Nonparametric prediction of the onset of regional floods: floods in north-western Bohemia, Czech Republic, 2010

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Abstract

Currently, ongoing global climate change brings, among other things, an increasing frequency of extreme weather events such as heavy rains, which can cause flash floods. Responsible authorities have tried to develop systems for early warning of such events. Such systems already exist in the US and in some European countries. They often rely on the prediction of extreme rainfall, possibly with the use of weather radar data, as well as rainfall-runoff models. The weakness in these systems, which limits their global usage, is based on the precise use of rainfall-runoff models and the attempt to quantify the impacts of extreme rainfall in the affected area. Therefore, we have developed a methodology based on the simplified data inputs (data from weather radar) that release a warning for potentially vulnerable areas in the longest time possible before extreme rainfall effects are due to occur. Our ambition is not to quantify these effects. Due to the short time interval between downpours and flash floods caused by them, we do not consider this information to be significant. We decided to test our methodology inter alia on a case of regional flooding, which was the result of regional precipitations combined with extreme local rains. The results presented in this paper show that, even in this situation, the proposed methodology allows us to provide an early warning for the population to take refuge in a safe area.
Keywords: flash flood, weather radar, GIS, early warning, geoinformatics.

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1 Introduction

On 1 August 2010, catastrophic floods hit northwest Bohemia in the Czech Republic. The floods were a result of long intense rainfall. Long duration (in most areas 30–36 hours) and pervasive nature of the heavy rainfall suggests that it was not typical local downpours that usually cause flash floods. However, some locally defined precipitation centers originated within the area of permanent precipitation, were matching the nature of extreme rainfalls (Kubát *et al.* [1]).

Such locally extreme nature of precipitation brought us the idea to test our currently developed methodology for the flash floods risk estimation within this rainfall period. Our methodology is purely based on the application of data from weather radars, which are available with a time step of 5 minutes. The results show that even in the case of this flooding, our proposed methodology would have been able to initiate an issue of early warning to the settlements along the rivers.

2 Flash flood

Flash floods are a natural phenomena which attract considerable attention both from the professional community and the general public. This is mainly due to short-term dramatic course and generally devastating consequences of the events. The World Meteorological Organization [2] reports a number of 5,000 casualties and enormous material damage annually (Grabs [3]). Furthermore, the ratio of death number to number of affected persons in the case of flash floods is higher than in case of regional floods (Jonkmann [4]).

The flash flood phenomenon is hardly predictable, as to the space, time, extent and progress. The European Flood Alert System (EFAS) is used also for long-term evaluation of likelihood of flash floods on the continental level, however this is not its main purpose (Alfieri *et al.* [5]). The short-term warning purposes are served by Automated Local Evaluation in Real Time (ALERT) system developed in the USA and used in many other countries [6].

Current data sources documenting direct and indirect factors in the formation and propagation of flash floods, in conjunction with modern processing methods, however, give hope that it is possible to predict course of the event with high probability, if causal phenomena are already registered and localized. As enormous local rainfalls represent the most common triggers of flash floods, the suspicion of local extreme precipitation event based on radar monitoring of the atmosphere above observed area is the launcher of set of procedures that may ultimately give an early warning for the endangered area and thus contribute at least to save lives effectively, if not to reduce material damages. At least the latter contribution is the reason to thoroughly deal with this phenomenon.

The main problem of the flash floods forecasting and construction of an early warning system (except of predictions of extreme rainfall itself) is known well, it is the short time between precipitation event and the flood peak discharge on the river. This extremely shortens the necessary time span between the evaluation of available data, the forecast production and the warning distribution to institutions and the population. In principle, the existing forecasting procedures are dominated by various rainfall and river-runoff models [7, 8]. A part of these models is based on the specific meteorological forecasts of intense rainfall which are combined with custom hydrological models. A relationship between the catchment area and the unit peak discharge (i.e., the ratio between the peak discharge and the upstream catchment area) represents the output of hydrological models (Borga *et al.* [9]). Using these models, it is possible to predict whether the flow rate from the upstream gauged catchment reaches the level of a flood. The data inputs into models are obligatory represented by the data from ground and satellite radars, data about previous precipitations, temperature data to estimate the evapotranspiration, data depicting the soil moisture and the land use of the area, DEM, etc. There is an additional information required by special models: current flow rates of rivers in the catchment area, or geometric and geomorphological characteristics of the catchment [3, 5]. Amount of reliability, i.e. the error in the amount of the expected flow rate, may vary between 10% and 30% – the error increases with increasing time interval (Blöschl *et al.* [10]).

