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Geological setting control of flood dynamics in lowland rivers (Poland)

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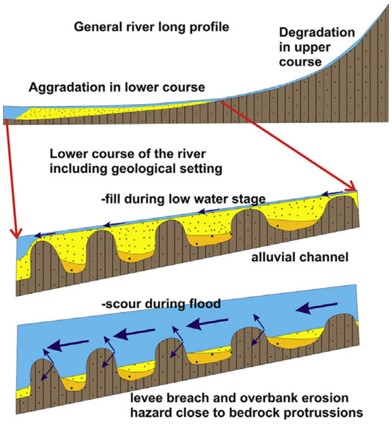
HIGHLIGHTS

- Bedrock protrusions exist along the courses of lowland alluvial rivers.
- Bedrock protrusions induce greater erosion of the overbank flow.
- Greater overbank erosion is written in the floodplain as crevasse channels.
- Crevasse channels are hazard indicators in embanked rivers - possible levee breach.
- Bedrock protrusions affect flood dynamics in both embanked and natural rivers.

GRAPHICAL ABSTRACT



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ABSTRACT

We aim to answer a question: how does the geological setting affect flood dynamics in lowland alluvial rivers? The study area covers three river reaches: not trained, relatively large on the European scale, flowing in broad valleys cut in the landscape of old glacial plains.

We focus on the locations where levees [both: a) natural or b) artificial] were breached during flood. In these locations we identify (1) the erosional traces of flood (crevasse channels) on the floodplain displayed on DEM derived from ALS LIDAR. In the main river channel, we perform drillings in order to measure the depth of the suballuvial surface and to locate (2) the protrusions of bedrock resistant to erosion.

We juxtapose on one map: (1) the floodplain geomorphology with (2) the geological data from the river channel. The results from each of the three study reaches are presented on maps prepared in the same manner in order to enable a comparison of the regularities of fluvial processes written in (1) the landscape and driven by (2) the geological setting. These processes act in different river reaches: (a) not embanked and dominated by ice jam floods, (b) embanked and dominated by rainfall and ice jam floods. We also analyse hydrological data to present hydrodynamic descriptions of the flood.

Our principal results indicate similarity of (1) distinctive erosional patterns and (2) specific geological features in all three study reaches. We draw the conclusion: protrusions of suballuvial bedrock control the flood dynamics in alluvial rivers. It happens in both types of rivers. In areas where the floodplain remains natural, the river inundates freely during every flood. In other areas the floodplain has been reclaimed by humans who constructed an artificial levee system, which protects the flood-prone area from inundation, until levee breach occurs.

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1. Introduction

Riverine floods attract the attention of specialists from many disciplines, but the most common perspective comes from hydrology, where a flood is defined as "*an overflow or inundation that comes from a river* (…) *and causes or threatens damage*" (Langbein and Iseri, 1960). The final word of the definition "damage", leads to completely different views on the riverine flood, which depend on how the flood-prone area is used: (1) if the risk of damage from inundation is expected (or had occurred) in the vicinity of a river channel, people focus on the river and try to understand how it works, as well as to mitigate or control the possible hazard. Unfortunately, the damage usually takes place in densely populated areas, where the human impact on the environment has changed the riverine landscape so far that "reading the landscape" (Brierley et al., 2013) to find out some regularities made by former floods is very difficult or almost impossible to do; (2) If a river inundates an area without settlements, intensive agriculture, or other valuable infrastructure, the flood itself does not happen as a hydrological event because of the lack of damage. As a result, there are only a few researchers who pay attention to the fluvial processes occurring in such a valley reach that is underused by humans. Therefore, it is necessary to study both types of flood-prone areas and compare the results from another point of view. In geomorphology, a flood is defined as: "*a period of high discharge of a river* (…) *exceeding a channel's capacity*, *and leading to the inundation of adjacent low-lying land* (*the flood plain*)" (Goudie, 2014). The floodplain and its inundation are key words in the geomorphological definition of a flood, as well as in the definition chosen for this paper.

Using the scientific journal browser Web of Science®, we can easily observe that the topic of "flood" coexists with the topic of "climate change" in more than 10,000 records. Both the topic of "geology" and the topic of "geomorphology" appear with the topic of "flood" in 1000 records. A false conclusion can be drawn from these data that the impact of climate change on floods (Fig. 1, blue) is 10 times greater (or 10 times more important) than the controls that originate from the lithosphere (Fig. 1, orange). Moreover, there are many studies that provide examples of the impacts that other spheres have on floods. Impacts of the biosphere (Fig. 1, green) include riparian vegetation (Croke et al., 2017) and the activity of beavers (Giriat et al., 2016). Impacts of the anthroposphere on floods (Fig. 1, grey) include artificial levee introduction and river training. Such examples from the Upper Vistula River by Łajczak (1995, 2007, 2014) and from the Mississippi and Lower Missouri Rivers by Pinter et al. (2010) show that the impact of river training and floodplain reclamation usually goes far beyond the intension primarily projected by humans. A combination of anthroposphere and biosphere impacts on floods can originate from the catchment reforestation efforts (Keesstra et al., 2005). Reforestation has occurred widely in recent decades in many parts of Europe (eg. the eastern headwaters of the Vistula River). We aim to use this paper to manifest that the geological setting plays an important role for flood dynamics in lowland alluvial rivers. Such interaction leaves legible traces in a floodplain's relief. Therefore, reading the geomorphological landscape of an alluvial river can prove useful for the detection of hazardous zones in river valleys, where flood risk is additionally increased by geological setting.

