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The impact of disturbance on the dynamics of fluvial processes in mountain landscapes†

Jakub Langhammer[1,*], Filip Hartvich[1,2], Zdeněk Kliment[1], Michal Jeníček[1], Jana Bernsteinová (Kaiglová)[1,4], Lukáš Vlček[1], Ye Su[1], Přemysl Štych[1], Jakub Miřijovský[3]

[1]*Faculty of Science, Charles University in Prague, Albertov 6, CZ-12843, Prague 2, Czech Republic*
[2]*Institute of Rock Structure and Mechanics CAS, V Holešovičkách 94/41, CZ-18209, Prague 8, Czech Republic*
[3]*Faculty of Science, Palacký University, 17. listopadu 50, CZ-77146, Olomouc, Czech Republic*
[4]*DHI Hydroinform a.s., Na Vršich 1490/5, Prague 10, CZ-10006, Czech Republic*
[*]jakub.langhammer@natur.cuni.cz

Abstract
The central part of Bohemian Forest represents important headwater region in central Europe, which plays important role in runoff generation. The area that is recently preserved at both Czech and German side as the National Park (Šumava National Park and Nationalpark Bayerischer Wald, respectively) has in past decades undergone extensive forest disturbance and is experiencing effects of ongoing climate warming. The research was focused on the effects of these factors as driving forces altering the natural runoff regime and associated fluvial dynamics of streams in mid-montane environment. The research project focused on changing dynamics of runoff and fluvial processes stemmed on preceding long-term research and built monitoring network that enabled to analyse the changes of dynamic processes at high level of spatial and temporal detail. The main objectives of research were (i) analysis of the principal forces, affecting the natural dynamics of runoff and fluvial processes in the area, (ii) analysis of the changing runoff response at different scales in the central part of Bohemian Forest, and (iii) to analyse the spatial and temporal patterns of recent dynamics of fluvial processes. The research was based on implementation of the latest technologies for non-invasive surveying, detection and monitoring of dynamic processes, including the automated sensor network for rainfall/runoff monitoring, the drone-based photogrammetry, terrestrial LiDAR scanning, optical granulometry, or electric resistive tomography.

Key words: runoff, fluvial dynamics, forest disturbance, climate change, Bohemian Forest

Introduction

The research of the effect of landscape disturbance and changing climate on the runoff response and fluvial dynamics is follow-up to the long-term research of hydrological processes in Bohemian Forest headwaters, aimed to the analysis of retention potential of the landscape and the effects of floods. The research project was aimed to analysing the impact of ongoing landscape disturbance and climate warming on the changing dynamics of runoff and fluvial processes in the headwater area of the upper Vydra basin.

The research was aimed to provide answers to the following research questions: (i) what are the key forces that drive changes to runoff dynamics and fluvial processes in montane regions; (ii) how significant is the role of landscape and forest disturbance in changing runoff response, governing the fluvial processes; and (iii) what are the spatial patterns and temporal dynamics of fluvial processes in streams?

† **Project guarantor** is Jakub Langhammer (jakub.langhammer@natur.cuni.cz).

In respect to these research questions there were addressed following major fields of research:

The first research aim of the project was the analysis of landscape disturbance and stream modifications in study area to determine the dynamics for different forms of disturbance within the study region. The majority of both rapid and protracted landscape changes is associated with changes in land use and land cover due to anthropogenic activities such as farming, constructing settlements, deforestation, or forest management techniques. One of the most important processes in montane regions is forest disturbance and decay, which were studied in the project. The forest disturbance can be caused by different factors including industrial air pollution, windstorms, widespread felling, or the spread of bark beetle.

The spatial and temporal dynamics of different types of forest disturbance within the study area were analysed as they represent here the dominant forms of landscape disturbance. The modification of streams in montane regions has a very significant effect on runoff dynamics as well as on the supply of material and fluvial morphology. The artificial modification of streams and riverbeds were analysed as well as the extent to which the drainage and road networks are important in affecting runoff dynamics during extreme events.

The second research aim was to analyse the effect of the key driving forces acting in the area – the changing climate and landscape disturbance on the runoff process. This enabled to identify the driving forces responsible for these changes and assess the influence of different initial physiographic conditions and differences caused by variation in the magnitude of the rainfall-runoff event.

The analysis focused on different aspects of runoff dynamics – from regional-scale analysis of shifting runoff patterns to the analysis of changing dynamics of runoff at the level of experimental catchments. The statistical analysis of time series was employed in order to identify changes in runoff dynamics within a number of catchments. Using non-linear statistical techniques, the detected changes in runoff dynamics and landscape/forest disturbance, stream modification, and the drainage and road networks were analysed.