3 Weather radars

In order to provide an early flash flood warning, it is necessary to find the source of information that could serve as a “trigger” of the processing procedure, in case of exceeding a certain (qualitative) limit, which starts the process of identifying areas at the intense flash floods risk. Data of weather radar seems to be a suitable source of the information enough. Such data provide an overview of the current distribution of rainfall within a rain system monitored by the radar in sufficient spatial and temporal resolution that is significantly higher than standard rain gauge networks and thus able to record even local rainfalls that would fall outside the area covered by automatic rain gauges and would therefore not be captured by the ground monitoring network. This is often the case of the intense rainfall over a relatively small area.

Radar data are affected by a variety of errors. Data description, analysis, quantification and impact on the accuracy of estimated rainfall have been investigated in a number of works [11–13]. The errors are mainly due to incorrect procedure during calibration of the radar, signal attenuation, increased reflectivity in a melting zone, anomalous propagation, eventually blocking of the beam and a height of the lowest beam.

For the quantitative estimation of precipitation, an adjustment of radar precipitation is usually carried out, based on editing the precipitation system derived from radar data using values measured by automatic rain gauges. The main disadvantage of this case is the time delay in the results delivery.

There are also other methods used, such as nowcasting, but real possibilities of all these methods are largely reduced due to the rapid dynamics of convective clouds, the source of extreme rainfalls. The exact location of occurrence, duration and intensity of extreme rainfall and thus the area of an eventual occurrence of flash floods is not possible to predict so far. For these reasons, the only rate of potential risk of flash floods is being usually evaluated.

4 Our approach

From our perspective, the basic drawback of existing approaches is the *attempt to the real prediction of the extreme rainfall, its subsequent quantification and modeling the local response to the predicted extreme rainfall*. It is generally known that the necessary data input for these procedures is affected by a high degree of uncertainty (Březková *et al.* [14]). Our goal was therefore to find a procedure that will work with a minimum of input data and will not rely on rainfall-runoff models. Such a procedure will be generally applicable also to areas without availability of detailed information and therefore without possibility to create a rainfall-runoff model.

Our approach is therefore different: we work with current data from the weather radar and we derive from them a (purely qualitative) information needed to issue warnings for municipalities potentially affected by rainfall-runoff. Our goal is therefore not to provide an accurate determination of the extent of the flooded area, but rather to notify timely residents in affected areas in order to allow them to leave safely the endangered area and thus to prevent particularly losses of human lives. With respect to the fact of the velocity at which flash flood occurs, the ambition of the developed way of data processing to rescue also properties and belongings is minimal. The time span between the occurrence of extreme rainfall and succession of the flash flood is from tens of minutes to early hours, what is the time sufficient just enough to save human lives. In addition, flash floods may occur even in areas with almost no rainfall if these are located downstream along water streams, draining areas affected by extreme rainfall. That makes timely release of warning to residents even more valuable.

Therefore, we have established following requirements:

- to perform only a qualitative evaluation, without quantification e.g. in the form of predictions of water levels in streams, extent of flooded area, etc.,
- for simplicity, to assume fully saturated catchment (i.e. the worst possible option),
- to identify areas affected by extreme rainfall based on monitoring of data from weather radars,
- to evaluate the amount of rainfall relatively,
- to evaluate the risk of flash floods for individual segments of watercourses, and
- to issue a warning in case of increased risk.

In the present, our approach accounts runoff within the individual catchment only. Surface runoff is neglected at the moment – our approach isn't focused on the indication of potential issues caused by surface runoff. These issues require a different approach, and. therefore, they will be addressed through further research.

5 Case study

Due to the uniqueness of rainfall episode from 6th and 7th of August 2010, which hit the region of northern Bohemia in the Czech Republic, we decided to verify whether our proposed methodology was able, even under conditions of this event, to identify hazardous watercourses in the area and to give an early warning of floods. This event took place simultaneously in two adjacent catchments with similar characteristics – the Lužická Nisa River and the Smědá River basins.

