Research Article

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Applying floodplain geomorphology to flood management (The Lower Vistula River upstream from Plock, Poland)

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Abstract: Using remote sensing extended on geological and topographical maps and verified by the field work, we present the flood management and study the geomorphic features of the floodplain of a large, sand bed, untrained but embanked river in order to determine the flood hazard and to predict future flood scenarios. In geomorphological mapping, we focus on the landforms: crevasse channels and splays, flood basin, chute channels, side arms, floodplain channels, dunes and fields of aeolian sand. We base the flood risk assessment on consultations with environmental engineers who design new technical structures that control inundation (cut-off walls and lattice levees). We describe a levee breach as a result of piping (inner erosion) in a high hydraulic gradient condition and its effect (scour hole) as an erosional landform consistent with the repetitive pattern of erosion and deposition formed by an overbank flow on a floodplain. We reveal an existence of homogenous morphodynamic reaches in the river valley.

Keywords: fluvial process, applied science, alluvial sediment, water engineering, dike, embankment

1 Introduction

Floodplain architecture (fluvial landforms and alluvial sediments) can be regarded as a natural archive of processes in the whole catchment [1] as well as a significant contribution to the wetland classification and management [2]. Lessons learnt from many centuries of

human efforts to control flood extent in the Lower Mississippi (in the USA) and the Lower Rhine (in the Netherlands) rivers show that the modern flood management science, traditionally based on hydraulics and hydrology, has to include a floodplain geomorphology as well [3]. Such an inclusion should involve a geomorphological mapping of the fluvial landforms and sediments that developed on large lowland floodplains as the “historical framework” in which present-day fluvial processes operate, because floodplain geomorphology still represents an active and dynamic control on the modern floods [3,4]. French geomorphologists have drawn a similar conclusion on the basis of the study of floods on the Lower Loire and Rhône rivers [5]: fluvial geomorphology meets the needs of environmental administrators and engineers.

Over 10 years have passed since these papers [3–5] were published, but a potential of fluvial geomorphology still has not been commonly applied to a flood management. Delimitation of flood-prone areas in Northern America and Europe focuses only on hydrological and hydraulic aspects of inundation, e.g. flood hazard maps and flood risk maps in Canada [6] and the EU [7] or federal flood insurance rate maps in the USA [8]. However, some of the states in the USA (Vermont, Massachusetts and Washington) have perceived floodplain geomorphology as applicable for the development of flood risk management tools in a systematic assessment [8].

In our paper: (1) we present flood management in the valley of a large lowland river and (2 – the main aim) we study the floodplain geomorphology in order to assess the efficiency of flood management and predict future flood scenarios.

2 Study area

The landscape of Europe can be divided in a simplistic way into two parts: (a) the southern one which has a

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domination of physical units related to structural geology, i.e. The Alps, The Carpathian Mountains and other Mediterranean mountain ranges and uplands that were uplifted and usually folded together with alpine structures and (b) the northern one, where glacial landforms from the last Scandinavian Ice Sheet compose the landscape. A transition between (a) the uplands and mountains of the Southern Europe and (b) Northern Europe (especially, southerly from the terminal moraines of the LGM – Last Glacial Maximum) is a belt defined by a different landscape: broad and flat lowlands partially covered by dunes (The European sand belt [9–11]) and cut by large rivers, thus named as The Belt of Great Valleys [12]. Overbank fluvial deposits on floodplains of these great rivers (Vistula, Bug and Narew in the middle; Prypeć and Dniepr in the east; and Warta and Odra in the west) usually create the most fertile soils in the whole belt defined above; therefore, the floodplain was reclaimed for grasslands, croplands and accompanying settlements.

The floodplain reclamation requires several hydro-technical structures in order to maintain an appropriate level of groundwater (e.g. drainage ditches and pumping stations) and to avoid an inundation of the reclaimed area coming from the adjacent river during a flood. A construction of artificial levees (also known as dikes) protects such areas from being flooded. Unfortunately, this type of protection works until a levee is breached. Overbank flow comes back then on a floodplain, sometimes after decades of lack of an inundation. Anyhow, the inundation takes place only in a small part of the floodplain, in comparison with the total area of the valley floor that has been reclaimed and efficiently protected from flooding.

