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Flood evolution assessment and monitoring using hydrological modelling techniques: analysis of the inundation areas at a regional scale

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Abstract. The primary objective of this study is to present techniques that cover usage of a hydrodynamic model as the main tool for monitoring and assessment of flood events while focusing on modelling of inundation areas. We analyzed the 2010 flood event (14th May – 20th May) that occurred in the Moravian-Silesian region (Czech Republic). Under investigation were four main catchments: Opava, Odra, Olše and Ostravice. Four hydrodynamic models were created and implemented into the Floreon+ platform in order to map inundation areas that arose during the flood event. In order to study the dynamics of the water, we applied an unsteady flow simulation for the entire area (HEC-RAS 4.1). The inundation areas were monitored, evaluated and recorded semi-automatically by means of the Floreon+ platform. We focused on information about the extent and presence of the flood areas. The modeled flooded areas were verified by comparing them with real data from different sources (official reports, aerial photos and hydrological networks). The study confirmed that hydrodynamic modeling is a very useful tool for mapping and monitoring of inundation areas. Overall, our models detected 48 inundation areas during the 2010 flood event.

1. Introduction

The floodplains of rivers play a significant role in hydrological cycles, and an understanding of floodplain hydrodynamic processes is therefore important for assessing and monitoring of water movements within river catchments [18]. Inundation areas may have different patterns and different histories of formation within the floodplains. They are very dynamic and their evolution is often very fast during flood events. Characterization of inundation areas and their dynamics over local geographical regions has been investigated using different hydrological techniques with different degrees of accuracy. In general, these techniques are based on the detection and estimation of the extent of inundation areas. The timing, extent, duration, and inter-annual variability of floodplain inundation are major drivers of floodplain ecosystem function [10].

There are a few major approaches for mapping inundations: (a) application of remote sensing techniques (e.g. microwave and optical satellite sensors – these two types of remote sensors are suitable for inundation detection) [16, 9], or (b) usage of hydrological models (e.g. hydrodynamic models) [13, 1]. Both approaches may provide information on the inundation dynamics of the region [16]. The combination of these approaches has been investigated by using assimilation methods in a few studies [8, 6]. This study is focused on the second approach, and thus, we used hydrodynamic model HEC – RAS ver.4.1 for our experiments. Specifically, we used a combination of hydrodynamic and rainfall-runoff models (HEC-HMS). The common outputs from hydrodynamic models are the spatial and temporal changes of inundated areas [12].

There are many studies that use hydrodynamic models for mapping inundation areas on the global or local scale. Rudorff et al. (2014) [13] used the hydrodynamic model LISFLOOD-FP for studying of the inundation dynamics for the large Amazon river floodplain (area 2440 km^2). Yamazaki et al. (2011) [17] proposed a new global river routing model, CaMa-Flood, that explicitly parameterizes the subgrid-scale topography of a floodplain, thus describing floodplain inundation dynamics. Several studies have used hydrodynamic models to estimate the dynamics of water for small areas based on gauge data [5, 4].

The primary objective of this study is to present techniques that cover usage of hydrodynamic modelling as the main tool for monitoring and assessment of flood event with focus on inundation areas. Data from local water networks and remote sensing data were used for analysis.

2. Study area

The Moravian-Silesian region (MSK) is located in the north-eastern part of the Czech Republic. The geography of the region is varied and contains many different landforms (e.g. the Moravian-Silesian Beskids and the Moravian Gate). Hydrologically, the area is divided into four main catchments: Odra, Ostravice, Olša and Opava catchments (figure 1).

