Conditional hydrological simulations as a tool for analysis of denudational transformation of post-glacial plains

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Abstract—**We propose here a new method of presentation and analysis of the morphometry of river basins developed on the postglacial lowlands. We use advanced conditional simulations based on the new tool designed to fast modeling of autocorrelated error surface and GRASS GIS hydro-geomorphological tools. We present two basins: Łupawa basin which represent very young postglacial area and Prosna basin which represent older surface, developed under preiglacial conditions. Preliminary studies show that morphometric characteristics of those two basins developed over the very similar substratum differ radically due to different developemnet conditions: Łupawa basin inherits fresh nature of postglacial surface while Prosna river has changed radically morphometry of its basin under periglacial condition during Weichselian.**

I. Introduction

Fluvial erosion is one of the most important processes which shapes the face of the Earth's surface. Unfortunately computer algorithms designed for hydro- and hydro-geomorphological modeling are designed to work on elevated areas already transformed by fluvial processes [1], leaving aside lowlands, especially the youngest surfaces which remained after last glaciations. Post-glacial lowlands, especially those in Central Europe consist of at least two types surfaces of different age: younger surface created during the last ice advance (ca. 22-14 ka BP), and older glacial surfaces originating from previous advances, remodeled under periglacial conditions [2,3] during last glacial period (ca. 110-14 ka BP). Those surfaces, developed over thick but soft glacial sediments, offer unique possibility to observe rapidly evolving lowland plains at different stages of their evolution. The morphometric characteristics will be presented as a relationship between existing channel network and extra-channel subsystem.

Despite years of research an accurate and universal method of distinguishing the overland-flow subsystem from stream-flow discharge one has not been developed. Extraction of drainage networks on lowlands is particularly difficult due to low diversity of the land surface which leads to high uncertainty of simulated models. On such areas threshold-based models usually produce equally-dense networks which arise from the fractal nature of river systems [4]. More complex methods that also utilize geomorphological components [5,6] are not sufficiently robust against small changes of the free parameters of applied models. Poor legibility of terrain forms on lowlands leads to considerable fluctuations in the drainage pattern even in the case of minor changes of input parameters. Moreover, the youngest surfaces have a very dense irregular pattern of small convex and concave forms created by sub-glacial processes. Algorithms designed to model drainage networks on mature areas usually confuse local convexity with channel heads which leads to unrealistic, very dense networks (see: [7]).

II. Study area

This paper presents a preliminary results of morho-hydrological modeling used to analyze of transformations post-glacial morainic plateaus. In order to demonstrate differences between young and old post-glacial plains, we have chosen two different drainage basins: one drains the youngest morainic plateau, and the other one has been evolving since Eemian interglacial. The first one, Łupawa River (98 km long), drains the youngest morainic plateau (Słupsk Plateau) which emerged after the main stage of the last glaciation, and has not been transformed under periglacial conditions. The second one, Prosna River (216 km long, Kalisz plateau), has a more complex history. While the first phases are identical to Łupawa's (short periglacial period at the end of Saalian Glaciation and normal cycle during

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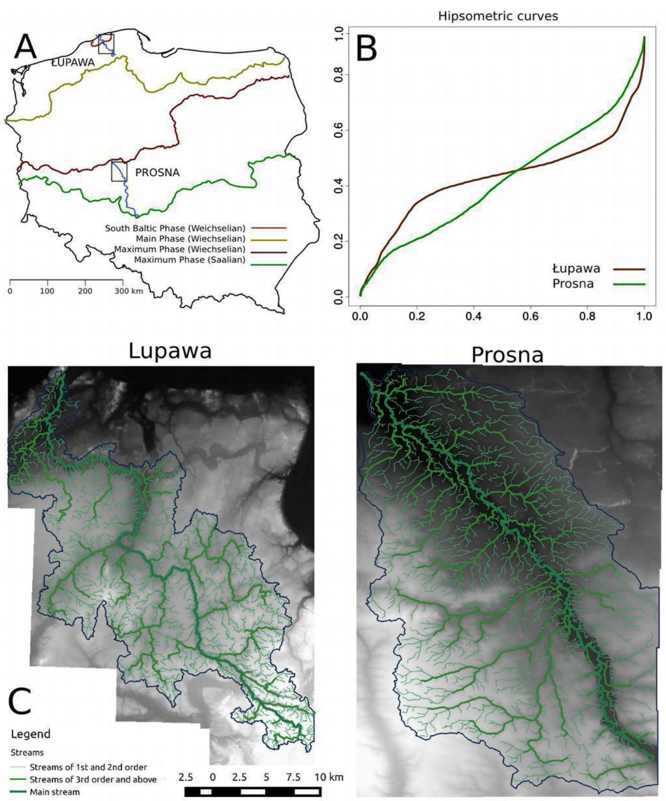