We performed the study in the reach of The Lower Vistula River valley located 80 km downstream from Warsaw and 15 km upstream from the city of Płock (Figure 1). The reach has a length of 27 km. The river has a sand-bed channel, 800 m up to 1,000 m in width. The channel assumes a braided type with many permanent islands covered by a riparian forest. The channel slope is low: ca. 0.0017. The floodplain is 5 km up to 6 km in width. The total area of the channel zone together with the floodplain is 135 km². The Vistula river valley within the study reach cuts at least three geomorphological surfaces of different origins and different ages: (i) the morainic plateau formed by the older Scandinavian Ice Sheet (the Warta Stadial of the Odranian Glaciation; marked in Figure 1 as Qp³); (ii) the sandur formed by the Vistula palaeo-ice stream of the LGM (Last Glacial Maximum – Poznań Phase of the Vistulian Glaciation;

marked in Figure 1 as Qp⁴ in the NW of the map) with many dunes on its surface; and (iii) the bottom of the Pleistocene ice-dam lake (marked in Figure 1 as Qp⁴ in the E of the map) developed by damming the proglacial pre-Vistula river by the ice sheet during the LGM [13–15].

3 Material and methods

We used different methods (Figure 1) and different data sources (Figure 2) for: (1) the presentation of the flood management, (2) the geomorphological mapping and (3) the assessment of efficiency of the flood management system and prediction of future flood scenarios in the study area. Using ArcGIS 10.2.1 (Esri) we combined all of the above (1, 2, 3) aims and present the results on maps (Figures 3, 4 and 6).

The minor goal of our study, (1) the presentation of flood management, we based on: (i) the detailed mapping of the floodplain hydrography. We used the topographical maps at a scale 1:10,000 to identify all the water courses on the floodplain and we divided them into four classes: main stream channels, secondary stream channels, main man-made channels and secondary man-made channels; (ii) the description and location of the structures constructed by humans in order to control the extent of inundation, namely: artificial levees. We identified the embankments (the dikes) on the topographical map at a scale 1:10,000 and we consulted their function and location with the engineers who projected an improvement in structures; (iii) the description and location of the structures planned to be constructed in the future, as well as the planned attempts to reinforce the way these structures work. All these data [16] we received from the engineers who designed a modernisation of the flood management system. We put these data gathered into a GIS database as well.

By the geomorphological mapping (the main aim of our study), we mean an attempt to derive single landforms or a set of landforms from the study area and to mark their boundaries as lines or polygons on large-scale base maps [17]. We used 16 sheets of the Topographical Map of Poland 1:10,000 (projection Pulkovo 1942, contour interval 1.25 m, the map reliability corrected to 1991–1992; Figure 2) as the cartographic basis for the mapping. We started from drawing the boundaries of the river channel banks which limit the floodplain from the inner side and the islands in the river channel, although we do not pay attention to these islands in this paper. Later, we mapped the river terrace

Figure 1: Methods and location of (B) the study area in Poland and in the surroundings of Warsaw and Płock cities. Age of the main geomorphological surfaces: Qh – Holocene, Qp⁴ – the last glaciation of the Pleistocene and Qp³ – the older glaciation of the Pleistocene. The maps are derived from the physico-geographical division of Poland [52,53].

fronts and edges of the river valley, which limit the floodplain from the outer side. These basic boundaries of

fluvial environment assume a linear feature [17] parallel to the river channel. Using these boundaries we delineate the

Figure 2: Maps and datasets used in the study and the year of their reliability. Source: [35].

extent of: (i) the floodplain, (ii) the upper terraces and (iii) the morainic plateau. We filled the polygons of these landforms with the hatching style, especially designed by Galon R (1962) for the presentation of the landscape of Polish lowlands [18–20]. In the next stage of geomorphological mapping, we searched for the dunes and landforms similar to dunes (that consist of aeolian sand, heights up to 1–2 m and dimensions: 50–200 m × 200–500 m). We identified the aeolian landforms on the Geological Map of Poland 1:50,000 (sheets: Wyszogród [21] and Słubice [22]; Figure 2) and drew their boundaries on the basis of the contour lines on the Topographical Map of Poland 1:10,000. Using the same method of the combined analysis of topographical and geological maps, we also identified the alluvial fans at the foot of the edges of the valley.

