoir decreasing in connection with a low level of water in the Vistula (8 April–19 August 1969), water level rising again (19 August–27 November 1969), and a slow rise in water level (27 November 1969–16 August 1970). The hydroelectric power plant in Włocławek was put into use on 17 October 1970 [8]. The reservoir is 58 km long and its total capacity is 408 million m^3 [8]. In the 1971–2015 period, the Włocławek reservoir was on average supplied with 931.8 $m^3 \cdot s^{-1}$ of water, while the outflow from the reservoir amounted to 905.7 $m^3 \cdot s^{-1}$ [22].

The hydroelectric power plant on the dam in Włocławek in the years 1970–2002 discharged water for electricity generation needs [22]. This led to changes in the level of water near the dam by 2 to 3 m and intensified erosion downstream of the dam due to sudden changes in kinetic energy [9]. From February to August 2002, the power plant worked as a run-of-the-river facility. Since September 2002, it has worked as a run-of-the-river and stand-by plant. The flow is stopped for a few hours during the day during dam overhauls. In addition, emergency water discharges are carried out in connection with the passage of vessels transporting a large amount of cargo [22]. This type of operation contributes to changes in kinetic energy, and thus the rate of erosion downstream of the dam, but to a much smaller extent than during the first period of the power plant's operation (1970–2002).

3. Results

3.1. Water Flow Conditions in the Analysed Period

In January 2012, the level of water at the Włocławek water gauge showed low values with an upward trend to medium level (Figure 3). At the end of January and in February, the air temperature dropped below zero, which resulted in a rapid development of ice cover on the Vistula [49]. Warmer weather at the end of February and in March contributed to increasing the water level as a result of ice melting in the river, melting of the ice cover in the catchment basin, and rainfall. In March and April, the water level was close to medium level. In May and at the beginning of June 2012, low water levels were recorded with an increase to medium level from mid-June. This increase was due to heavy rainfall during storms. From July to September, the level of water gradually decreased and was classified as low. In October and November, the level of water increased but was still low. In December, ice phenomena, such as frazil ice, appeared on the Lower Vistula.

In 2012, emergency discharge of water from the dam in Włocławek was carried out three times: in May, June, and November. In May, over 57 h the flow of water through the dam was stopped twice in connection with technical works. The level of water at the dam decreased by 74 cm over 10 h, increased by 161 cm over 20 h, then decreased again by 185 cm over 7 h and increased again by 107 cm over the following 17 h. The maximum increase in water level was 23 cm h^{-1}, and the maximum decrease in water level was 44 cm h^{-1}. In June, water was discharged for transportation needs. The discharge took place at two intervals of several hours (the flow was stopped to replenish water in the

Włocławek reservoir). The maximum increase and the maximum decrease in water level were both 27 cm h^{-1}. The third emergency water discharge was made in November. This was connected with the passage of icebreakers from Gdańsk to Włocławek. In the case of that discharge, a one-time increase in water level occurred, followed by a decrease. The maximum increase in water level was 13 cm h^{-1}, and the maximum decrease in water level was 18 cm h^{-1}.

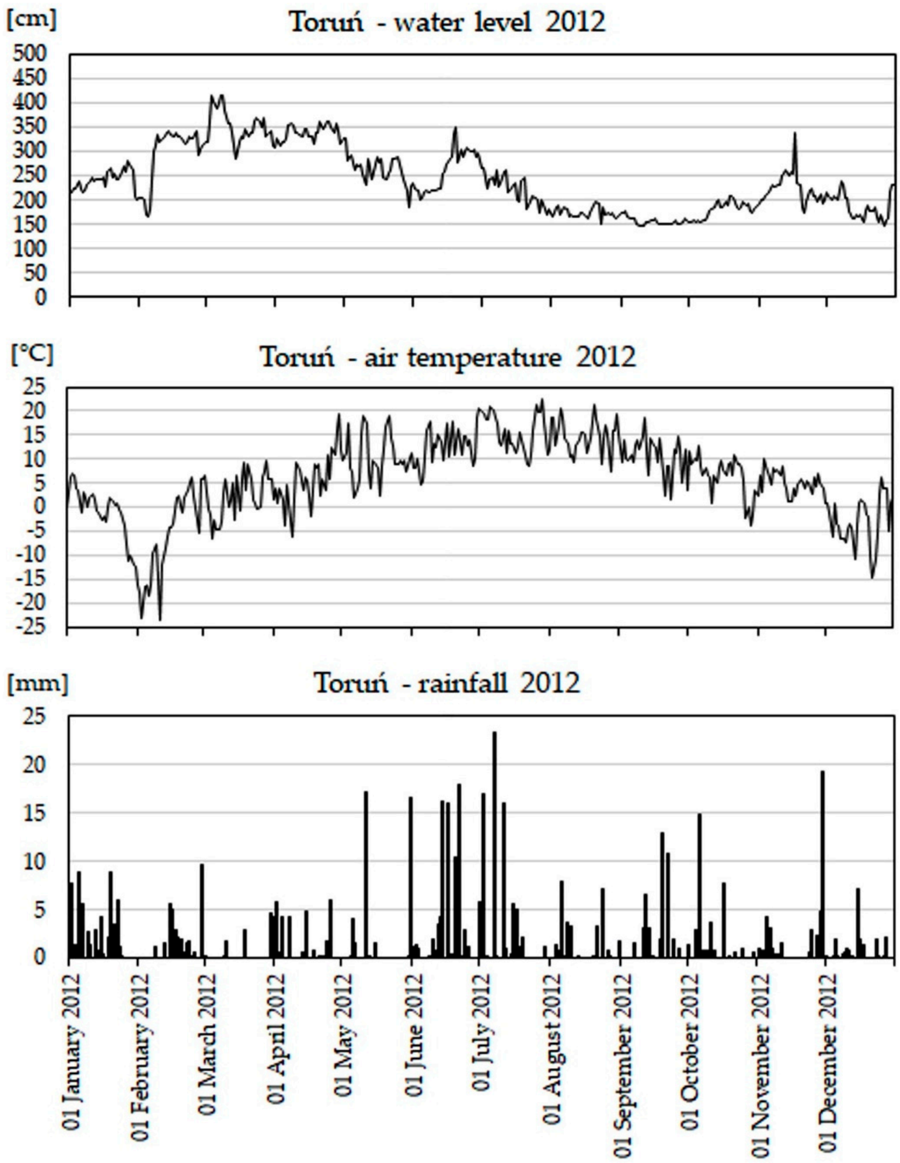

Figure 3. Water levels at the Toruń water gauge, year 2012, and air temperature and precipitation at Toruń Meteorological Station 12250 WMO (World Meteo Orgnisation), year 2012. Own elaboration. Data source: www.pogodynka.pl.

3.2. Byzie Site

On the date on which the pit was made on the Byzie site (19 October 2012), the level of water in the Vistula in Włocławek was 172 cm. The highest part of the bar head was 110 cm above the water table, so it was assumed that the bar emerged above the water table when the water level was 280 cm (Figure 4). Analysis of sedimentary structures in the pit and analysis of the water level showed that the reactivation surface was formed during a sudden decrease in water level (Figure 5). Over 7 h after the emergency discharge in May 2012, the level of water decreased by 185 cm (the maximum decrease over an hour was 44 cm). This led to the formation of a thin layer of silt with a thickness ranging from 0.5 to 1 cm. The head of the sand bar was also above the water table when the water level was 280 cm. Until 25 May 2012, the highest parts of the sand bar were flooded by a thin (5–7 cm) layer of water more than once. Due to the location of the bar at the left bank of the river channel—out of the mainstream—conditions for water stagnation and very poor flow existed, which resulted in the deposition of another thin (1–2 cm) layer of silt and silty sand and very fine sand. These deposits form a reactivation surface composed of sediments from the emergency discharge made on 18–20 June 2012.