Figure 1. Study area: A) Location of testing areas; B) Hypsometric curves (area/altidude); C,D Łupawa and Prosna basins with stream network

Eemain interglacial), the main erosional phase took place under periglacial conditions during 100 ka years of Weichselian Glaciation. Analyzes were limited only to the ca. 50 km sections of both rivers which pass directly through morainic plateaus. The elevation ranges on investigated areas are also of the same order: 4-99 m a.s.l (locally up to 133 m.a.s.l) for Łupawa river and 74-160 m.a.s.l for Prosna. We assume that both rivers developed after the retreat of respective main ice sheet advances, under the same initial conditions: stable tectonic areas and thick glacial deposits underneath. For analysis we used two 5 m resolution DEM 5000x8000 cells each, created by manual digitization of 1:10000 topographic maps. Both areas are covered by more than 50 sheets of 5x8km extent.

III. Methods

Horton's statistics is a popular and mature tool designed to quantitative description of drainage networks but, not for summarizing its geomorphometric properties of entire basin including slope subsystem. The simplest method of summarizing the geomorphology of drainage basins are hypsometric curves [8]. This method is often too general (see Fig. 1B). A usual approach to obtain more detailed information is to extract local transverse cross-sections through main axis of the basin. Unfortunately, it is difficult to generalize such data and use them to compare two (or more) separate basins. To avoid the mentioned limitations, we introduce a new approach where the overall morphometry of the investigated area is presented as average stream profile along the all watercourses which lead to the local erosional base. To obtain a network which consists of all the recognizable channel forms, including those without active flow on the terrain with high uncertainty, we employed conditional simulations that are widely applied to assess uncertainty of DEMs [9,10]. Stochastic simulations assume that the DEM uncertainty is propagated into terrain forms with manipulation of terrain data [9]. The addition or subtraction of elevation bias affects the terrain surface. If a channel form is distinct, small error (we used 1m) shall do not alter its geometry, so the channel course will remain unchanged. If a channel is poorly marked in the terrain or is just conformed, elevation bias will change the local morphometry and the stream line will be modeled at a somewhat different course. Conditional simulations require the surface error to be autocorrelated (see: [9] for in-depth discussion). The commonly used cell-swapping algorithm (Fisher, 1998) works in polynomial time. Considering at least 400 realizations for every area, it means a very long calculation time. To speed up this process, we decided to create a new GRASS GIS module: **r.random.corr** which adopts the concept from [11] designed to calculate a long-range correlation for large systems in Fourier space. It has reduced ~60 times the time needed to calculate Gaussian autocorrelated for 5000x8000 cells DEM and 30 cells autocorrelation range, in comparison with the mentioned cell swapping method.

If DEM is altered by autocorrelated error surface produces by default numerous closed depressions which are required by most of algorithms to be filled or removed. This process causes the loss of the DEM's local convexity and runs streamlines in one of eight main directions. GRASS GIS **r.watershed** [12,13] module (and following it r.stream toolbox – [7]) use an original least-cost path algorithm which do not require DEM conditioning so the error surface generally do not affect terrain convexity. At each step of the simulation we model the network with a relatively small flow accumulation threshold (25000m2), and add the result of a simulation to the probability map. After 400 realizations we have obtained a layer showing the probability (between 0 and 1) of the existence of any-order stream at a given cell (Fig. 2B).