Mapping of the most important landforms of fluvial origin on the floodplain we performed on the basis of orthophotomaps (scenes taken by satellites: Ikonos 2 in June 2008 and by WorldView 2 in July 2012; pictures

taken from the plane by the MGPP Aero Company in June 2010) and LIDAR DEM (MGPP Aero Company, June 2010) combined with the topographical map. We presented the details of using remote sensing to detect the landforms in the previously published papers [23,24]. On the floodplain we searched for: (i) the flood basin – compare the study from the Rhine–Meuse delta in the Netherlands [25]; (ii) the former side arms (usually deactivated by the river embankment), the chute channels and the floodplain channels – compare the study from the Indiana state in Northern America [26]; (iii) the crevasse channels (also crevasses) cut in the natural and artificial levees by an overbank flow during the floods [23,24,27]; (iv) the crevasse splays and natural levees deposited by an overbank flow during the floods [23,24,27–30].

We compared the pattern of the landforms which can be identified by the remote sensing to the pattern visible on topographical maps in order to extend the geomorphological mapping to the whole coverage of the study area. In

Figure 3: Hydrography, flood management and main landforms of the study area: 1 – morainic plateau Qp^3 & Qp^4 ; 2 – upper terrace Qp^4 ; 3 – floodplain Qh ; 4 – edges eroded by the river; 5 – the Vistula river kilometre markers; 6 – the Vistula river channel with islands; 7 – artificial levees; 8 – lattice levees designed but not constructed yet; 9 – man-made channels; 10 – stream channels on the floodplain and tributaries of the Vistula river; 11 – crevasse channels; 12 – flood basin. Source: [35].

some places, we also used geological maps for such an extension. We verified in the field the boundaries and a type of landform identified through the remote sensing and read on the maps. In order to locate accurately in the field (that usually poses the shape of a flat and broad surface) the lines and the polygons created in GIS, we copied them to the portable device (a simple smartphone with a GPS module) and displayed them in a mobile GIS software (ArcPad 10 by Esri). We also performed geological drilling on the surface of some landforms, especially: crevasse splays and fields of aeolian sand on the floodplain. We put these data gathered in the field into the GIS database.

To discuss the assessment of the efficiency of flood management system and predict future flood scenarios, we combined in ArcGIS the result of the geomorphological mapping with the analysis of flood management. We also included the inundation pattern of the last two floods that occurred in the study area in 1982 and 2010 years.

4 Presentation of flood management in the study area

The flood management in the study area is based on the system of artificial levees – Figure 3. The levees were rebuilt many times, what always caused narrowing of the inter-dike zone where the river acts. The present-day system of levees can be dated back to the time of construction of the Włocławek dam (located 60 km downstream from the study area; [31]) in 1970 and some latter reworks in the years 1980s. Older artificial levees are usually used today as a road embankment, what causes for us some difficulties during the correct mapping of their extent; thus, we drew on the map (Figure 3) only a section of the inactive levee that stays behind the present-day levees. From the fact of the location of many crevasse channels far away from the present-day channel and the present-day levees, we presume that the older levees were breached many times

Figure 4: The past (on the left) and future (on the right) extreme hydrological events in the study area: 1 – morainic plateau Qp^3 & Qp^4 ; 2 – upper terrace Qp^4 ; 3 – floodplain Qh ; 4 – edges eroded by the river; 5 – the Vistula river kilometre markers; 6 – the Vistula river channel with islands; 7 – flooded area; 8 – artificial levees; 9 – lattice levees designed but not constructed yet; 10 – crevasse channels

during the flood. We legitimate our presumption by the location of these “distant” crevasse channels next to the present-day road embankments.