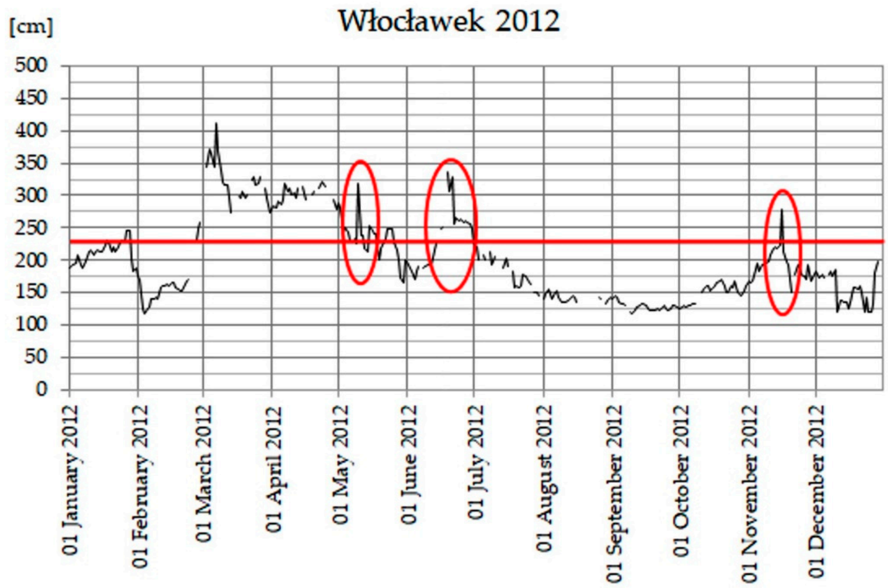

Figure 4. Water levels at the Włocławek water gauge. Red ellipses—emergency discharge, red line—flooding of the channel bars.

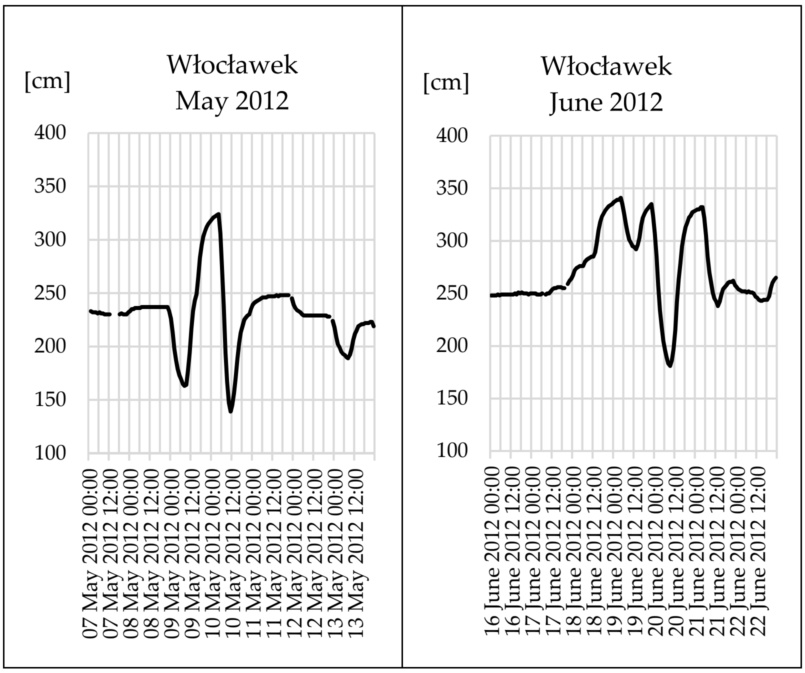

Figure 5. Water levels at the Włocławek water gauge during emergency discharge from the dam in Włocławek. Own elaboration. Source: www.pogodynka.pl.

The movement of 2D dunes across the surface increased the height of the sand bar by about 0.3 m. This process was fostered by increases in the level of water and flow rate: the first on 18 June 2012 and the second on 20 June 2012 (Figure 5).

The emergency water discharge in June 2012 resulted in displacement of the bar head by 2.2 m over 81 h—that is, 0.65 m/24 h^{-1}.

Sedimentary structures exposed in the pit on the Byzie site reflect the emergency discharges from May and June 2012. In the vertical section, 75 cm-thick foreset *Sp* structures inclined at an angle of 28°–30° are predominant. Sediments of those structures were formed in May 2012 and consist of medium-grained sand with grain size D_{50} = 0.33–0.39 mm (Figure 5). They are well sorted. The foreset bed *Sp* structures are covered with sediments of low-energy *Sp* megaripples and *St* shallow troughs connected with a decrease in the flow rate at the end of the emergency discharge. These sediments are also built of medium-grained sand with grain size D_{50} = 0.44 mm. They are moderately sorted. These structures are overlain by a 0.02 m-thick reactivation surface composed of a thin layer of *Fl* silt covered by medium-grained sand. A layer of silt reflected in the reactivation surface was formed during a fast decrease in water level (157 cm over 5 h, max. 44 cm in one hour). The grain size D_{50} in the reactivation layer is smaller than in *Sp* structures. The reactivation layer is moderately and moderately well sorted. Silt making the reactivation surface is covered by a layer of sand (2 cm) deposited over several hours during which the surface of the bar was under a thin layer of water (Figure 6). The reactivation surface is overlain by foreset *Sp* structures formed as a result of the emergency discharge from June 2012. The structures are built of medium-grained sand with grain size D_{50} = 0.36–0.48 mm. They are well and very well sorted. The ceiling of foreset *Sp* structures contains layers of coarse-grained and very coarse-grained sand with grain size D_{50} = 0.86–1.09 mm. They are moderately sorted and poorly sorted. Their presence in the lower portion of the foreset structures is due to gravity falling of coarser grains on the downstream slope of the bar. During the emergency discharge in June, *Sp* and *St* megaripples (2D dunes) migrated across the surface of the bar. They featured planar cross-stratification with a thickness of up to 10 cm. Sediments of these ripple marks are coarse-grained and have a similar grain size D_{50} = 0.53–0.55 mm. Their sorting is moderate and moderately good.

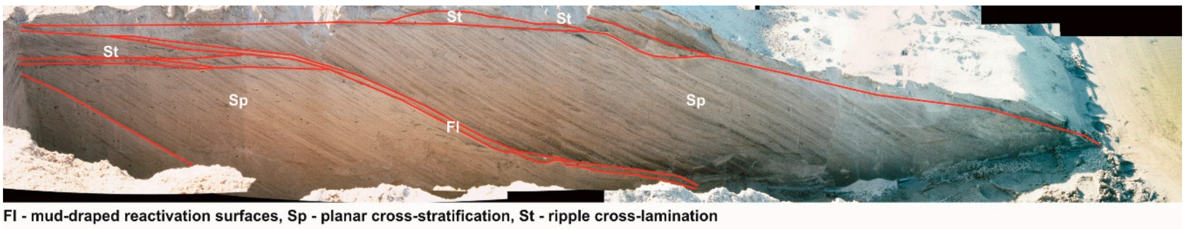

Figure 6. Sedimentary structures-Byzie bar head 19 October 2012.

The sediments of 2D and 3D dunes feature coarser grains and are sorted worse than sediments of *Sp* large-scale cross-stratified (foreset) structures associated with gravity falling of sand on the downstream slope of the channel bar.

3.3. Solec Kujawski Site

Pits on the Solec Kujawski site were made on 2 and 20 November 2012. The water level on both dates was about 160 cm at the Bydgoszcz Fordon water gauge, which is the closest water gauge to the Solec Kujawski site. The sedimentary structures of the transverse bar on the Solec Kujawski site reflect three emergency discharges from May, June, and November 2012 (Figures 7 and 8). The discharge from May was recorded at a distance of 21–24 m from the bar head, and the emergency discharge from June could be seen in the pit made in the bar head on 2 November 2012, whereas emergency discharges from both June and November were reflected in the pit made in the bar head on 20 November 2012.