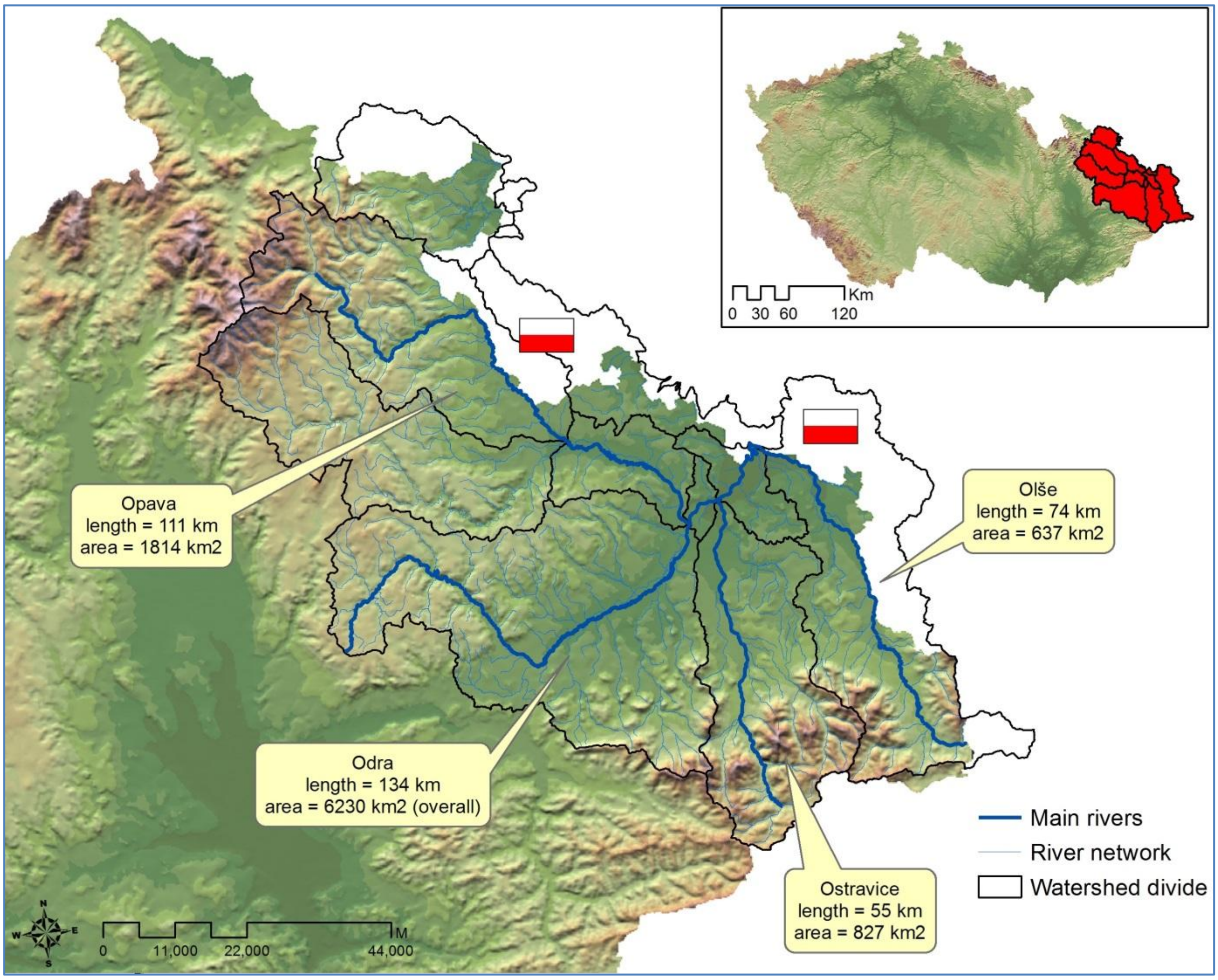

Figure 1. Study area with highlighted major catchments.

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2.1. Precipitation situation during flood event

For our experiment, we used data of a flood event that occurred from 14th May to 20th May 2010 in the Moravian-Silesian region. The precipitation situation during the flood event was described by [2]: "More than 100mm fell in the 24 hours to the morning of 17 May in the border region of Poland and the Czech Republic in the Western Beskids, not far from the border with Slovakia. The highest rates were approx. 180 mm (figure 2). The following day brought precipitation averaging about 80mm with a maximum of 115 mm, followed by a further 50 mm next day. At the stations, Lysa Hora (catchment of the river Odra) and Bielsko-Biala (river Vistula) about 320mm was measured during this period. The area of precipitation was small and stationary. Only 22mm fell south of the Western Beskids."