As a part of the flood management system we can also regard the artificial channels (draining ditches) dug in the floodplain and pumping stations located at the outlet of the main draining ditches and channels into the Vistula river channel. These facilities do not directly control the extent of inundation coming from the river, but decrease the water table on the floodplain during flood events when the groundwater flow occurs under the artificial levees. We marked on the map (Figure 3) all the water bodies readable on 1:10,000 topographical map, both: natural (like streams and oxbow lakes) and artificial (like ditches and ponds).

After the ice-jam flood in 1982 (Figure 4, top left), engineers designed [32] a system of four lattice levees (Figure 4, right), but only one of them (located next to

the 595 km river kilometre marker) was built (Figure 3). After the rainfall floods in 2010 (Figure 5, bottom left), engineers designed a new way to protect the existing levees from the breach by filling the embankments with a cut-off wall (Figure 5, top right).

5 Results – floodplain geomorphology

The results of the geomorphological mapping we present on a map (Figure 6). A floodplain in the longitudinal profile (along a river course) can be divided into different morphodynamic reaches by analogy to a river channel – compare the method of river channel mapping [33,34]. In the study area, we found three such reaches on the

Figure 5: Cross-sections of the artificial levee at a place of the breach during the 2010 flood: a breach mechanism (on the left); its geomorphological effects (at the bottom) few hours after the breach (on the left) and one week after the breach (on the right). The artificial levee reinforced by the cut-off wall (top right). Source: Hydroprojekt Włocławek 2010 [54] and Dobrzelewski B – pers.comm.

floodplain: (a) upstream from the 600 km river marker; (b) between the 600 km and the 607 km river markers; (c) downstream from the 607 km river marker; thus, we describe the results below in the foregoing order.

The study floodplain in the (a) reach located upstream from 600 km (Figure 6) is similar in width at both sides of the river (ca. 2 km each one). The floodplain landscape is dominated by a variety of floodplain channels and aeolian landforms. Most of the floodplain channels have the features typical for a side arm. On the right-side floodplain (northerly from the main river channel), some of the channels are shorter, shallower and more similar to chute channels. The two of them are completely different, because they assume the shape of palaeomeanders, what we also confirmed on LIDAR DEM [35]. The palaeomeanders have a radius of 0.5 km and the length of their channels – ca. 1.5 km each. The floodplain channels do not occur behind the dunes on

the left (southern) side of the floodplain, but a narrow (300 up to 600 m of width) flood basin appears over there and it continues downstream. The dunes on the left (S) side of the river are 5 m in height, but the largest one is 10 m in height. The lengths of the three largest dunes are: 4, 3 and 1.8 km. The width of the largest one exceeds 1 km; thus, the dunes assume a longitudinal shape like the seifs (the linear dunes produced in areas with a bimodal wind regime – compare the definition in the AIG Glossary of Geomorphology by Goudie 2014 [36]); however, they have very sharp edges, possibly eroded by an overbank flow. There are also eight smaller dunes on the left (southern) side of the floodplain. On the right side (northerly from the river), there are flat fields of aeolian sand only and a lack of typical dunes.

In the (b) reach, an asymmetry appears between both sides of the floodplain. The asymmetry

Figure 6: Geomorphological map of the study area: 1 – morainic plateau Qp^3 & Qp^4 ; 2 – upper terrace Qp^4 ; 3 – floodplain Qh ; 4 – edges eroded by the river; 5 – the Vistula river kilometre markers; 6 – the Vistula river channel with islands; 7 – side arms, chute channels and floodplain channels; 8 – crevasse channels and splays; 9 – flood basin; 10 – dunes and fields of the aeolian sand; 11 – alluvial fans; 12 – tributaries of the Vistula river. Source: [35].