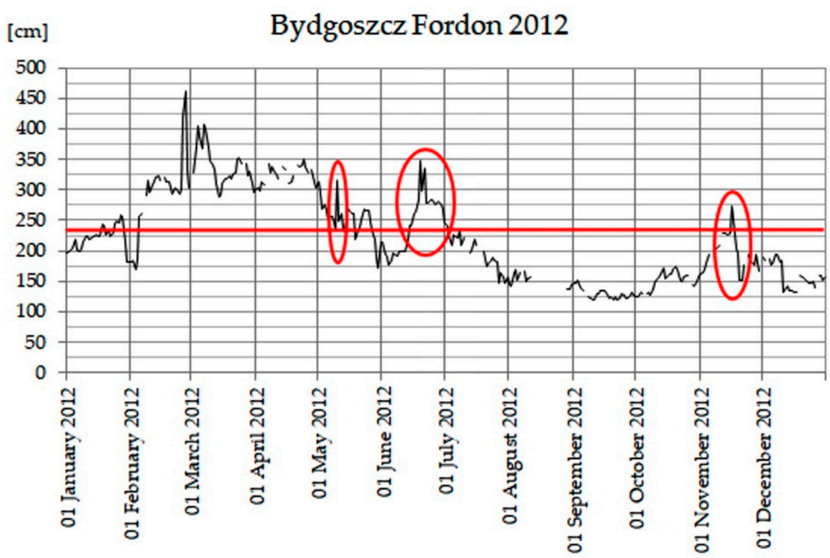

Figure 7. Water levels at the Bydgoszcz Fordon water gauge. Red ellipses—emergency discharge, red line—flooding of the channel bars.

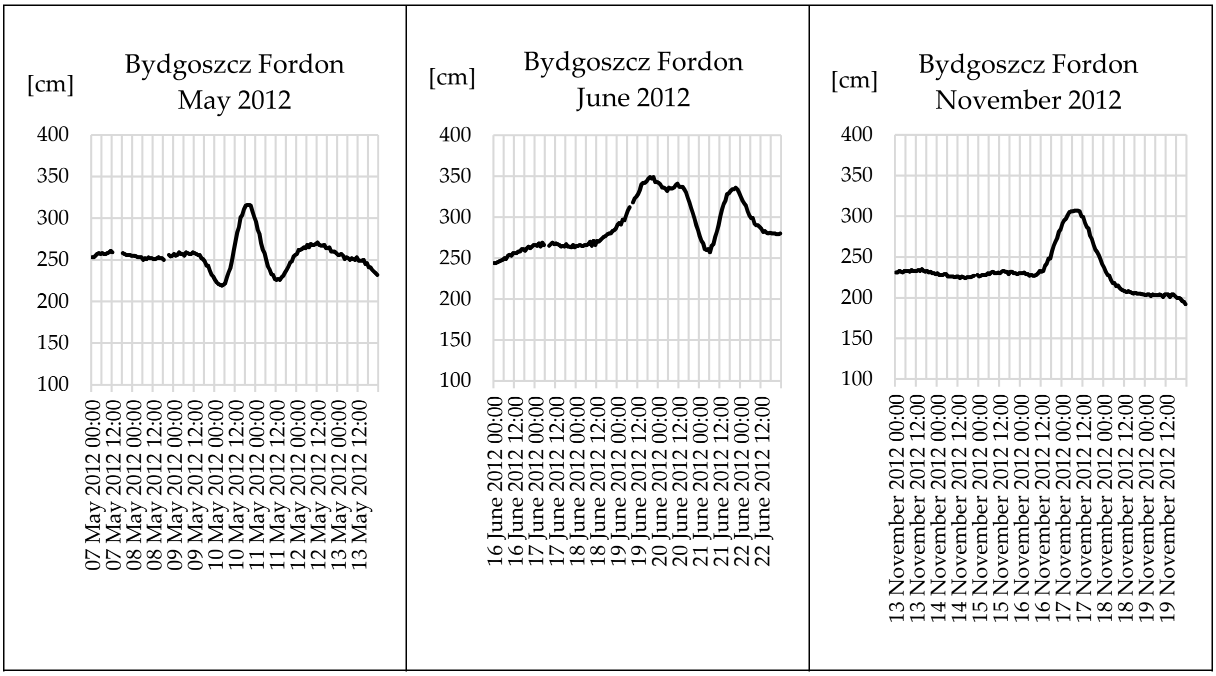

Figure 8. Water levels at the Bydgoszcz Fordon water gauge during emergency discharge from the dam in Włocławek. Own elaboration Source: www.pogodynka.pl.

3.3.1. Pits Made on 2 November 2012

The first pit was 21–23 m away from the bar head. It contained sedimentary structures reflecting the bar head formed in May 2012. Sediments of that bar head were composed of medium-grained sand with grain size D_{50} = 0.29–0.38 mm. Medium-grained sand was well sorted. The bar head featured structures deposited at an angle of 8°–10° (Figure 9). The bar head structures from May 2012 are overlain with *Sp* large-scale cross-stratified structures associated with the emergency discharge from June 2012. Initially, they are inclined at an angle of 20°, and further the angle of inclination of the strata increases to 28–30°. The lower portion of these structures is built of coarse-grained sand with grain size D_{50} = 0.51 mm that is moderately and moderately well sorted. The presence of coarse-grained sand is connected with gravity movement of coarser grains on the downstream slope of the bar. The upper portion of *Sp* stratified structures is built of medium-grained sand with grain size D_{50} = 0.34–0.39 mm. The sand is well sorted. *Sp* structures are overlain by three sets of structures associated with the movement of planar megaripples (2D dunes) across the surface of the bar. Each set is about 8–10 cm thick. The ceiling of *Sp* structures is cut by erosion. The sediments of planar megaripples (2D dunes) consist of medium-grained sand with an addition of coarse-grained sand with grain size D_{50} = 0.44–0.57 mm. The sand is moderately and moderately well sorted. Samples were also taken from a thin (1 cm) layer of sand covering the surface of the bar. This was coarse-grained sand with grain size D_{50} = 0.56–0.62 mm, moderately and moderately well sorted. The presence of coarse-grained sand on the surface of the bar is associated with finer fractions being blown out by the wind and the formation of aeolian deposits. From the beginning of July until November, the bar was underwater.

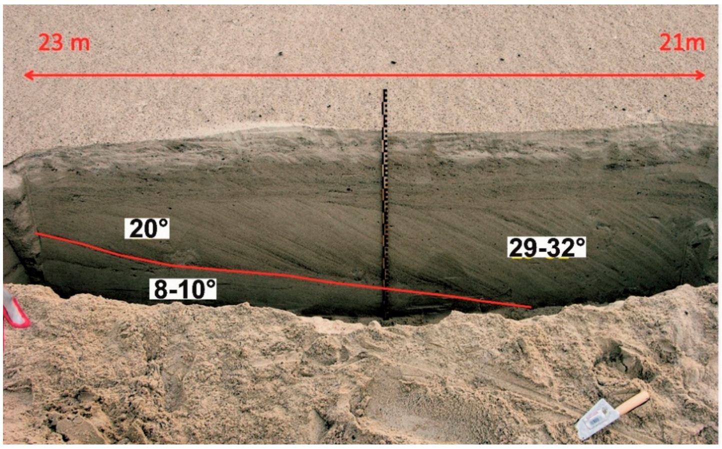

Figure 9. Sedimentary structures in the first pit.