5.1 Description of the area of interest

Lužická Nisa River is a left side tributary of the Oder River. It rises in the Czech Republic on the southern slope of the Jizerské hory Mts. at an altitude of 765 m. From its total length of 252 km, the Czech section is 55.1 km long. The total catchment area in the Czech Republic, Poland and Germany is 4297 km^2, the Czech part spreads into area of 375.3 km^2 (Tomášek [15]). The catchment area of the Smědá River continues to the north to the Czech part of the Lužická Nisa River catchment area. It is a right side tributary of the Lužická Nisa River in the territory of Poland. Smědá River rises on the northern slopes of the main ridge of the Jizerské hory Mts. at an altitude of 875 m. The river is 51.9 km long, of which 45.9 km is in the Czech Republic. From the total catchment area of 331 km^2, the Czech part contains 273.8 km^2. Natural features of both catchment basins are quite similar. The upper halves of both catchments in the Czech Republic lie in the rugged forested mountainous terrain of the Jizerské hory Mts. (granites) and Ještědsko-kozákovský hřbet Ridge (mostly phyllites and granites) with large differences in the sea elevation (about 800 meters) between the watershed plateaus and the mountain feet (Czudek [16]).

Steep slopes accompany water courses in deeply dissected valleys from the edge of the plateaus to the margins of the mountains. Foothills at Lužická Nisa River are represented by Žitavská pánev Basin diverging to the north-west, containing a hilly bottom on the crystalline basement and Neogene deposits (clays with layers of lignite), overlain in the western part of clayey sediments of Pleistocene continental glaciation and loess (Pospíšil and Domečka [17]). Behind the mountains, Smědá River flows to the north-west into the rolling hills of Frýdlantská pahorkatina Upland whose varied bedrock consists of pre-Variscan granites and Tertiary volcanic rocks, abundantly covered by slope deposits and glacilacustrine clays (Chaloupský [18]). The average long-term annual air temperature in the upper parts of the both river catchments around 1000 m above sea level reaches 4°C and the annual rainfall is more than 1200 mm, the same air temperature is about 7–8°C with the annual rainfall of 800–1000 mm at the mountains foot [19]. Those natural conditions led to the development of heavy and wet soils as dominantly deforested gleyic albeluvisols and haplic luvisols, pseudogleys and gleys in the foothills, while the forested slopes of the mountains are covered by cambisols, above them entic podsols and haplic podsols [15], and an organosols (peat) on flat watersheds.

5.2 Data sources

For the application of the experimental methodology, we have had following data available:

- map of outlines of 4th level catchments,
- map of the river network, and
- data from weather radars.

We have applied maps of the catchments and the river network provided by the T. G. Masaryk Water Research Institute. We have acquired data from weather radars for this rainfall episode from the Czech Hydrometeorological Institute. We have used in total data from the period from August 6 2010, 22:00 UTC (24:00 CEST) to August 7 2010, 21:30 UTC (11:30 p.m. CEST).

5.3 Results

The success of predictions according to our methodology can be illustrated by a simple comparison of the water discharge culmination and the flow development predicted by us for gauged segments of the rivers with known or estimated values of the culmination time.

We have chosen four examples for the demonstration of our methodology:

- the culmination in the Chrastava municipality at the River Jiřice (the right side tributary of the Lužická Nisa River),
- the culmination in the Hrádek nad Nisou municipality at the Lužická Nisa River,
- the culmination at the Smědá River below the confluence with its tributary the Lomnice River, and
- the culmination in the Višňová municipality at the Smědá River.

Table 1 provides the basic information about the culminations in the selected gauged sites (gauge no. 1, 2 and 4) and the estimation derived from the model for the unmonitored site no. 3.

Table 1: Culmination water flow rates and their repetition time at selected gauging stations; the third row contains only an estimate of the extremity and size of peak discharge in the unmonitored site [1].