accompanies to the shift of the main river channel course, which turns from parallel into northwest (NW) direction. The floodplain asymmetry comes from a change in their width at both sides. The right (northern) side of the floodplain gradually becomes narrower. A width of 2.300 m at the beginning of the reach (measured exactly at the 600 km river marker) decreases downstream to 400 m at the end of the reach (measured exactly at the 607 km river marker). The main river channel becomes narrower as well. A width of the channel measured in the same location decreases from 1.300 m (measured together with the islands) to 580 m. In opposite to the right side (and to the main river channel), the left (southern) side of the floodplain becomes wider and wider. A width measured in the same location as above increases from 1.700 m at the beginning up to 4.300 m at the end. The striking contrast between both sides of the floodplain in the (b) reach also manifests itself in a type of landform developed there. The right (N) side remains similar to the (a) upper reach, but the left one (S) differs completely from the (a) reach. The flood basin in the (b) reach becomes wider there. It

ranges from 800 m up to 1.200 m in width. The aeolian landforms vanish at all in the (b) reach, apart from one linear dune located in the middle of the flood basin. This single dune is relatively small in comparison to the dunes in the (a) reach – the dune's dimensions are: $600 \times 125 \times 5$ m. As the most significant change in the (b) reach in comparison to the (a) reach, we consider an existence of completely new landforms that do not occur upstream: crevasse channels and crevasse splays. The two sets of crevasse channels appear at the beginning of the (b) floodplain reach. The other two sets occur at the end of the (b) reach. The broad surface of floodplain between these erosional landforms is covered by many crevasse splays and finger-shaped sandy lobes which terminate in the flood basin. These depositional landforms completely dominate ca. 40% of the left-side (S) floodplain. This zone, with the domination of crevasse splays, is located (see Figure 6) between the side arms (cut from the main channel by river embankment) on the right (N) and the flood basin on the left (S). The sediments' architecture over there forms a typical margin of the alluvial ridge. By the alluvial ridge we

mean – compare [27–30] – a proximal zone of a floodplain which is shaped by the levee overbank deposition.

The (c) reach of the floodplain has a geomorphological style similar to the style of the (b) reach, but some features intensify and become clearer than upstream. Aeolian landforms do not occur in the (c) reach of the floodplain. It looks like the aeolian landforms were completely eroded by the river. The dunes remain only at the upper terraces. The dunes, which remain over there, have a steep erosional slope which is unified with the front of the terraces. The side arms and flood channels dominate on the right (N) side of the floodplain. This right side is narrow. A width decreases in some locations below 300 m, and even – below 200 m, but usually fits between 800 m and 1.500 m. The left (S) side of the floodplain is very wide: from 3.800 m up to 4.300 m. The side arms do not occur on the left side of the floodplain, either the floodplain channels or the chute channels. A few channels appear only at the beginning and at the end of the (c) reach. Crevasse channels and crevasse splays absolutely dominate the left-side floodplain in the (c) reach. We identified 15 separate sets of such landforms. They covered an area of 22 km². Detailed results of the remote sensing of the crevasse channels and the crevasse splays developed in the (c) reach we presented in [23,24]; however, the presentations in previously published papers have a limited coverage in comparison to the map in Figure 6. The flood basin in the (c) reach becomes wider than upstream. Its width is 1.400 up to 1.500 m, but at the end of the study area it exceeds 2.400 m; however, margins of sandy lobes of the crevasse splays cover these concave landforms in many places, especially in the middle of the (c) reach next to the 610 km river kilometre marker. The widest part of the flood basin (a total area of 5 km², it assumes a shape similar to a circle) looks like a recipient of the overbank flow in the whole left-side (c) reach. It looks so, because all the axes of all the crevasse channels (that we mapped in the (c) reach along 10 km of the river course) concentrically converge over there, exactly into the centre of gravity of this concave landform.