The second pit was made in the bar head on 2 November 2012. The pit contained *Sp* large-scale cross-stratified structures reflecting the emergency discharge from June 2012 (Figure 10). The dip angle was 28°–30°. The *Sp* structures were built from medium-grained sand with grain size D_{50} = 0.31–0.43 mm (on average 0.36 mm). Samples collected from the surface were composed of medium- and coarse-grained sand with grain size D_{50} = 0.41–0.53 mm. The sand was moderately well sorted. Small ripple marks associated with a thin layer of water covering the sand bar and a low rate of flow moving across the surface of the bar were observed. The bar head was displaced by 22 m in June. The surface of the sand bar was underwater for 436 h. This results in the bar being displaced by 1.21 m/24 h^{-1}.

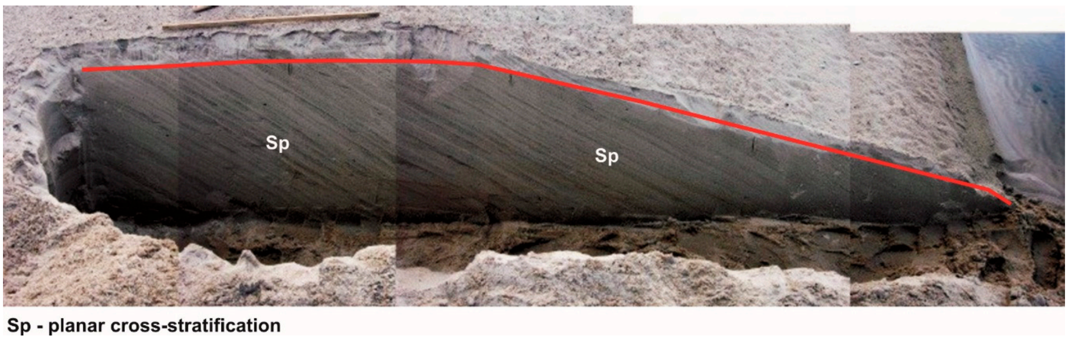

Figure 10. Sedimentary structures in the channel bar head—2 November 2012.

3.3.2. Pit Made on 20 November 2012

Sediments of the bar head deposited in June 2012, exposed in the third pit, are sediments included in fluvial transport at the initial stage of increase in the water level and flow rate due to the emergency discharge from November 2012. They can be clearly seen in the pit on the reactivation surface as medium-grained laminated deposits with an addition of coarse-grained sand. Their grain size is similar to that of 3D dunes. The grain size D_{50} of these sediments is 0.46 mm and they are moderately well sorted. At a further stage of increase in the water level, *Sp* large-scale cross-stratified structures were formed (Figure 11). Their grain size is finer than that of structures covering the reactivation surface. This is medium-grained sand with grain size D_{50} amounting to 0.35–0.42 mm. The gradient of *Sp* structures is 28°–30°. In the cross-section of the bar, *Sp* structures are overlain by two sequences of megaripples (3D dunes). They were formed during the emergency discharge of water in November 2012 when the water level and flow rate rapidly increased. Due to high water energy, the sediments were transported across the bar surface forming megaripples (3D dunes). The ceiling portion of the *Sp* bar was scoured to a depth of 25 cm and then covered with the sediments of migrating megaripples (3D dunes) with parasitic ripples on their surface. The megaripples are 15–20 cm thick and have a span of 2–2.5 m. The megaripples (3D dunes) are built of medium-grained sand with grain size D_{50} amounting to 0.41–0.49 mm. They are usually moderately well sorted and less often well and moderately sorted.

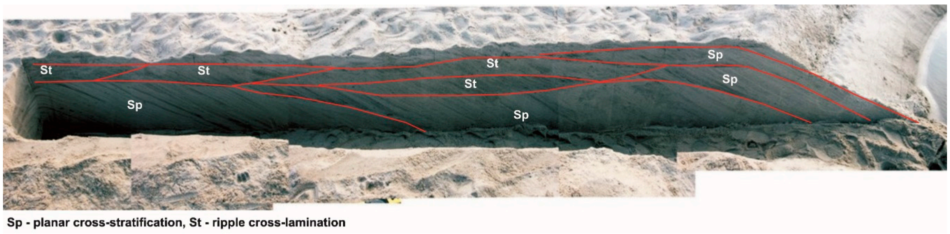

Figure 11. Sedimentary structures in the channel bar head—20 November 2012.

The bar head also reflects two sequences associated with the megaripples (3D dunes) crossing the bar head. Changes in the flow rate in the foreground of megaripples (3D dunes) led to scouring of the upper ridge of the bar head and forming of the reactivation surface. The average grain size D_{50} of these sequences of sediments was 0.43 mm. This was medium-grained, well and moderately well sorted sand. During the emergency discharge of water in November 2012, the bar head was displaced by 4.4 m over 32 h, which corresponds to 3.3 m in 24 h (Figure 12). It was the largest distance among the analysed sedimentary structures.

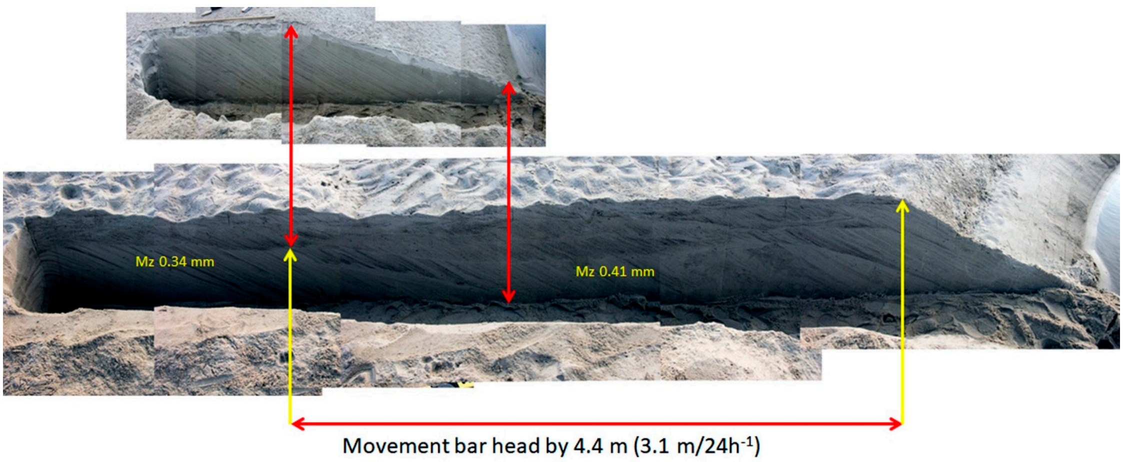

Figure 12. The record of bar head movement in sedimentary structures of the channel bar—20 November 2012.

3.4. Model of Emergency Discharges Recorded in the Sedimentary Structures of Channel Bars

The processes of erosion and accumulation connected with the movement of water and bed load transported on the bottom of the river lead to the formation of channel bars. The bars are created as a result of overloading the river with sediment load and a sudden loss of the river's transport capacity. Studies and field observations provided data for determining the stages of emergency discharges from the dam in Włocławek reflected in the sedimentary structures of channel bars in the lower flow regime of the River Vistula.

Stage 1. Emergence of bars

The starting point is the high waters at the end of winter and in early spring when snow melts in the mountains and the meltwater runs off into the Vistula. All the channel bars are then under the water and move downstream. After the spring swell, the water level in the Vistula gradually drops. The first, the highest bars emerge when the water level is about 250–280 cm (Figure 13A). There are several such bars in the analysed section (3–5). The largest number of bars can be seen in the channel of the lower flow regime of the Vistula when the water level falls below 180 cm (Figure 13B). There can be 50–80 bars along the analysed section of the river (100 km). The end of the swell is recorded in the sedimentary structures as large-scale cross-stratification with a thickness ranging from 60 to 120 cm depending on the height of the bar. When the water level drops and the bar emerges, its surface shows clear freshly formed 2D dunes and 3D dunes with parasitic ripples on their surface (Figure 13A,C).