Hydrological and hydraulic models were used to simulate the propagation of flood waves in selected stream segments. Using the MIKE SHE model there was built a hydrodynamic model covering the Czech and German part of the area namely the upper Vydra and Grosse Ohe basins to study and understand the changing response and dynamics of runoff processes.

The rapid development in surveying technologies and analytical techniques enabled to study the dynamics of fluvial geomorphology in the area in high level of spatial detail and by non-invasive techniques. The aim of the research was to assess the natural dynamics of fluvial processes in the headwater region in response to the runoff events. The primary interest was to analyse the natural fluvial dynamics of the environment, to identify the triggering mechanisms and to assess the effect of disturbances on the fluvial processes in stream channels, floodplain, and valley floor.

Combination of non-invasive field survey techniques was applied to disclose spatial patterns and dynamics of the fluvial activity. Field mapping was applied to understand spatial distribution of fluvial activity after the flood in June 2013. To achieve high precision of survey, the new and emerging approaches were applied in surveying. The unmanned aerial systems (UAS or drones) were used to repeatedly derive extremely precise digital elevation model of the area and its changes. The optical granulometry was used to analyse the changing granulometric distribution of material after the flood events. We have used the hydrodynamic model coupled with the sediment transport module to analyse the thresholds of forces, triggering fluvial processes in relation to the initial runoff events to understand the response of the changing environment.

Materials and methods

Project duration

Monitoring of rainfall–runoff processes using the automated sensor network in 10 experimental catchments in the upper Vydra basin commenced in 2005 and has been continuously maintained for the future as core research facility. The field survey and mapping of fluvial dynamics was done in snapshots capturing stream changes after flood events in 2002, 2009 and 2013. Monitoring of fluvial dynamics including UAS photogrammetry, optical granulometry, electric resistivity tomography, or bedload tracking in selected active stream segments has commenced in 2012.

Site and method description

The study area of the project and follow-up research consist of a set of experimental catchments in headwaters of the central Bohemian Forest. The core of the study area where most of monitoring and survey activities occur is in the upper Vydra basin, completed by the reference monitoring sites in the Blanice and Volyňka Rivers.

Monitoring of rainfall–runoff processes

The core study area is the upper Vydra basin, where 10 experimental catchments equipped with automatic water level monitoring are operated. The experimental catchments are comparable in terms of size and basic physiographic parameters, but differ in terms of patterns of forest vegetation, management practices, and the intensity and nature of the disturbance.

The automated sensor network, continuously build and operated since 2005 is designed for high frequency monitoring of rainfall–runoff processes in the headwaters of the upper Vydra basin. The base of the network represents the gauges for continuous monitoring of the water level using the ultrasonic and hydrostatic pressure sensors at 10 monitoring stations at outlets of key tributaries to the Modravský Potok and Roklanský Potok streams (Fig. 1).

Additional hydrochemical monitoring is carried out in the majority of stations (pH, conductivity, and redox). Air temperature, air moisture, global solar radiation, wind speed, wind direction, precipitation, soil moisture, soil and snow temperatures, snow depth and snow water equivalent are measured in some of the above mentioned meteorological stations, according to the research needs (Fig. 2a). Systematic hydrometric measurements of discharge and control sampling of hydrochemical parameters were carried out to get accurate and up-to date rating curves in each locality with water stage measurement. Two acoustic Doppler velocimeters (i.e. FlowTracker) were used for the measurement (Fig. 2b). Several hydrometric campaigns caught both high and low flows, which were crucial for the accuracy of rating curve.

The sensor network serves as the basis for detailed analyses of runoff response and dynamics, focused on the effect of physiography, landcover and disturbance on runoff generation. The analysis of paired catchments with contrasting landcover is used to disclose differences in daily flow variability between forest and grassland dominated catchments (Kalkus, 2014). The high frequency rainfall–runoff monitoring data are applied for analysis of evapotranspiration (Kofroňová 2014) and interception (Macounová 2014, Nedělčev 2015).

The analysis of peat bogs effect on the runoff response dynamics is a topic of long-term interest. There were identified representative localities for analysis of peat bog hydrological properties in terms of their physical-geographic heterogeneity (Vlček et al. 2012).