6 Discussion

In order to assess the efficiency of the flood management system and predict future flood scenarios, we additionally included on the map (that presents the hydrography of the study area juxtaposed with artificial levees; Figure

3) the two geomorphological features of the floodplain, namely two types of landforms. We consider these landforms as the most significant indicators for an efficient flood management of the study area: the flood basin and the crevasse channels. We derived these features from the geomorphological map (Figure 6). We treat a crevasse channel as an evidence of a place where the levee breach occurred [23,24]. Similarly, we assign for a flood basin the role of a recipient of an excess water during the flood events. We do so, despite the fact that the flood basin in the study area has no hydraulic connection with the river channel after the artificial levees were constructed in the past.

Considering the assumptions given in the paragraph above and the problems of flood management which arise in the study area (presented in Section 4), we predict three different scenarios of future flood events: (1) scenario 1 – without construction of the lattice levees in the future; (2) scenario 2 – with the lattice levees constructed and a levee breach occurring in the most probable location; (3) scenario 3 – with the lattice levees constructed and a levee breach occurring in the less probable location (Figure 4).

In scenario 1, we presume an occurrence of levee breach on the left side of the river in the (c) study reach, namely downstream from the 607 km river kilometre marker. Such a situation happened in January 1982, when an inundation covered the area of 100.5 km² (Figure 4, top left); however, a part of the land that was inundated then is located beyond our study reach [37]. A breach almost recurred in March 2010 [38]. Ice jams induced these two (in January 1982 and in March 2010) extreme hydrological events, what we comment in the paragraph below. The levee breach recurred (sufficiently for naming it as a catastrophic disaster) in May 2010 [23,24]. As a result, an inundation covered ca. 60 km² of the area which was protected by dikes, thus almost a half of the study area (Figure 4, bottom-left). Levee breach resulted from the high hydraulic gradient that induced piping and hydraulic failure of the embankment (Figure 5, left). The breach triggered not only inundation, but also a process of scour in the floodplain which formed a scour hole of 10 m depth (Figure 5, bottom) and the crevasse channel. We marked these landforms on the maps – Figures 3 and 6; the accurate location is 2 km downstream from the 610 km river kilometre marker on the left (S) river bank. The set of scour hole and crevasse channels, which was developed during the 2010 flood, is an example of catastrophic impact of flood, a geomorphological topic that most of the flood specialists usually are not aware of [8].

In scenario 2, we presume a levee breach that would take place in a similar location as in scenario 1. The difference between the scenarios 1 and 2 is that the lattice levees designed in the 605 km and in the 615 km river kilometre markers are constructed in the second case (Figure 4, top right). We based our presumption (of breaching in the (c) morphodynamic reach of floodplain) on the existence of many crevasse channels that cross embankments over there (Figure 4, top right). We suppose that even if some of the embankments are reinforced by cut-off walls in order to diminish the risk of hydraulic failure because of piping (Figure 5, top right), a breach can occur near the cut-off wall in the embankment that has not been reinforced. The inundation in scenario 2 will cover an area of 41 km²; thus, ca. 30% lesser than in the case of the 2010 flood and scenario 1 – without the lattice levees constructed. Unfortunately, ca. 10–15% of the area flooded in scenario 2 is inhabited. The inundated area will store flood water at a volume of 50,00,000 m³.

Scenario 3 will locate a possible breach between the lattice levees designed and constructed next to the 600 km and to the 605 km river kilometre markers (Figure 4 bottom right). The smaller (than downstream) number of crossings of the crevasse channels with the present-day levees (namely two) enables us to diminish the possibility of a breach over there. However, if the breach occurs, the lattice levees will reduce an area of inundation down to 11 km².

In the results of geomorphological mapping of the floodplain, we focused on the fluvial landforms, but we should discuss another type of landform as well. An existence of the dunes on the Holocene floodplain seems to be unusual in the middle of Europe, where a lack of dry period defines a climate type. We drilled on the surface of the aeolian landforms located in the floodplain in the (a) study reach and we found a glacial till directly underneath the aeolian sand. It means that the dunes and the fields of aeolian sands are a relic of a Pleistocene surface within the Holocene floodplain – surrounded by the floodplain. The relics are not parts of an alluvial ridge of the present-day river (sandy bars, levees and crevasse splays), which are entrained by wind like it happens on the floodplains of rivers flowing in an arid climate zone, e.g. in the Salta province of Argentina [27]. The relics undoubtedly were being eroded by an overbank flow in Holocene. For some reason, they have persisted the erosion and did not receive a deposition of an overbank alluvial sediment on their surface.