Stage 2. Surface transformation

The emerged surface of channel bars in the Vistula dries out. Aeolian processes smoothing the surface of the bars can often be observed (Figure 13D,E). Aeolian transport of sand building the surface portion of the bar initially leads to erosion of the ridges of parasitic ripples (Figure 13F,G) and then also of 2D dunes and 3D dunes (Figure 13H,I) and recesses between ripple marks are filled with sand. The finest-grained sand is blown out into the water and included in fluvial transport again. If the bars are emerged for a long time, their surface becomes flat and is covered with aeolian deposits with grain size D_{50} = 0.5–2 mm. At the topmost parts of the bars, the coarsest-grained aeolian deposits form so-called granule ripples [50] (Figure 13J). The surface of the bars is also transformed by birds often sitting on sand bars in whole flocks. In addition, traces of beavers, foxes and other migrating animals were observed. Traces of animals and birds are not reflected in the sedimentary structures of channel bars (Figure 13K).

Stage 3. Submergence of bars

During the emergency discharge of water from the dam in Włocławek, the water level and kinetic energy of the river increase rapidly. The surface of the bar is subject to fluvial erosion. At this stage, erosive reactivation surface is created on the bar head. Erosion cuts the structures existing on the channel bar surface and the released grains are transported to the bar head. Sand moving across the surface (2D and 3D dunes) falls due to gravity on the bar head forming subsequent large-scale cross-stratification (Figure 13L). For 2D dunes, the grains fall by gravity right to the foot of the bar and are overlain by medium-grained laminated sand. For 3D dunes, coarse-grained sand lamination is also formed. The surface of the bar is covered by one or more lamination sets formed during the migration of megaripples. At this stage, fine-grained (granule) gravel fractions accumulated in the recesses between 3D dunes are also dragged across the surface of the bars.

Stage 4. Emergence of channel bars

End of emergency discharge. At this stage, depending on the method of ending the discharge (decreasing the flow or suspending the flow on the dam in Włocławek for a few hours), the level of water drops by several to several dozen centimetres in an hour. Fresh bedforms can be seen on channel bars emerging from the water. These are most often megaripples (2D dunes and 3D dunes) with parasitic ripples. The type of bedform reflects the flow conditions that dominated on the bar during the discharge of water. The fresh bedforms (Figure 13M–O) are clearly recorded in the sedimentary structures exposed in the pits. At the same time, a new bar head is formed with an accumulative reactivation surface (silt). During the next increase in the water level the bar head can become an erosive reactivation surface. In bars situated next to the bank of the channel (out of the mainstream), the bar head surface can be covered with a thin layer of silt formed during a rapid decrease in the water level.

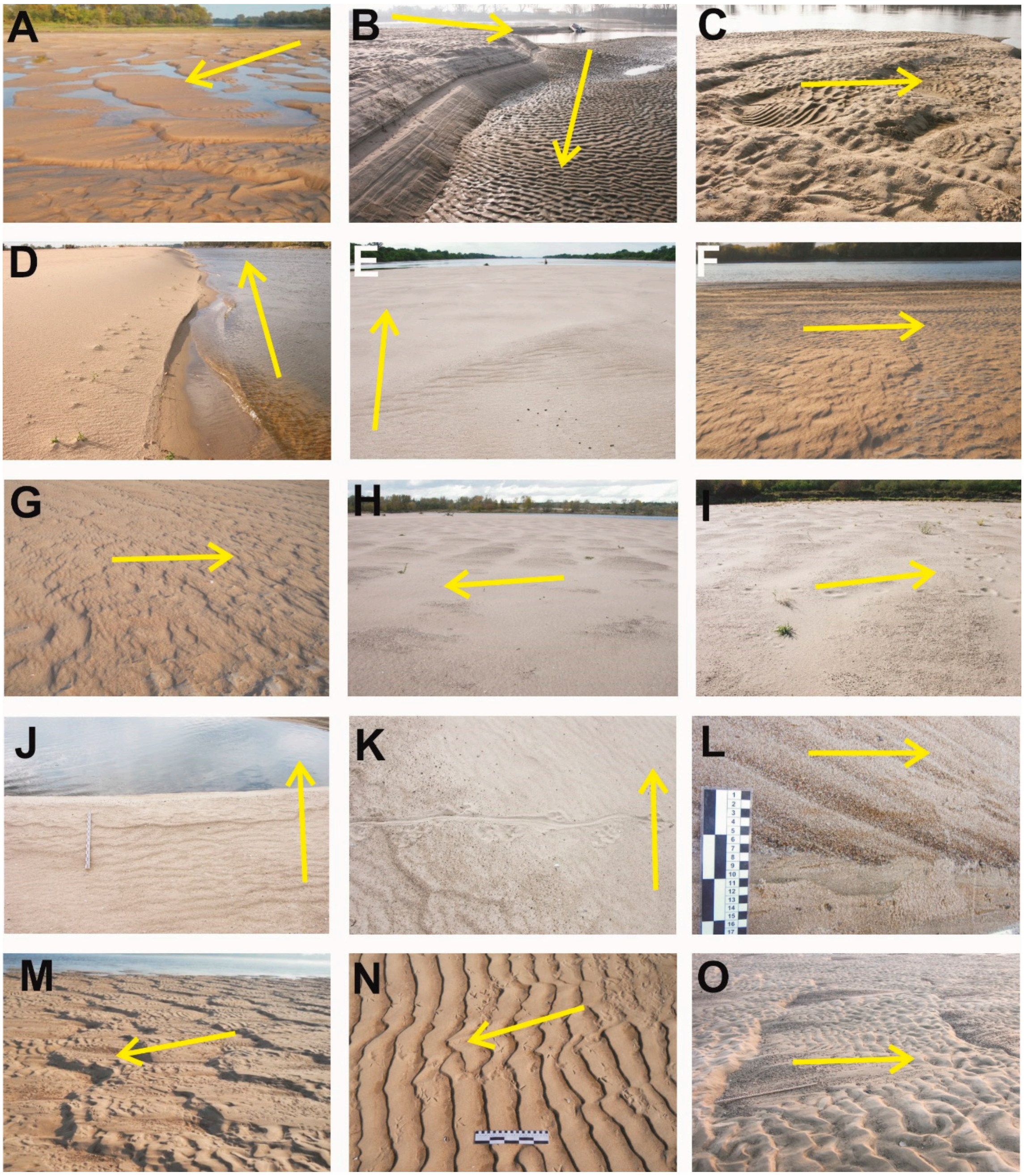

Figure 13. Types of bedforms on channel bars. The yellow arrow marks the water flow. (**A**)—the surface of the bar after lowering the water level with clear freshly formed 2D dunes, (**B**)—bar surface during lower flow regime, (**C**)—clear freshly formed 3D dunes with parasitic ripples on their surface, (**D**,**E**)—aeolian processes on bars, (**F**,**G**)—aeolian erosion of parasitic ripples, (**H**,**I**)—aeolian erosion and accumulation of 2D dunes and 3D dunes, (**J**)—coarsest-grained aeolian deposits (granule ripples), (**K**)—traces of a beaver on the bar, (**L**)—large-scale cross-stratification, (**M**–**O**)—typical fresh bedforms on the analyzed bars.