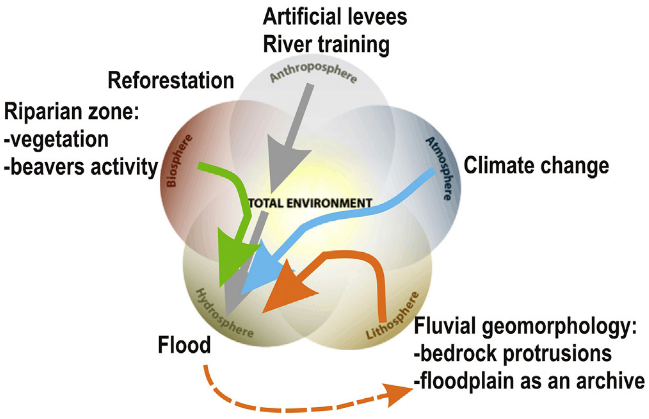

Fig. 1. A riverine flood as an overlap of the total environment with specific emphasis on the linkage between the hydrosphere and the lithosphere. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

By looking at the world-wide list of Quaternary floods with peak discharges greater than 100,000 $m^3 \cdot s^{-1}$ compiled by O'Connor et al. (2002), we realise that only 15% of the greatest documented floods were induced primarily by a meteorological factor (rainfall). Most of these catastrophic hydrological events resulted from geomorphological processes related to the breaching of natural dams (e.g. glacial lake outburst flood in Norway – Høgaas and Longva, 2016), or an intensive ablation of glaciers due to a subglacial eruption (e.g. glacial outburst floods in Iceland – Baynes et al., 2015). A rapid release of the water stored behind the dam or within the glacier occurred in the case of all the greatest floods with peak discharges greater than 500,000 $m^3 \cdot s^{-1}$ (O'Connor et al., 2002).

The importance of geological and geomorphological background on the greatest and most spectacular flood events in the Quaternary is obvious, but providing a clear example of the influence of the geological setting on the dynamics of the recent floods is difficult, especially in alluvial rivers. Such rivers shape their valley floors in an alluvium that covers the bedrock. Alluvium is usually non-resistant to erosion. It used to be eroded, transported, and redeposited on channel bottoms, and within banks and other fluvial landforms. In that sense, alluvial river valleys are self-formed (Phillips and Slattery, 2008) and morphologically sensitive (Fryirs, 2016) in opposition to bedrock channels.

Fluvial erosion and deposition are defined as degradation and aggradation if they occur over an extended time period (Leopold et al., 1964, p. 227). These processes are generally assigned to dominate in the upper or in the lower course of the river (Fig. 2A). River bed erosion and sedimentation that occur during a single flood passage are described as channel scour and fill (Leopold et al., 1964, p. 227). A systematic measurement of scour and fill processes in rivers is usually performed by applying the scour chain method (e.g. in the middle reach of the Loire River (France) by Wintenberger et al. (2015), in the context of the origin and the morphodynamics of fluvial islands). The scour chain method together with stream gauge observations enabled Levy et al. (2011) to determine a linear relationship between the stage and the scour depth in the Great Miami River that flows through the lowland landscape of southwest Ohio (USA). It is commonly believed that the lower course of large rivers is alluvial and dominated by aggradation, and thus the alluvium thickness in this section is great (Fig. 2A); so great, in fact, that scour is unable to expose bedrock. The maximum scour depth in lowland rivers does not exceed 0.1 m and 0.8 m according to the values measured by Levy et al. (2011) and by Wintenberger et al. (2015). We assume that scour and fill in the channels of the largest Polish river can reach a depth of over 12 m, which is indicated by the low density of the alluvial sediments deposited after the passing of a floodwave, as well as by the concrete crumbs derived from the destructed hydrotechnical structures that were encountered in drillings under the bottom of the alluvial channel (Falkowski et al., 2017). High scour values are also manifested by differences in the channel bottom altitude on bathymetric charts, based on echo-sounding measurements performed on different water stages (Falkowski, 2007a, 2007b; Ostrowski, 2011 and Wierzbicki, 2015).

Works carried out by Falkowski (1997, 2006, 2007a, 2010) in many lowland Polish rivers revealed a specific relief of bedrock surface which assumes the shape of a sine wave in longitudinal profile (Fig. 2B). The author found many places among alluvial rivers where the bedrock forms protrusions or vast convex structures hidden shallowly under alluvium (Fig. 2B). The alluvial layer is so thin there that, during a flood passage (and the accompanying increase in water velocity and shear