The palaeomeanders, which we mapped in the study area in the (a) reach of the floodplain, seem to be very

questionable. The Lower Vistula River has never possessed a meandering type of channel (personal communication with Piotr Weckwerth, [39]); however, the widest part of the flood basin in the (c) study reach of the floodplain was defined in the study of Florek and Mycielska-Dowgiałło [40] as the oldest surface of the Holocene floodplain shaped by a meandering river (TH1; dated back to the initial phases of Holocene before Sub-Boreal period). These authors [40] were the first ones who described the crevasse channels and the crevasse splays in the (c) reach of the study area. They dated the age of these landforms to the Sub-Atlantic period of Holocene.

Opposite to large rivers of the southern and western Europe [3,5,7,41], the (1) flood management in The Lower Vistula River has faced with jams for ages [42]. Frequent floods induced by jamming of the flow in the channel by ice phenomena had forced people in the XIX century to perform a heavy work of efficient training of the Vistula river within the extent of a former Prussian Partition of the Polish Kingdom – downstream from the 715 km river kilometre marker next to Ołtoczyn and Silno until its outlet to the Baltic Sea (the 941 km marker). The regulation enabled the use of icebreaking boats in order to diminish the risk of ice jams. The dam on the Vistula river (constructed in 1970 in Włocławek; the 675 km marker, [31]) enhances the process of ice-jam formation in a very long reach upstream from the dam. The impact covers the whole study reach and continues further upstream to the beginning of the Lower Vistula River in Modlin (at the outlet of Narew and Bug Rivers, 551 km river kilometre marker, thus more than 120 km upstream from the dam), according to [42,43]. The backwater from the dam (during an ice-free condition) reaches 58 km upstream from the dam [44,31] and terminates at the lowest margin of the study area; thus, the dam impact on ice phenomena undoubtedly can reach so far upstream.

We based the assessment of flood management system on searching for the locations of a potential levee breach. The crevasse channels indicate such locations. We discussed a method of identification of crevasse channels in the other paper [23], where we included only the most visible landforms filled with water. Crevasse channels due to their hydraulic conductivity become pathways of the groundwater flow within the alluvial aquifer [45], “the preferred pathways” from the perspective of hydrogeology [46]. If these pathways cross the artificial levees, the sequence of processes induced by the flood (presented in Figure 5, left) can lead to an inner erosion of the levee resulting in its breach. Cut-off wall as a solution to the problem of

piping (Figure 6, top right) can have a negative impact on the groundwater flow under the condition of low water stage when the river channel drains the alluvial aquifer [45].

The lattice levees designed in the study area (Figure 4, right) were not constructed because of the objections coming from inhabitants of the floodplain. People who live on the flood-prone areas treat potential lattice levees as a structure that allows to inundate their properties in order to prevent properties of other people who live outside of the polder. The lattice levees were successfully built on the floodplain of Yellow River in China 450 years ago [47], but they linked the inner levees and the outer levees. They did not link the levees (dikes) built along a river channel with the front terraces like it was designed in The Lower Vistula River. The lattice levees in Imperial China also had another role to play. They narrowed the main channel together with inner levees in order to raise the velocity of flow and therefore maintain a high sediment-carrying capacity of the flow, preventing the suspended load and bed load from deposition or even promoting the scour in the channel [47].