4. Discussion

Changes within river channels are caused by natural and anthropogenic factors. These factors contribute to the occurrence of various geomorphological processes within the river channel and during swells also on the plane bed of the flood plain. One of the anthropogenic factors is water dams dividing the river channel which leads to changes in the transport of sediments and the shape of the river channel before and downstream of the dam [12]. Erosion processes activate sediments downstream of the dam that, transported by saltation, suspension and creep, constitute the material building channel bars. Downstream of the dam in Włocławek (674.9 km), an erosion zone was formed which in 2016 reached the section 720–740 km along the Vistula [18]. During the initial years of operation of the hydroelectric power plant, the erosion zone moved at a speed of 2.3 km year^{-1} [21]. In 1973–1984, the rate of movement of this zone dropped to 0.6–2.3 km year^{-1} and increased back to 2.7 km year^{-1} in 1985–1987 [21]. At present, the rate of movement of the erosion zone is estimated at 2.2 km year^{-1} [51]. The volume of transported load ranged between 0.5 and 1.6 million m^3 a year. The accumulation zone downstream of the erosion zone (740 km) leads to the emergence of channel bars obstructing navigation.

Water dams operating in the river ecosystem give rise to a number of environmental changes. Initially, the hydroelectric power plant in Włocławek generated power through two discharges of water a day [22]. This resulted in intense riverbed erosion downstream of the dam [9]. At present, the run-of-the-river mode of power generation is a preferred solution worldwide [19]. This is also the operating mode of the power plant in Włocławek (with the exception of emergency water discharges) [22]. The operation of the water dam in Włocławek brought about environmental changes, including partial retention of suspended sediments, complete retention of bedload sediments, lateral erosion within the storage reservoir, changes in groundwater level before and after the dam, riverbed erosion and formation of a new flood plain downstream of the dam, and inhibited migration of fish [21]. The possibility of fish migration was restored in 2014 due to the construction of a so-called fishway [52]. Sedimentary structures in channel bars reflect the flow of water. The classification of sedimentary structures refers to the works of [46–48]. The lithofacies code used in structure identification points to similarities with other studies [34,53]. Refs. [34,53] gave a very detailed description of the internal structures of channel bars. The Vistula features different hydraulic parameters to the River Saskatchewan [32]. The sedimentary structures alone are notable. The results obtained during exploration of sedimentary structures indicate that changes in the flow due to natural and anthropogenic factors are reflected identically in the strata of channel bars.

The record of sedimentary structures in channel bars should be backed up by grain-size analysis also indicating changes in the flow rate of water in the longitudinal and vertical section. Works involving the grain-size analysis of sediments in the Vistula [29,54] corroborate the effect of changes in the flow on grain size distribution in the sediments. However, the number of samples analysed and the sampling methods (one sample every 5 km of the river) [29,54] do not clearly point to options of interpreting the water flow in the river channel. The grain-size analysis carried out for this study was based on 160 samples from two bars. The results of grain-size analysis point to variation in sediment fractions and can be correlated with a previous work of the authors [31].

Sedimentation indicators presented by Folk and Ward [42] such as mean grain size (Mz) and sorting (∂_1) are most often described in works based on grain-size analysis. In the previous studies concerning the valley of the lower Vistula [29,31,54], they were taken into account in changes of the sedimentary environment of the selected sections of the river. The share of medium-grained sand fraction is the largest. In addition, medium-grained sand with an addition of coarse-grained sand and sporadically coarse-grained sand alone was found. Similar results of grain-size analysis in channel bars were presented in other studies [29,31,54]. Coarse-grained sand having a small share in the analysed forms points to energy changes during the flow of water.

Sorting is an indicator describing the process of transport and accumulation. The degree of sorting indicates the conditions in which the movement of grains starts. The better the sorting, the smaller the energy variation in the environment. In works presenting results of the analysis of grain-size of sediments in the Vistula [29,54], the sediments are moderately and poorly sorted. In the work by [31], sediment is described as well sorted. Differences are due to the number of analysed samples and sampling places. In this work, sediment is described as moderately well sorted. Sorting points to a variation in the energy environment but changes in the structure of sediments building the bars indicate that there were considerable differences in the energy environment and the sedimentation process alone (content of coarse-grained fraction and the addition of fine-grained sand). Therefore, it is advisable to analyse as many sediment samples from a single bedform as possible.

The processes of bedform erosion are conditioned by the variability of the flow of water in the channel. Studies show that it is possible to determine the flow rate of water leading to relief transformations of bedforms [27]. Based on the analysis of changes in the water level in the Vistula caused by natural factors (rainfall), flow rate values leading to erosion and displacement of bedforms within the area of the bars were determined [27]. They indicate that the movement of ripple marks across the bars occurs when the flow rate oscillates from 0.17 to 0.48 m s^{-1}. The formation and migration of dunes on the bars occurs at flow rates ranging from 0.48 to 1.1 m s^{-1}. When the value of 1.1 m s^{-1} is exceeded, erosion processes become dominant and transform all accumulative forms. These results can be referred to the analysis of changes in the flow recorded in sedimentary structures of bars analysed in this work. During field studies, ripple marks and megaripples such as 2D dunes and 3D dunes were found on the surface of the bars. They are also reflected in the sedimentary structures. This points to variations in the flow of water after the discharge which caused their displacement. Erosive surfaces formed by water flowing faster than 1.1 m s^{-1} are perfectly visible. A flow rate exceeding 1.1 m s^{-1} should be associated with the second smooth phase leading to erosion of all forms on the surface of channel bars.

Reactivation surfaces [55] are an important indicator of changes in the water level and flow rate. The formation of reactivation surfaces is also associated with changes in the direction of water flow in the river channel [56,57]. The low level of water above the surface of the channel bar leads to rounding of the bar ridge, and when the water level rises again, the sand falls on the downstream slope [55]. Then lamination occurs parallel to previous lamination (formed during a decrease in flow) and is called the minor reactivation surface [34]. It is formed during the migration of low-amplitude superimposed dunes or superimposed ripples [34]; that is, 2D dunes and small ripple marks. The minor reactivation surface is built of fine- and medium-grained well sorted sand. In the study carried out at the Byzie site, the minor reactivation surface was composed of a thin mud-draped layer (ca. 2 mm) covered with a layer of fine-grained sand (ca. 15–20 mm). This minor reactivation surface was most likely formed by very slowly flowing or stagnant waters above the channel bar (the bar on the Byzie site was located towards the left bank of the Vistula, out of the mainstream). In this case, the minor reactivation surface built of mud-draped and fine-grained sand can be deemed an accumulative reactivation surface.

The formation of reactivation surfaces was analysed in the conditions of natural flow (without human interference) [32,34,55,56], when the water level and flow rate increase slowly. Emergency discharges of water from the dam in Włocławek lead to a sudden increase in the water level and flow rate in the Vistula, so the kinetic energy of the river and its erosive capacity grow rapidly. This leads to erosion of the surface of the channel bar, release of sand and its transportation in the migrating 3D dunes. Bar surface erosion is reflected in sedimentary structures as a major reactivation surface [34]. When 3D dunes migrate, the coarse-grained moderately and poorly sorted sand is also transported and accumulates on the erosive reactivation surface.

The reactivation surfaces and sedimentary structures formed under natural conditions and during emergency discharges of water make it possible to determine the distance by which the channel bar is displaced. The record of emergency discharge of water in sedimentary structures is very significant since it reflects specific changes in the water level and flow rate. On the Vistula, the channel bar at the Byzie site (the bar next to the left bank of the Vistula, out of the mainstream) was displaced by 0.65 m in 24 h during the emergency discharge in June 2012. On the other hand, at the Solec Kujawski site, an alternating transverse bar [13] situated in the centre of the channel of the Vistula River was displaced by 1.21 m in 24 h. The difference in distance is due to the longer time of the channel bar remaining submerged. The longer time of submergence of the channel bar was connected with the fact that the further from the dam in Włocławek, the more flattened and elongated the wave became [30]. The distance is similar to the distance measured by [25]. The largest distance by which the sand bar was displaced over 24 h was 3.3 m at the Solec Kujawski site after the emergency discharge in November 2012. The distance is not average and is referred to as a threshold connected with sudden changes in the river channel [13].