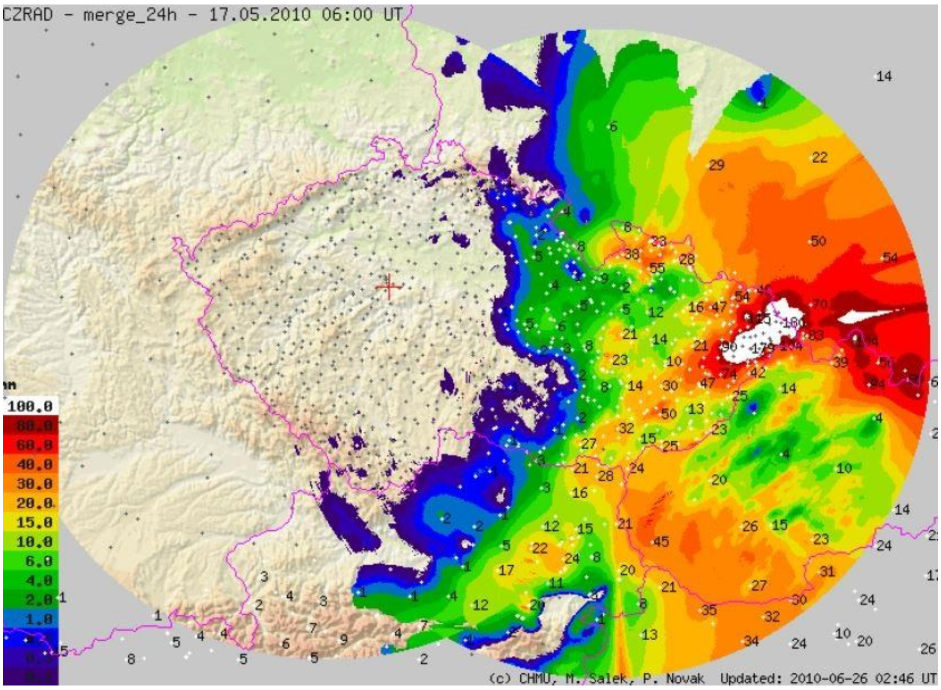

Figure 2. Daily rainfall intensity (from 16th May 8:00 CET to 17th May 2010 8:00 CET) source: CHMI 2010.

3. Methods

3.1. Topographical and hydrological data

The topographic component plays a key role in hydrodynamic flood modelling accuracy. A typical approach used to display topography is the LIDAR [3] or photogrammetry method. The input DEM in this study was created using photogrammetry data from 2010 (resolution 10x10m). The topographical dataset was evaluated by means of RMS (Root Mean Square) error in two parts: (a) floodplain area, and (b) land out of the floodplain. Overall, nearly 250 GCPs (Ground Control Points) were used for evaluating (150 points were placed within the floodplain area). The vertical accuracy of the DEM reached 0.49 m in the floodplain area and 0.75 m out of the floodplain.

Evaluated DEM was used as a background for deriving further data, which are necessary for numerical modelling. Cross-sections were derived from input DEM, and then they were incorporated into the 1D hydrodynamic models. The created cross-sections were compared and completed with real field measurements (approx. 50 cross-sections were geodetically measured). Values of the Manning roughness coefficient were attached to the river channel (range 0.035 – 0.04) and overbank areas (taken from aerial photographs).

Tributaries to the main rivers were recorded via 85 gauging stations. In this research, hourly observations of rainfall discharges water levels and temperatures at the above gauging stations for the period from 14th May to 20th May 2010 were used. The runoff from areas without any water stations was computed by simple rainfall-runoff simulations.

3.2. Hydrodynamic modelling

The calculation of river overflow and inundation areas was achieved by four hydrodynamic models (one model = one catchment). In order to study the dynamics of the water, we applied unsteady flow simulation to the entire area (HEC-RAS 4.1). For unsteady flow, a mechanism was based on Saint-Venant equations. The relation (1) is applied to the continuity equation, whereas relation (2) is applied to dynamics [14].