No.	Gauge	Water course	Water-shed area	Culmination data				
				Day	Time	Water level	Flow rate	Repetition time
			[km^2]		CEST	[cm]	[m^3/s]	[years]
1	Chrastava	Jiřice	76.3	7 Aug	12:30	433	271	>>100
2	Hrádek n. Nisou	Lužická Nisa	355.8	7 Aug	17:20	395	410	>100
3	Conflict with Lomnice	Smědá	122.4	7 Aug	14:15	---	409	>100
4	Višňová	Smědá	187.5	7 Aug	14:30	541	440	>100

Locations of gauges on watercourses is demonstrated in the Figure 1. For each gauge site and from the evaluated data, we have constructed a course of relative flow rates for individual gauges and compared them with the time at which the real water flow culmination occurred on individual gauge sites.

It is visible within all the courses water flow that they contain two peaks, corresponding to the real development of precipitation in the area. Already usually the first peak signifies the beginning of evacuation at the site. For reader's interest, we have inserted data on the real initial evacuation into some of the figures, where available. As in case of the culminations as well as in case of evacuation, it is evident from the figures that our methodology would allow to indicate a dangerous condition sufficiently in advance to release a timely notification to the population and thus to prevent a fierce evacuation at the last minute with a high probability.

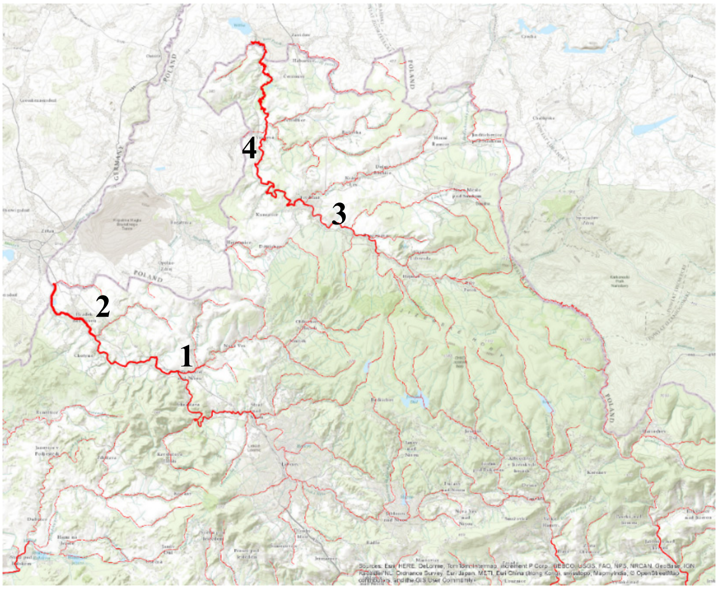

Figure 1: The distribution of evaluated gauge sites on the rivers in the area of interest. 1. Gauge in Chrastava on Jiřice River; 2. Gauge in Hrádek nad Nisou on Lužická Nisa River; 3. Unmonitored site on Smědá River below the confluence with the Lomnice River; 4. Gauge in Višňová on Smědá River (Map base: World Topographic Map, ESRI).

On the gauge no. 1 in Chrastava at Jiřetice River, the culmination happened at 12:30, while our methodology predicted the culmination of a half hour in advance, as is visible in Figure 2. The comparison with the times of evacuation is interesting: at 9:05 – the evacuation of some parts of Chrastava was already running in the area adjacent to the Jiřetice River which was already being flooded. It would be possible to infer the threat of flooding within several hours in advance from the predicted curve. One hour later, the citizens were evacuated from other parts of the municipality located further from the Jiřetice River flow when people were already waiting for the rescue on roofs of their submerged houses. Also here a warning would be possible several hours in advance.

On the gauge no. 2 in Hrádek nad Nisou at Lužická Nisa River (see Figure 3), the culmination discharged at 17:20. Also here, it can be observed that it was possible to predict the culmination within several hours in advance. However far more important, it would be possible to release the indication of the flood danger in the city itself early enough. The first evacuation took place already after 9 a.m.