5. Conclusions

These studies indicate that emergency discharges are recorded in channel bar sediments. The thickness and structural features of sediments within the bars are similar. Changes in the grain size of sedimentary structures are associated with flow rate changes during the emergency discharge of water.

Reactivation surfaces are not erosive forms at all times. They can also be accumulative forms, such as a thin layer of silt precipitated during a rapid decrease in the water level. The presence of silt associated with rapid decreases in the level of water can be observed at a distance of several dozen kilometres from the dam due to a decrease in the kinetic energy at greater lengths from the dam and the flattening of the wave formed during the emergency discharge. Mud-draped reactivation surfaces can also occur in sedimentary structures of channel bars located next to the river bank, out of the mainstream.

The structures and the duration of water discharge can be used to estimate the distance by which an accumulative transverse channel bar is displaced. The displacement of bar heads ranged from 0.65 to 3.3 m over 24 h. This variation is due to the location of the bar in the river channel and the dynamics of the flow. The lowest values of displacement of the bar head were recorded at the bank of the river (away from the mainstream) on the Byzie site. The largest displacement of the bar was noted in the central part of the river channel on the Solec Kujawski site.

Variations in the conditions of transport and accumulation of sediments are visible along the whole section of the Vistula downstream of the dam in Włocławek. Further studies are required in order to unambiguously determine the processes of erosion, transport and accumulation of channel sediments.

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References

1. Grześ, M. *Ice Jams and Floods on the Lower Vistula River*; Institute of Geography and Spatial Organization Polish Academy of Sciences: Warsaw, Poland, 1991; ISBN 83-00-03450-1.
2. Pawłowski, B. *Course of Ice Phenomena on the Lower Vistula River in 1960–2014*; Nicolaus Copernicus University Press: Toruń, Poland, 2017; ISBN 975-83-231-3885-3.
3. Petley, D.N.; Rosser, N.J.; Karim, D.; Wali, S.; Ali, N.; Nasab, N.; Shaban, K. *Non-Seismic Landslide Hazards along the Himalayan Arc*; Williams, A.L., Pinches, G.M., Chin, C.Y., McMorran, T.J., Massey, C.I., Eds.; Geologically Active; CRC Press: London, UK, 2010; pp. 143–154.
4. Cui, P.; Dang, C.; Zhuang, J.-Q.; You, Y.; Chen, X.-Q.; Scott, K.M. Landslide-dammed lake at Tangjiashan, Sichuan province, China (triggered by the Wenchuan Earthquake, 12 May 2008): Risk assessment, mitigation strategy, and lessons learned. *Environ. Earth Sci.* **2012**, *65*, 1055–1065. [CrossRef]
5. Rurek, M.; Śnieszko, Z.; Makohonienko, M. *Contemporary and Fossil Beaver Ponds in Small River Valleys on the Area of Bory Tucholskie (North European Plain)*; Kazimierz Wielki University Press: Bydgoszcz, Poland, 2016; ISBN 978-83-8018-109-0.
6. Śnieszko, Z.; Rurek, M.; Hojan, M. *The Role of Beavers in the Holocene Landscape Evolution of the Small River Valleys (the Tuchola Forest–North European Plain)*; Kazimierz Wielki University Press: Bydgoszcz, Poland, 2020; ISBN 978-83-8018-344-5.
7. Czech, A. *Bóbr–Budowniczy i Inżynier*; Foundation for the Support of Ecological Initiatives: Kraków, Poland, 2010; ISBN 978-83-62598-04-5.
8. Babiński, Z.; Grześ, M. *Hydrological Monograph of Włocławek Reservoir*; Institute of Geography and Spatial Organization Polish Academy of Sciences: Warsaw, Poland, 1995; p. 30. ISSN 0867-6836.
9. Babiński, Z. The influence of the water dam in Włocławek of fluvial processes of the Vistula River. In *Geographical Studies*; Institute of Geography and Spatial Organization Polish Academy of Sciences: Warszawa, Poland, 1982; pp. 1–2. ISSN 0012-5032.
10. Majewski, M. The development of hydro power in Poland. The most important hydro engineering facilities. *Acta Energetica* **2013**, 45–53. [CrossRef]
11. Kaniecki, A.; Ptak, M. Changes in the Noteć channel in its central section. *Bad. Fizjogr. Geogr. Fiz.* **2016**, 69–76. [CrossRef]
12. Suwal, N.; Huang, X.; Kuriqi, A.; Chen, Y.; Pandey, K.P.; Bhattarai, K.P. Optimisation of Cascade Reservoir Operation Considering Environmental Flows for Different Environmental Management Classes. *Renew. Energy* **2020**, *158*, 453–464. [CrossRef]
13. Babiński, Z. The present-day fluvial processes of the lower Vistula River. In *Geographical Studies*; Institute of Geography and Spatial Organization Polish Academy of Sciences: Warsaw, Poland, 1992; p. 157. ISBN 83-04-04016-6.
14. Banach, M. About the disturbance of bank evolution of reservoir in Włocławek. *Geogr. Work. Słupsk* **2007**, *3*, 95–106.
15. Banach, M. Dynamics of the lower Vistula banks. In *Geographical Documentation*; Institute of Geography and Spatial Organization Polish Academy of Sciences: Warsaw, Poland, 1998; p. 9. ISBN 83-86682-25-6.
16. Babiński, Z. The relationship between suspended and bed load transport in river channels. In Proceedings of the International Symposium held at the 7th Scientific Assembly of the International Association of Hydrological Sciences, Foz do Iguaçu, Brazil, 3–9 April 2005; pp. 182–188.
17. Gierszewski, P. Warunki transportu zawiesiny w Zbiorniku Włocławskim w świetle analizy jej składu i tekstury. *Nauka Przyr. Technol.* **2007**, *2*, 1–18.
18. Szatten, D.A.; Babiński, Z.; Habel, M. Reducing of Water Turbidity by Hydrotechnical Structures on the Example of the Wloclawek Reservoir. *J. Ecol. Eng.* **2018**, *19*, 197–205. [CrossRef]
19. Kuriqi, A.; Pinheiro, A.N.; Sordo-Ward, A.; Garotte, L. Water-Energy-Ecosystem Nexus: Balancing Competing Interests at a Run-of-River Hydropower Plant Coupling a Hydrologic–Ecohydraulic Approach. *Energy Convers. Manag.* **2020**, *223*, 113267. [CrossRef]
20. Kondolf, G. Hungry water: Effects of Dams and Gravel Mining on River Channels. *Environ. Manag.* **1997**, *21*, 533–551. [CrossRef]
21. Babiński, Z. *Impact of Dams on Fluvial Processes in Alluvial Rivers with Particular Emphasis on the Włocławek Water Level*; Kazimierz Wielki University Press: Bydgoszcz, Poland, 2002; ISBN 83-7096-423-0.
22. Gierszewski, P.J.; Habel, M.; Szmańda, J.; Luc, M. Evaluating effects of dam operation on flow regimes and riverbed adaptation to those changes. *Sci. Total Environ.* **2019**. [CrossRef]
23. Szatten, D.; Habel, M.; Babiński, Z.; Obodovskyi, O. The Impact of Bridges on the Process of Water Turbidity on the Example of Large Lowland Rivers. *J. Ecol. Eng.* **2019**, *20*, 155–164. [CrossRef]
24. Knighton, D. *Fluvial Forms and Processes—A New Perspective*, 1st ed.; Arnold: London, UK, 1998; ISBN 034066313.
25. Simon, A.; Curini, A.; Darby, S.E.; Langendoen, E.J. Bank and near-bank processes in an incised channel. *Geomorphology* **2000**, *35*, 193–217. [CrossRef]
26. Hooke, J.M. Spatial variability, mechanisms and propagation of change in an active meandering river. *Geomorphology* **2007**, *84*, 277–296. [CrossRef]
27. Strużyński, A.; Wyrębek, M.; Nowak, A.; Woś, A.; Florek, J.; Książek, L. Sand Island Reshaping in Response to Selected Discharges: The Vistula River Returning to Its Natural State. In *Recent Trends in Environmental Hydraulics*; Kalinowska, M., Mrokowska, M., Rowiński, P., Eds.; Springer: Cham, Switzerland, 2020; pp. 263–275. ISBN 978-3-030-37105-0. [CrossRef]
28. Kociszewska-Musiał, G. The Grain-Size of Channel Deposits of the Vistula. In *Evolution of the Vistula River Valley during the Last 15000 Years. Part III*; Starkel, L., Ed.; Geographical Studies SI 5; OSSOLINEUM The Publishing House of the Polish Academy of Sciences: Wrocław, Poland, 1990; pp. 76–79. ISBN 83-04-01236-7.