Analysis of runoff dynamics is performed on different spatial scales. The analysis of long-term trends of mean monthly discharge data was focused on the large-scale transboundary region of Bohemian Forest to disclose differences between northern and southern slopes of the mountain range (Fiala 2012). The effect of climate change at the complex basin was studied in respect to the hydrological drought (Šachová 2013) and in respect to the peak flows (Kodádková 2014). The complex analysis of changes of the hydrological response of

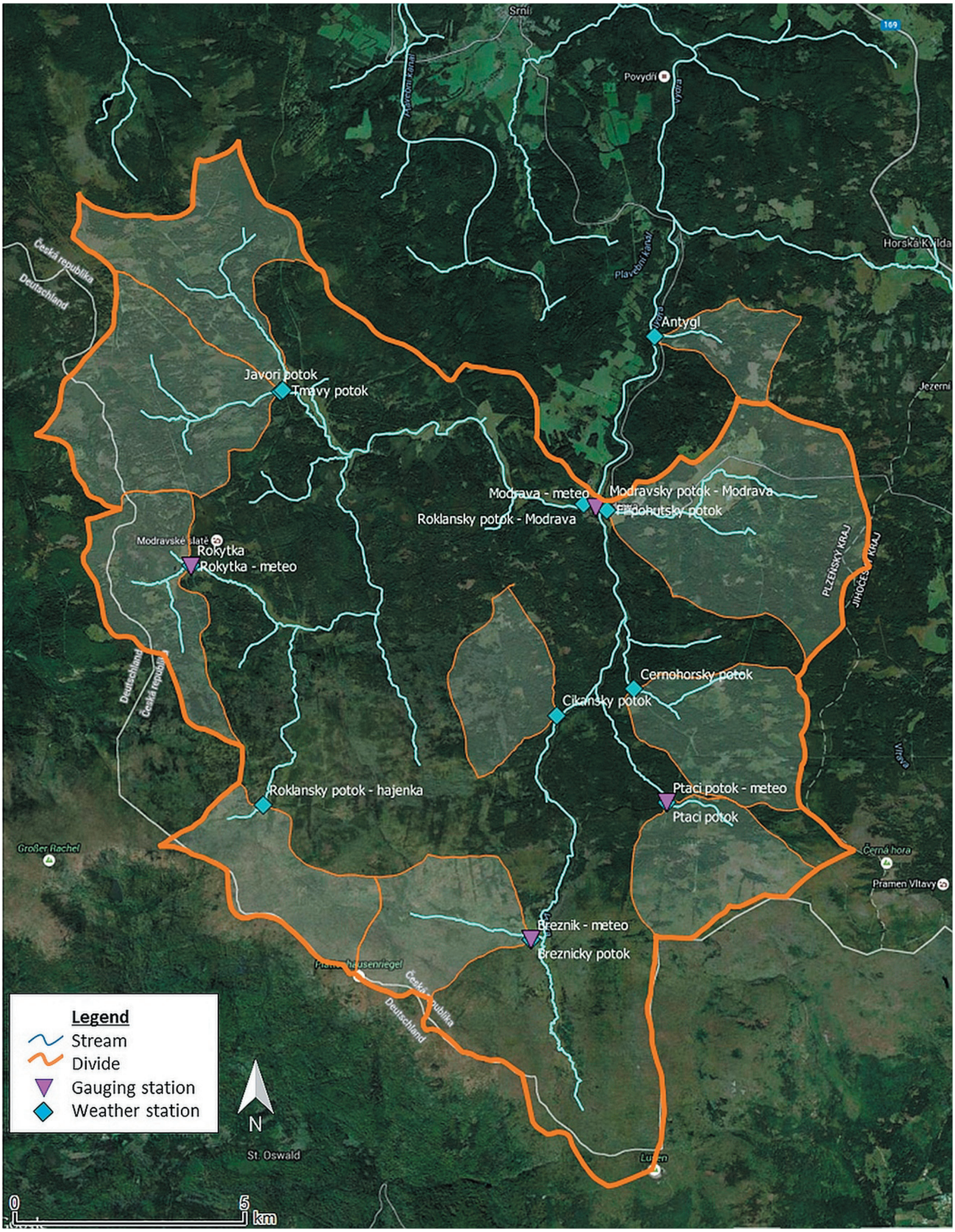

Fig. 1. Study area – the upper Vydra basin with experimental catchments.

a)

b)

Fig. 2. Hydrological monitoring and survey: Automated sensor network, operated by the Charles University at the Březnický Potok gauging station (a); Hydrometric measurement using the FlowTracker velocimeter (b). Photo J. Langhammer, 2012

the upper Vydra basin to the forest disturbance and climate warming was given by Langhammer et al. (2015).

Snowpack monitoring

Repeated measurements of snow depth and snow water equivalent (SWE) are carried out in experimental catchments during winter seasons. The research of snowpack variability and snowmelt rate was based on instrumental monitoring and modelling. All measurements considered different snow depth and SWE distribution in the open area in disturbed and healthy coniferous forest sites.