Final networks were extracted using GRASS GIS r.stream.extract module. We have modeled networks using a product of flow accumulation map and probability map to

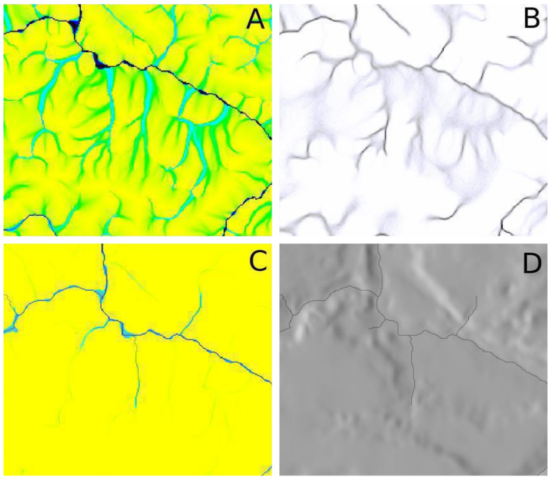

Figure 2. Steps of network modeling: A) Flow acumulation map; B) stream probablilty map; C) initiation map; D modeled streams over shaded relief

initialize channel heads while drainage system was determined using both flow accumulation and elevation surfaces (see: [7] for details). This way doubtful or fake “channels” are attenuated while those which are clearly marked in terrain remain unchanged. Using the same accumulation threshold as for probability map we reduced impact of surface specificity and extracted final networks (Fig. 1CD). Finally, with r.stream.order module, both networks were divided into three subsets: 1) first and second order streams which represents forms usually without or with limited active flow; 2) third order and above channels but without a main channel representing tributaries with active flow; and 3) main channel which represents erosional base for entire basin.

In order to produce vertical/horizontal distance profiles we calculated appropriate maps for every subset of the network using **r.stream.distance** tool. Pairs of numbers representing horizontal and vertical distance were assigned into 20m wide bins of horizontal distance while vertical distance was averaged (Fig. 3) for every bin.

IV. Discussion and conclusions

All profiles show that Łupawa and Prosna have completely different characteristics. In Łupawa basin channels of 1st and 2nd order streams are narrow (up to 200 m) and clearly incised into terrain up to 5 meters deep. Averaged profile gains maximum convexity at 400 m and shows a smooth character up to 800 m from the channel, which can be interpreted as an average extend of denudational transformation in the vicinity 1st and 2nd order channels. On the other hand 1st and 2nd order channels in Prosna basin are not marked as distinguishable terrain forms.

Different morphometric characteristics appear at the level of tributaries to the main stream (3rd order and higher). For Łupawa basin the extent of the denudational profile reaches 2000 m, due to the inclusions of subbasins of lower order. The profile in the part of the distance from stream longer than 2000 m reveals unsuitability as a result of specific properties of post-glacial surface that has not been included into the global surface discharge system yet. On the contrary, Prosna basin shows regularity up to 6000 m from stream lines. Prosna tributaries are located in shallowly incised (up to 3 m) narrow valleys which turns into a gently inclined smooth waste plain.

Profiles above the main channels show overall comparison of both basins. In Łupawa basin the main channel consists of a narrow (up to 500m) deeply incised (25m) valley, which clearly becomes an irregular moranic plateau. Local flattenings visible at the plateau (at ca. 2-3km; 4-5km; 8-10km distance from the stream) represent fragments of the older, pro-glacial outwash system adopted later by modern Łupawa, which is still well visible in terrain relief. The rest of the profile is completely random and is typical for fresh post-glacial surfaces. Prosna profile is divided into three parts: 1) main valley, 2-2.5km wide; 2) smooth, gently inclined terrace system up to 15 km range from the main channel along the watercourse; and 3) upper terraces and plateau plain. Profiles for Łupawa and Prosna converge at the distance of ~15km which allows to compare these curves to show a huge scale of transformation which took place during the periglacial period.