29. Giriat, D. Impact of the Water Stage in Włocławek on Selected Texture Features of Riverbed Sediments, on the Włocławek-Grudziądz Section. Ph.D. Thesis, University of Warsaw, Warsaw, Poland, 2003.
30. Habel, M. *Zasięg oddziaływania stopnia wodnego we Włocławku na wahania stanów wód dolnej Wisły*; Monografie Komitetu Inżynierii Środowiska PAN: Warsaw, Poland, 2010; Volume 68, pp. 251–261. ISBN 978-83-89293-93-0.
31. Hojan, M.; Rurek, M. Particle-size distribution of channel bars of the lower Vistula between Bobrowniki and Bydgoszcz-Fordon. *Geogr. Tour.* **2017**, *5*, 97–104. [CrossRef]
32. Reesink, A.J.H.; Bridge, J.S. Evidence of bedform superimposition and flow unsteadiness in unit bar deposits, South Saskatchewan River, Canada. *J. Sediment. Res.* **2011**, *81*, 814–840. [CrossRef]
33. Babej, J.; Omáčka, Z.; Ondrejka, P.; Peterová, P. Surface grain size variation within gravel bars: A case study of the River Opava, Czech Republic. *Geogr. Fis. Din. Quat.* **2016**, *39*, 3–12. [CrossRef]
34. Herbert, C.M.; Alexander, J.; Amos, K.J.; Fielding, C.M. Unit bar architecture in a highly-variable fluvial discharge regime: Examples from the Burdekin River, Australia. *Sedimentology* **2020**, *67*, 576–605. [CrossRef]
35. Ciszewski, D.; Malik, I.; Wardas, M. Geomorphological influences on heavy metal migration in fluvial deposits: The Mała Panew River valley (southern Poland). *Geol. Rev.* **2004**, *52*, 163–174.
36. Macklin, M.G. Fluxes and storage of sediment-associated heavy metals in floodplain systems: Assessment and river basin management issues at a time of rapid environmental change. In *Floodplain Processes*; Anderson, M.G., Walling, D.E., Bates, P.D., Eds.; John Wiley & Sons: Chichester, UK, 1996; pp. 441–460.
37. Szabó, Z.; Buró, B.; Szabó, J.; Tóth, C.A.; Baranyai, E.; Herman, P.; Prokisch, J.; Tomor, T.; Szabó, S. Geomorphology as a Driver of Heavy Metal Accumulation Patterns in a Floodplain. *Water* **2020**, *12*, 563. [CrossRef]
38. Ciszewski, D. Channel processes as a factor controlling accumulation of heavy metals in river bottom sediments: Consequences for pollution monitoring (Upper Silesia, Poland). *Environ. Geol.* **1998**, *36*, 45–54. [CrossRef]
39. Ladd, S.C.; Marcus, W.A.; Cherry, S. Differences in trace metal concentrations among fluvial morphologic units and implications for sampling. *Environ. Geol.* **1998**, *36*, 259–270. [CrossRef]
40. Strzebońska, M.; Kostka, A.; Helios-Rybicka, E.; Jarosz-Krzemińska, E. The effect of flood on heavy metals contamination of the Upper Vistula River floodplain sediments in Kraków; historical mining and smelting as the most important source of pollution. *Pol. J. Environ. Stud.* **2015**, *24*, 1317–1326. [CrossRef]
41. Rice, S.P.; Church, M. Grain-size sorting within river bars in relation to downstream fining along a wandering channel. *Sedimentology* **2010**, *57*, 232–251. [CrossRef]
42. Folk, R.L.; Ward, W.C. Brazos River bar: A study in the significance of grain size parameters. *J. Sediment. Res.* **1957**, *27*, 3–26. [CrossRef]
43. Babiński, Z.; Habel, M. Hydromorphological conditions of the lower Vistula in the development of navigation and hydropower. *Acta Energetica* **2013**, *2*, 83–90. [CrossRef]
44. Mojski, J.E. Budowa geologiczna i tendencje rozwoju doliny Wisły. *Przegląd Geol.* **1980**, *28*, 332–333.
45. Starkel, L. *Evolution of the Vistula River Valley since the Last Glaciation till Present*; Institute of Geography and Spatial Organization Polish Academy of Sciences: Warsaw, Poland, 2001; ISBN 83-87954-12-8.
46. Miall, A.D. (Ed.) Lithofacies types and vertical profile models in braided river deposits: A summary. In *Fluvial Sedimentology*; Geological Survey of Canada: Calgary, AB, Canada, 1978; Volume 5, pp. 597–604.
47. Miall, A.D. Architectural-element analysis: A new method of facies analysis applied to fluvial deposits. *Earth-Sci. Rev.* **1985**, *22*, 261–308. [CrossRef]
48. Zieliński, T. *Sedimentology. Rivers and Lakes Sediments*; Adam Mickiewicz University Press: Poznań, Poland, 2014; ISBN 978-83-2322-80-80.
49. Pawłowski, B. Uwarunkowania i przebieg zlodzenia dolnej Wisły zimą 2012 r. *Gospod. Wodna* **2012**, *10*, 414–418.
50. Sharp, R.P. Wind ripples. *J. Geol.* **1963**, *71*, 617–636. Available online: https://www.jstor.org/stable/30061128 (accessed on 17 November 2020). [CrossRef]
51. Habel, M.; Babiński, Z.; Szatten, D.; Chalov, S.; Zakhar, R.; Maerker, M. Clastic sediment transport renewal below Włocławek Reservoir. In *Geography in the Face of Modern World Challenges*; Chaberek-Karwacka, G., Malinowska, M., Eds.; Wyd. LIBRON: Kraków, Poland, 2016.
52. Dębowski, P. Migracja ryb przepławką na stopniu wodnym we Włocławku w 2016 roku. *Komun. Ryb.* **2017**, *157*, 1–6.
53. Reesink, A.J.H.; Bridge, J.S. Influence of bedforms superimposition and flow unsteadiness on the formation of cross strata in dunes and unit bars—Part 2, further experiments. *Sediment. Geol.* **2009**, *222*, 274–300. [CrossRef]
54. Habel, M. *Dynamics of the Vistula River Channel Deformations Downstream of the Włocławek Resevoir*; Kazimierz Wielki University Press: Bydgoszcz, Poland, 2013; ISBN 978-83-7096-984-4.
55. Collinson, J.D. Bedforms of the Tana River, Norway. *Geogr. Ann. Ser. A. Phys. Geogr.* **1970**, *52*, 31–56. [CrossRef]
56. Klein, G. *Clastic Tidal Facies*; Continuing Education Publishing Company: Champaign, IL, USA, 1977; pp. 1–149.
57. McCabe, P.J.; Jones, C.M. Formation of reactivation surfaces within superimposed deltas and bedforms. *J. Sediment. Petrol.* **1977**, *47*. [CrossRef]