We performed measurements of the canopy fraction in selected localities in order to make better classification of different types of forest (Matějka 2015). The hemispherical camera (fish eye) was used for imaging at all localities with SWE measurements. Based on hemispherical photography, we calculated skyview factor and leaf area index (LAI). Referenced images also allow us to extract the potential amount of shortwave radiation for each locality.

The research was aimed to disclose the role of physiography and forest cover in snowmelt process (Beitlerová 2012, Fliegl 2013). Analysis of snowmelt rates in different land cover environments (different types of forests and open area) indicated that the differences in snow accumulation and snowmelt in various types of vegetation are caused mainly by the interception and different amount of solar radiation (Kučerová & Jeníček 2014, Jeníček et al. 2012).

Monitoring of fluvial processes

Monitoring of fluvial dynamics and its effects on morphological changes of stream channels and floodplain was based on the latest technologies for non-invasive surveying, detection and monitoring. In particular, we have employed the drone-based imaging and photogrammetry, terrestrial LiDAR scanning, optical granulometry, RFID tracking of bedload material or electric resistive tomography (ERT).

There was started repeated imaging and photogrammetric analysis of selected stream stretches using the UAS platforms. We have used the multirotor Mikrokopter Hexa platform (Fig. 3a) and field photogrammetry to acquire high precision digital elevation model (DEM), enabling reconstruction of the riverbed and of individual erosion and sedimentation forms at selected stretches of the Javoří Potok stream.

Since 2013, the repeated scanning has been used to capture situation before and after flood events to perform quantitative analysis of volumetric changes related to initial events (Fig. 4). The photogrammetric reconstruction enabled to build the accurate DEM of riverbed and floodplain before and after the initial event and to calculate the extent of volumetric changes (Miřijovský & Langhammer 2015).

The detailed geodetic surveys using terrestrial LiDAR scanning (TLS) was performed in 2012 and 2014 on selected reaches of the Javoří Potok stream and the Volyňka River (Fig 3b). The TLS monitoring was focused on the stream reaches, where the fluvial dynamics is evaluated by using complex hydrodynamic modelling approaches in order to find causing conditions of fluvial morphology changes and its variation according to changes in rainfall–runoff conditions.

The snapshot field mapping campaigns analysing the hydromorphological status of streams and flood effects were performed on the core streams of the river system to capture information on spatial distribution of fluvial morphology features and stream modifications (Langhammer et al. 2014, Leipeltová 2014).

The channel and floodplain optical granulometry survey in order to complete data basis a)

b)

Fig. 3. The tools applied for research in fluvial geomorphology: The UAS platform MikroKopter Hexa XL applied for acquisition of detailed DEM (a); The terrestrial LiDAR scanning using Optech Ilris 3D scanner (b). Photo J. Langhammer, 2013

for sediment transport modelling of selected reaches in the Javoří Potok stream and the Volyňka River with the highest fluvial morphology dynamics observed (Skrčená 2013). Two methods were employed. First, the optical granulometry based on digital image scanning and processing was applied for analysis of fluvial depositions outside the stream channel. Second, the conventional field granulometric analysis of in-stream material was used (Bakešová 2014).

Analysis of the recent fluvial activity of the montane streams indicated that despite the lack of stream regulations there is high level of spatial concentration of active fluvial processes into isolated zones. The spots of active bank erosion and accumulations correspond to the distribution of traces of the past fluvial processes. The results, gained from the coupling of UAS photogrammetry, automated sensor network and hydrodynamic modelling indicated that the highly dynamic fluvial processes in active zones are triggered already by the floods with recurrence periods of 2–5 years (Miřijovský & Langhammer 2015).

Monitoring of forest disturbance and restoration

Natural regeneration and vegetation changes were monitored after two main types of natural disturbances in central European spruce mountain forests, bark beetle outbreak, and windfall. In both cases the impact of the original natural disturbance, as well as the impact of anthropogenic disturbance in the form of salvage logging was investigated.

Fig. 4. The high precision digital elevation model (DEM), derived using UAS photogrammetry. The DEM resolution of 2 cm per pixel enables to perform highly accurate calculations of areal and volumetric changes in riverbeds and riparian zone.

The effect of bark beetle disturbance was evaluated in 2012 in 17 permanent research plots, 400 m^2 each, located in the area of Březník. Following types of plots were monitored: (1) The climax mountain spruce forest attacked by bark beetle between 1997 and 1998 resulting in nearly complete mortality of trees in the tree layer. (2) The clear-cut climax mountain spruce forest, which was attacked by bark beetle and completely cut down in 1997. (3) The waterlogged spruce forest attacked by bark beetle between 1999 and 2004 and partly survived (Nováková & Edwards-Jonášová 2015).