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \quad (1)$$

$$\frac{\partial \mathrm{y}}{\partial \mathrm{x}} + \frac{\partial \mathrm{y}}{\partial \mathrm{x}}\left(\frac{\mathrm{aQ}^2}{\mathrm{A}}\right) + \mathrm{gA}\frac{\partial}{\partial \mathrm{x}}\mathrm{h} + \frac{\mathrm{gQ}|\mathrm{Q}|}{\mathrm{C}^2\mathrm{AR}} = 0 \quad (2)$$

where: h = lateral inflow, Q = discharge, a = momentum distribution coefficient, C = Chezy resistance coefficient, A = flow area, g = gravitational acceleration, and R = hydraulic or resistance radius.

Boundary conditions were entered to all open ends of the model schematization. The upstream boundary conditions were chosen as flow hydrographs (relationship discharge and time) whilst downstream conditions were entered as a rating curve (relationship discharge and stage). Flow hydrographs and rating curves were constructed from real measurements provided by water stations.

3.3. Rainfall-Runoff modelling

Rainfall-Runoff modelling results were used for ungauged parts of the catchment. At this point, semi-distributed model HEC-HMS was used as an appropriate approach for such a task. The method SCS-CN (Soil Conservation Service) was selected for determining the amount of direct runoff from a rainfall [15]. Basically, the curve number is an empirical parameter that is based on the hydrologic soil group, land use and hydrologic conditions (range of CN was from 30 to 98).

3.4. Platform for monitoring

The hydrological models made in this study were incorporated into the Floreon+ platform [11]. In this case, Floreon+ was mainly used as a tool for semi-automatic monitoring of inundation areas within the study area. The Floreon+ system is developed for monitoring, modelling, prediction and support in disasters, and it is primarily intended for the Moravian - Silesian Region. As it is a web-based platform, its modularity and responsiveness allows easy integration of various thematic sections, regions and data. Its main contribution is at the area of disaster management support, not only the processes but also in the way of simulations. The system is currently comprised of: (1) prediction and monitoring of flooding, (2) modelling of air pollution caused by leakage of dangerous substances and (3) monitoring of real-time traffic situations [11].

4. Results

We analyzed the 2010 flood event (14th May – 20th May) that occurred in the Moravian-Silesian region. Under investigation were four main catchments: Opava, Odra, Olše and Ostravice. Four hydrodynamic models were created and implemented into the Floreon+ platform in order to map the inundation areas that arose during the flood event. However, the hydrodynamic models did not cover the entire domain because the mainly upstream parts of the catchments are not covered by important data (lack of information about channel geometry, no water stations, streams too small for modelling-insufficient DEM resolution).

Inundation areas were monitored, evaluated and recorded semi-automatically by means of the Floreon+ platform. We focused on information about the extent and presence of the flood areas. The modelled data obtained from the semi-automatic process are depicted in table 1 (For detailed information about methods and algorithms for flood areas detection, please visit Floreon+ internet pages – floreon.it4i.eu).

Table 1. Results of semi-automatic process for inundation areas.

Catchment	Modelled area (%)	No. of detected flood areas	First occasion (time/date)	Flood area < 1 km^2	Flood area 1 km^2 <x<5 km^2	Flood area > 5 km^2
Ostravice	70	20	01:00/17th May	14	2	4
Odra	70	14	07:00/17th May	9	5	0
Olše	40	8	20:00/16th May	6	1	1
Opava	20	6	08:00/17th May	6	0	0

First, inundation areas were detected after two days of rain in the north-east part of the study area (specifically – Olše and Ostravice catchment). This was expected because the storm was stationary over this part of the region. As an example, we introduced the situation within the inhabited area in the Ostravice catchment (figure 3). In this example is depicted the inundation dynamics every 6 hours during May 17th. This inundation area was confirmed (presence as well as an area of inundation), and thus, in this case, the hydrodynamic model worked well. Fortunately, this area was densely covered by all kinds of hydrological data, and therefore the validation process was fully completed (mainly, aerial images were helpful).