We shared some of the results derived from our study [35] with engineers who design the improvement of the flood management system in the study area. We did so generously (without financial or individual benefit for our professional recommendations) in the hope of further application of our study by environmental administrators. Unfortunately, we suppose that our recommendations will not be realised in the near future by environmental administrators who manage the flood protection system. Engineers, environmental administrators and environmental stakeholders usually exchange their opposite views on our study area through an idle discussion: nature conservation vs flood protection in a river valley. The arguments put forth by both sides in the dispute raise only from the interpretation of the law in force, less often – from economic and environmental aspects of the flood impact. Fluvial geomorphology does not exist in this dispute because it is perceived: (i) by environmental stakeholders who usually have roots in biology or ecology – as a science related to deep time (geological timeline), thus having no input into a present-day ecosystem, (ii) by environmental engineers – as an academic theory rather than an applied science. It looks like fluvial geomorphology has no promotion beyond the society of geomorphologists, beyond the “academy”, thus – a problem with communication [48].

Another problem in applying fluvial geomorphology to a flood management, or in general in a better

mitigation of floods, is a short period of “collective memory” of a flood as a disaster [49–51]. As a result, people who live in an embanked flood-prone area usually do not perceive the reclaimed floodplain as a hazardous zone. Such a perspective – a lack of flood hazard on a floodplain sometimes appears even in local municipalities and administrators, especially if the last flood occurred more than 5 years ago.

We consider the methods, namely the datasets we used for geomorphological mapping, as the last issue worthy of discussion. We covered only a minor part of the study area by innovative datasets, i.e. Very High Resolution (VHR) scenes from Ikonos 2 and WorldView 2, LIDAR DEM and an associated picture taken from the plane (MGGP Aero Company); compare Figure 2. The major part of our study area was mapped on the basis of topographical maps supplemented by geological maps. Some of the researchers found these materials to be old-fashioned. We think that accuracy of the topographical map (which we used) is still adequate to the main purpose of our study. An efficient accuracy raises from the specific features of the study area: broad, flat surface of a floodplain without a riparian forest. We purchased the scene from WorldView 2, especially in order to verify by remote sensing a lack of crevasse channels in the right-side (N) floodplain. Such a verification can be effectively performed on topographical maps by an experienced fluvial geomorphologist who analyses the shape of contour lines with an interval of 1.25 m. In some cases, an additional view on orthophotomaps may be necessary, but the image maps, which are commonly available online, seem to be good enough. Detection of crevasse channels on the basis of searching for water bodies [23] limits the amount of identified landforms only to less than 10% of landforms visible on topographical maps by contour lines or – on LIDAR DEM [24]. VHR remote sensing is essential for the detection of more subtle erosional landforms on a floodplain, e.g. chute channels and palaeomeanders; however, these landforms do not have such a significance which we assign for crevasse channels.

7 Conclusions

1. Geomorphological mapping of the floodplain combined with the analysis of flood management can be an efficient tool for flood hazard assessment and prediction of future flood scenarios. The efficiency of this tool will be verified by future extreme hydrological events.

2. We consider the crevasse channels as the most significant geomorphological indicators of the risk of a levee breach.
3. The flood basin remains a recipient of floodwater even in the embanked rivers, but in such a condition an underground flow replaces an overbank flow.
4. A floodplain, likewise a river channel, consists of the reaches that differ with their geomorphological evolution (type of morphodynamics). Such reaches are visible in the longitudinal profile and they have a repetitive pattern of erosion and sedimentation. It repeats every flood event.
5. The construction of lattice levees and a reinforcement of existing levees by cut-off walls can be reasonable solutions to the problems that flood management has to face in the study area.
6. Fluvial geomorphology seems to have great potential in solving the problems of flood management. Unfortunately, geomorphologists still do not contribute to the projects of flood management and river engineering. They very often do not take interest in application of their research. Engineers do not consult their attempts to control fluvial processes with fluvial geomorphologists. The engineers usually even do not know that geomorphology can be an applied science. A lack of communication between both the societies and an idiosyncratic haughtiness of “a professional” are the root problems in a subjective opinion of the authors.
7. Dunes and the other aeolian landforms located on a floodplain (of rivers flowing in the climate zone without a dry period) indicate the erosional origin of the floodplain and lack of fluvial deposition on such surfaces in Holocene.

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