The spatial patterns of forest disturbance and regeneration were analysed using various types of multispectral data. Multiple data sources, spectral indices and classification approaches were tested, while the MERIS, SPOT and Landsat data served as the basic data source (Štych et al. 2015). The object-based classification was the main used method for classification of forest, while the accuracy assessment was processed by aerial photographs. The classification based on fusion of multispectral and LiDAR data was tested to detect and analyse the progress of forest disturbance in higher level of precision (Lihanová 2013).

Hydrodynamic modelling

The triggering hydrodynamic factors of and the adequate discharge conditions were examined regarding the non-stationarity of the system proved by the statistical evaluation of the long-term rainfall-runoff relationship. The hydrological response alteration was supported by the deterministic fully distributed 3D physically based hydrological model MIKE SHE. The model covers an area of the upper Vydra basin up to the Modrava station and the upper Grosse Ohe basin up to the Tafelruck station (Bernsteinová et al. 2015).

Hydrodynamic models of the Javoří Potok stream (2D model MIKE 21 FM, MIKE 21 C) and the Volyňka River (1D model, MIKE 11) consisting of detailed topographical data were set up and calibrated by field surveyed data of the flow velocity. The morphological changes

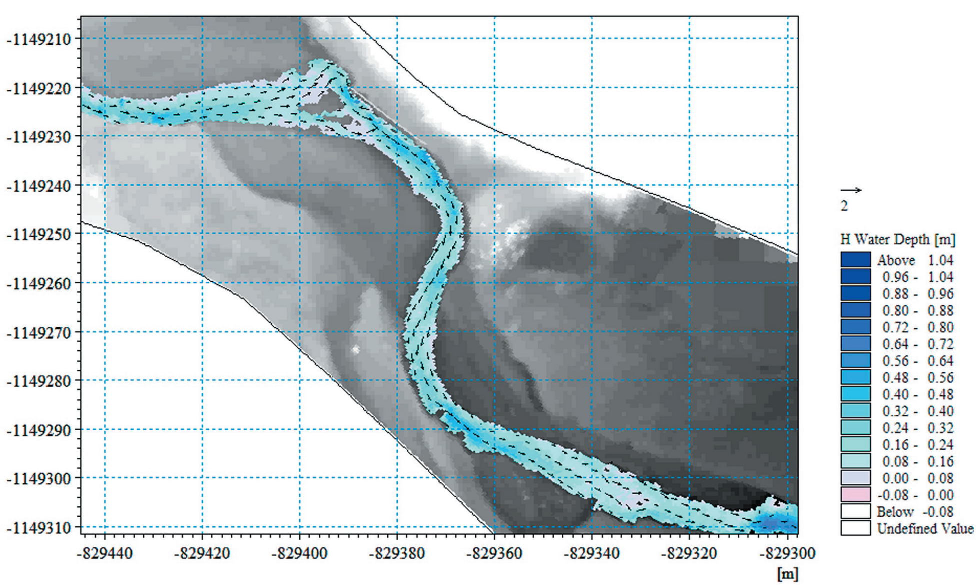

Fig. 5. Hydrodynamic model of a stretch of the Javoří Potok stream, designed to analyse hydrodynamic properties of flow and to identify the thresholds for bank erosion and material transport.

observed from different time horizons evaluated by UAS photogrammetry served for the verification of the simulated bank erosion as a part of the morphological modelling (Fig. 5). The method of the remobilisation competence evaluation was further tested in different geographical conditions (Kaiglová et al. 2015).

Research outputs

The principal research results were published in peer-reviewed journals and presented at international conferences. Besides this, there were 15 master and bachelor theses elaborated and defended based on the topics of the framing research project.

Key findings on the changes of runoff response at the upper Vydra basin in response to forest disturbance and climate warming are given by Langhammer et al. (2015). The first information on the recent fluvial dynamics of streams in response to flooding, resulting from UAS imaging is given by Miřijovský and Langhammer (2015). Findings on the retention potential of the headwater areas are given by Vlček et al. (2012).

The research results were presented as lectures at the principal research conferences in the field: European Geosciences Union (EGU) 2012, 2013 and 2014 in Vienna, International Association of Geomorphology (IAG) 2013 in Paris, or American Geosciences Union (AGU) 2014 in San Francisco.

The research is providing valuable and unique data on the rainfall–runoff processes in the headwater area of Bohemian Forest and information on spatial distribution and dynamics of the fluvial processes in streams, which may serve for further search and as reference information for comparative studies.

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