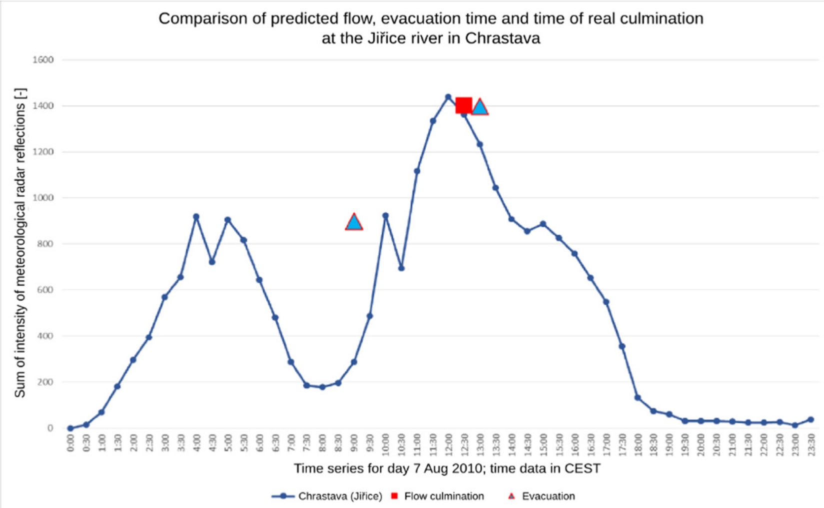

Figure 2: Course of relative flows in Chrastava at Jiřice River (gauge 1). The culmination of the flow occurred at 12:30. The first evacuations happened at 9:05, at 12:52 people were still waiting on rooftops.

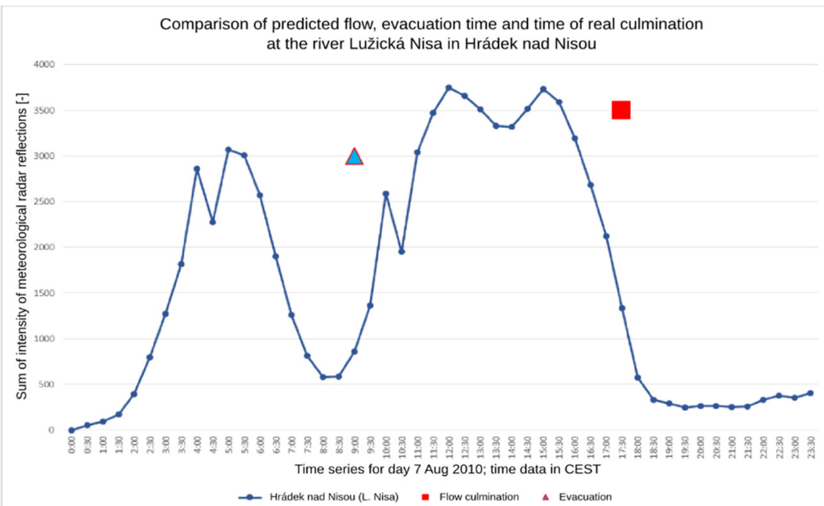

Figure 3: Course of relative flows in Hrádek nad Nisou at the Lužická Nisa River (gauge 2). The culmination of the flow discharged at 17:20. The first evacuations started already at 9:06.

while the threat of flooding could be predicted already within a few hours earlier. In the case of site no. 3, the information about the start time of the evacuation wasn't available, however also here it is visible from the depicted waveform in the Figure 4 that it would be possible to release a sufficient advance flood threat warning for the municipality. The prediction of the peak water flow forestalled the real culmination for two hours. Even in case of the gauge no. 4 we did not have any information about the start time of the evacuation, but even here it was possible to provide a flood threat warning already at around 10 a.m. (see Figure 5).