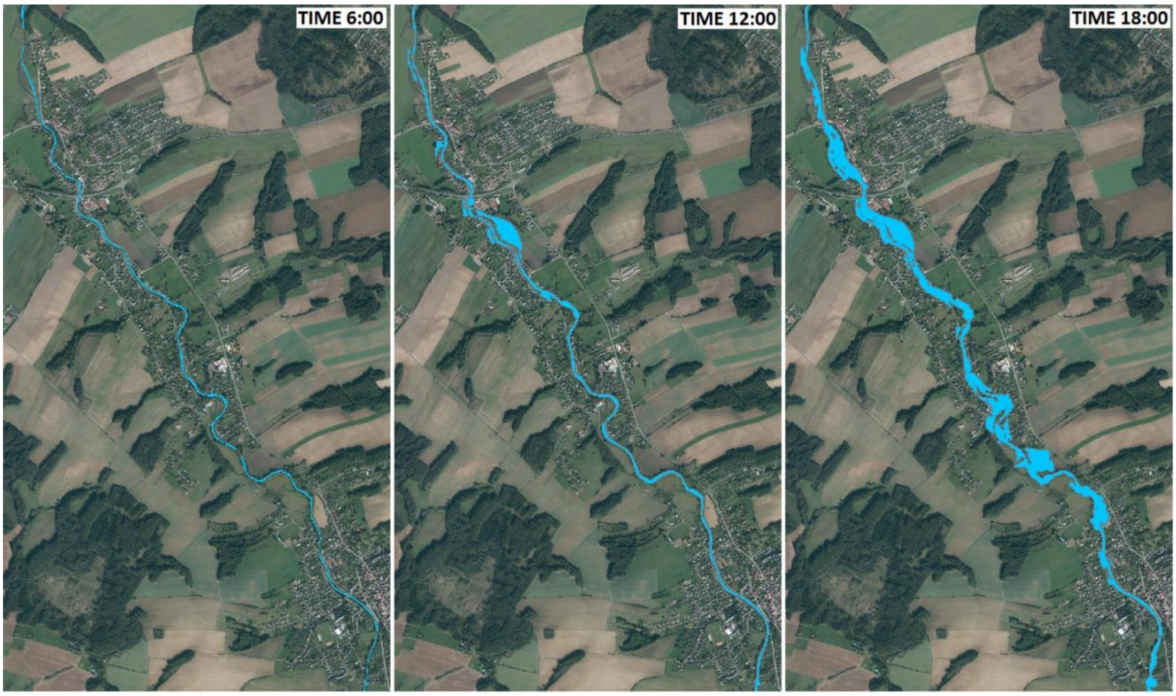

Figure 3. Inundation dynamics (6 hour step, 17th May 2010, part of Ostravice catchment, inhabited area).

A different kind of example is a situation within an uninhabited area. We recorded 44 inundation areas in uninhabited areas, but only 16 of them were confirmed by validation data (36%). In the case of unconfirmed areas, there is a problem to determine if the flooded area was created by real water conditions or it is an error of the hydrodynamic model. In figure 4 is depicted an example of the uninhabited area at the confluence of Odra river with two major tributaries (Lubina and Ondřejnice).