These preliminary, yet promising, results do not allow to draw more general conclusion about differences between young and old glacial plains now. It is required to test the proposed

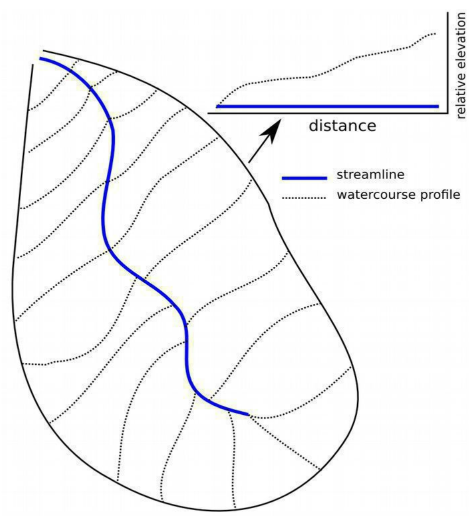

Figure 3. Stream channel and water-course profiles averaged into one resultant profile

method on a larger set of basins developed on post-glacial lowlands.

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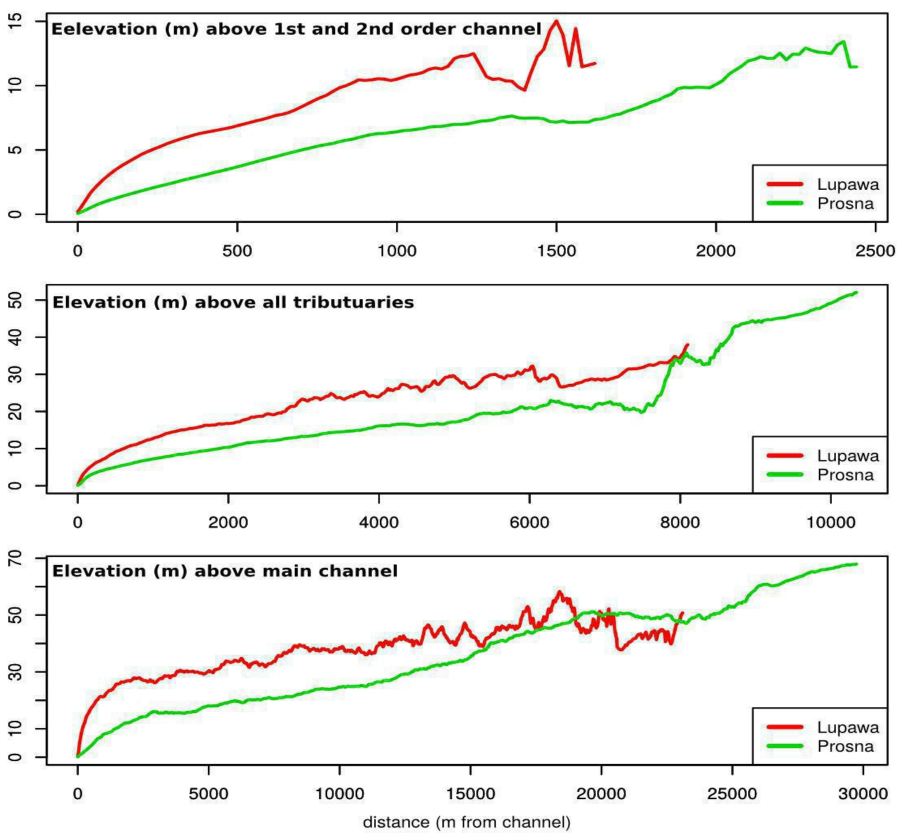

Figure 4. Profiles showing relative elevation (vertical axis) of basin surface over the streams of given order at the distance from stream calculated along watercourses.