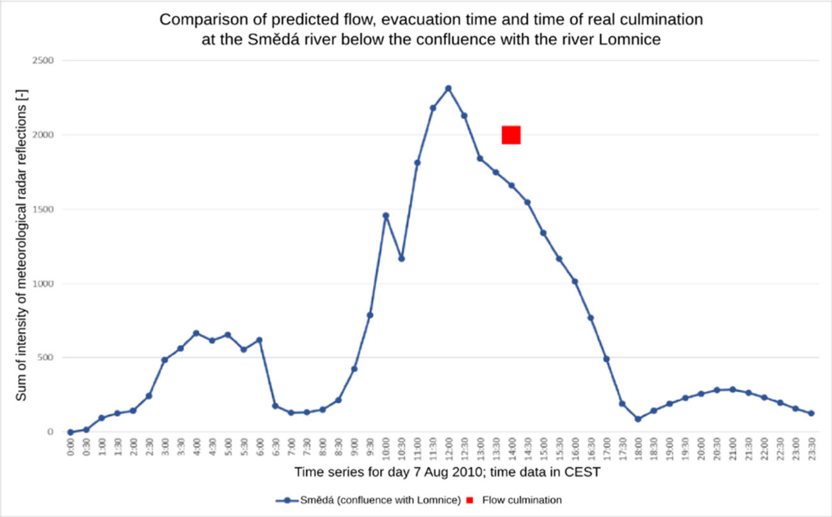

Figure 4: Course of relative flows at Smědá River below the confluence with the Lomnice River (site 3). The culmination at the water flow has been estimated on the basis of modelling as at 14:15.

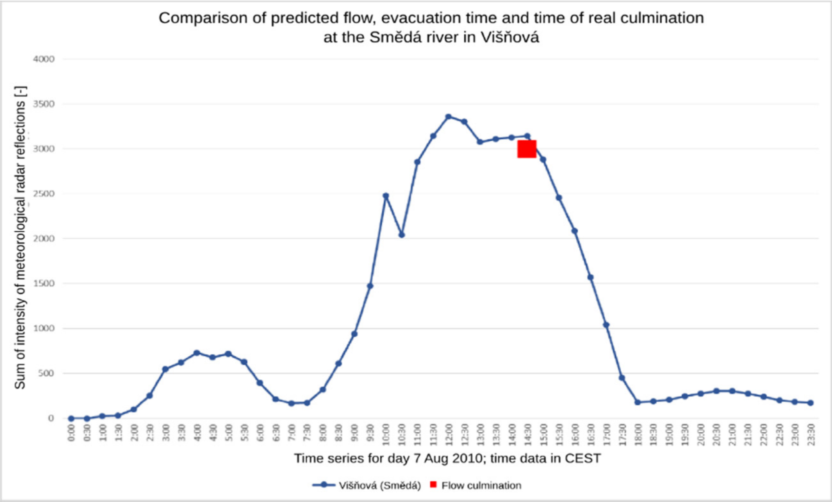

Figure 5: Course of relative flows in Višňová at Smědá River (gauge 4). Culmination discharged at 14:30. Data on the evacuation not available.

6 Discussion

The currently applied or developing processes to predict extreme rainfall and rainfall-induced flash floods work normally with quantified data, such as saturation of the area by previous rainfall, radar estimation of precipitation in millimeters of water column etc. (see [2]). These processes are dependent on a large amount of input data, which on one hand are not always available and on the other hand their processing may cause a delay in the prediction behind the progress of the situation, due to strict time demands. From this perspective, our approach is significantly simpler, more operational, but it is necessary to repeat again that it allows only to generate a warning of danger, without any quantified estimation of the impact (e.g. demarcation of the flooded area etc.).

On the other hand, the given speed of development of the situation in case of flash floods raises the question to what extent the quantified information is really needed. The primary concern in this situation is to save human lives, thus in this case a rapid notification of residents and their fast transfer by their own to locations within higher positions of the affected municipality.

In the present step of the research, our goal was to find the simplest methodology of the indication of flash flood threats, based on the minimum data input and the methodology applicable almost in any area. Therefore we have abstracted the information from the surface runoff – we have focused only on runoff in watercourses. This limitation is relatively rigorous at the first glance, but the methodology has proved an easy applicability and it provides interesting results. The issue of the surface runoff will be investigated by the further research Followed by joining the two methodologies, a robust process flash floods threat assessment will be completed.

7 Conclusions

The proposed procedure represents a simplified way to predict the possible occurrence of flash floods in the endangered territory and to generate early warning information for potentially affected municipalities. Our aim was to verify if the procedure is applicable also in the initial phase of regional floods. It is agreed that upon completion, the proposed method will be implemented into the system (Vondrak [20]), which is developed at the VŠB-Technical University of Ostrava for the needs of the Integrated Rescue System of the Moravian-Silesian Region. It is focused on the current flood prediction and is to be developed also towards the prediction of flash floods.

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