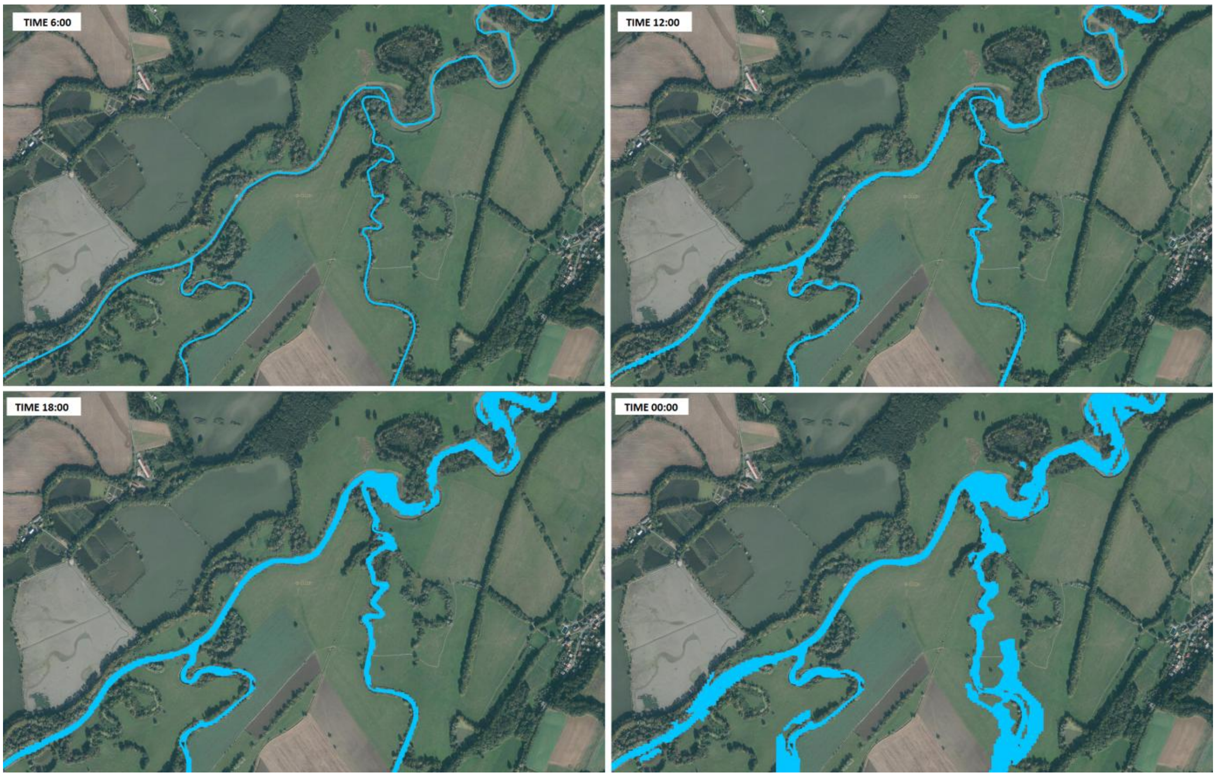

Figure 4. Inundation dynamics (6 hour step, 17th May 2010, part of Odra catchment, uninhabited area).

As a result of the stationarity of the severe storm, all inundation areas bigger than 5 km2 were created within the Olše and Ostravice catchment (north-east part). Partly affected were the Odra and Opava catchments, and thus no inundation areas with such extent were detected. Extremely important is the fact that all inundation areas bigger than 5 km2 were detected and localized correctly.

Flood areas in the MSK region were verified by comparing them with data from different sources (official reports, aerial photos and hydrological networks). However, these sources did not cover the entire study domain and therefore this study suffered from an inability to determine the presence of some inundation areas in uninhabited areas.

5. Conclusion

This study revealed the following conclusions: (1) Hydrodynamic models detected 48 inundations during the 2010 flood event within the MSK region. (2) The presence of 20 areas was confirmed by validation data. (3) 8 were fakes (model detected but no presence in the land), which was confirmed by validation data (4) 10 were placed out of the range of validation data, and therefore we cannot say whether they existed or not. (5) All inundation areas bigger than 5 km^2 were detected and estimated correctly. (6) All fakes were inundations with sizes less than 1 km^2. (7) The first flood area was detected after two days of heavy rains in the Olše catchment.

The presence and size of flood areas were evaluated based on three simple categories in this study. The study confirmed that hydraulic modeling is very useful tool for mapping and monitoring of inundation areas. This approach can bring helpful information about the size, distribution and evolution of flooded areas, and these data may therefore have high value for prevention and protection against floods in the MSK region.

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