Philipp Thumser[1], Vyacheslav V. Kuzovlev[2], Kyrill Y. Zhenikov[2], Yuri N. Zhenikov[2], Max Boschi[3], Peter Boschi[3], Martin Schletterer[4]

[1]P. Thumser, I AM HYDRO GmbH - Investigation and Monitoring of Hydrosystems, iamhydro.com, Märtishofweg 2, 78112 St. Georgen, Germany

[2]V.V. Kuzovlev, K.Y. Zhenikov • Y.N. Zhenikov
Tver State Technical University, Chair of Nature Management and Ecology
nab. Afanasiya Nikitina 22, 170026 Tver, Russia

[3]M. Boschi, P. Boschi
droneproject.at, Schneeburggasse 225, 6020 Innsbruck, Austria

[4]M. Schletterer (*) University of Innsbruck, Institute of Ecology
Technikerstrasse 25, 6020 Innsbruck, Austria e-mail: martin@schletterer.co.at

USING STRUCTURE FROM MOTION (SFM) TECHNIQUE FOR THE CHARACTERISATION OF RIVERINE SYSTEMS - CASE STUDY IN THE HEADWATERS OF THE VOLGA RIVER

ABSTRACT. Digital terrain models (DTM) were produced with the structure from motion (SfM) technique, using data from high resolution terrestrial photography. In addition 360-degree spheres were created from ground taken photos. These spheres allow capturing the environment at this moment and coming back to the environment virtually later on. Also overlapping this virtual realty of the environment with model results can be used for distributing study results to a broad audience. On this basis hydraulic and morphological conditions were assessed and compared to field records. The proposed methods enable the creation of a detailed view on different riverine systems, i.e. from small to large rivers. This enables a morphodynamic characterisation which can be linked with the biological dataset of the monitoring project REFCOND_VOLGA. We propose that environmental intelligence gathering using ground-based as well as remote sensing observations can be applied increase the scope of scientific surveillance, and can lead to new opportunities to detect and quantify complex ecological interactions across a wide spectrum of scales.

KEY WORDS: photography, photogrammetry, 360° panorama, environmental intelligence

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INTRODUCTION

A wide range of applications and benefits of this novel image-based remote sensing technology is already shown (Everaerts 2008; Remondino et al. 2011; Nex and Remondino 2013; Whitehead et al. 2014), mostly taking the sensors up in the air with a Unmanned Aerial Vehicle (UAV), but surveys are basically also possible from the ground. Systems with advanced measurement equipment have become smaller, safer, and more efficient, due to advances in materials, electronics and software. A common application is the generation of high-resolution geo data, with a relatively small expenditure of time. Besides interesting new perspectives on nature, the most promising advantages of this new technology are a decrease in time and effort for surveying as well as an increase of safety and accuracy.

For claiming a fast method, a new approach was derived from photogrammetric analyzes of satellite and aerial imagery: the Structure from Motion (SfM) (Fig. 1) method (Snavely et al. 2006, 2007). Both photogrammetric and SfM generated geo data and their accuracy have been proofed over the last decades, now both on large scale and small scale (Eisenbeiss and Zhang 2006; Mancini et al. 2013; Hugenholtz et al. 2013; Smith and Vericat 2015; Smith et al. 2015). Related to progress in software development and increases in computer performance, the generation of digital elevation models (DEM) and orthomosaics imagery using SfM is becoming increasingly common.

Therefore the application of this technology within the field of hydro sciences and engineering is a promising tool, especially for modeling purposes. Hydraulic models are used and developed commonly, to study a variety of hydrogeomorphic processes as well as to design river rehabilitation projects. Advances in hardware and model coding bring model application and performance to new levels (Barker et al. 2010). Boundary conditions for hydraulic models as well as changes from erosion and deposition of sediments can be tracked through transect measurements over long periods (Klein et al. 2007). Natural and near-natural rivers often feature a large variety of morphological characteristics, which cannot be measured simply as a series of two-dimensional transects (Buffington and Montgomery 2013). This leads to the necessity of increasing advances in data ascertainment, especially in topographic mapping, to provide data for driving these large and detailed simulations. For larger scale this can be performed with Aerial Photogrammetry (Dietrich 2015) and Airborne Laser Scanning (ALS) (Charlton et al. 2003). But they are also limited by equipment costs, which can become critical considerations for smaller projects or if surveying has to be conducted regularly with these methods. UAV can be one solution for this situation, but depending

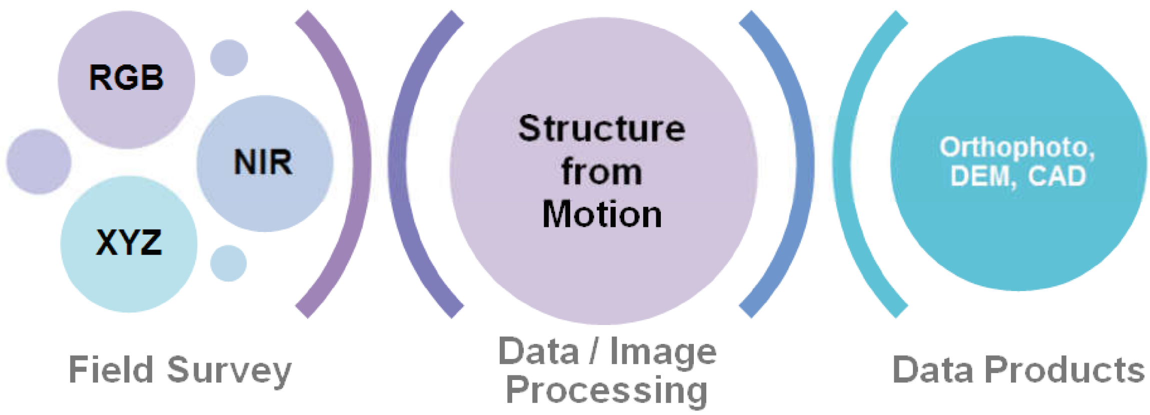

Fig.1. The structure from motion (SfM) technique increases scope and accuracy of river surveys.

on regulations also UAV flights might not be possible, especially when date and time for the field survey are fixed very shortly before starting. Also for practical reasons other solutions can be easier to conduct compared to ground based survey, e.g. for very remote places with re-charging opportunities.

Overall image (photo) based surveys and post-processing with SfM can provide reliable data with a very high accuracy an appropriate amount of time and with the added advantage of easy and fast replication and repetition (Fonstad et al. 2013). This data combinded with appropriate post-processing can be used for mapping topography in river environment (Room and Ahmad 2014; Thumser et al. 2015), mapping river bathymetry (Flener et al. 2013; Javernick et al. 2014; Ouédraogo et al. 2014; Bagheri et al. 2015; A. Tamminga et al. 2015; Woodget et al. 2015), mapping vegetation (Berni et al. 2009; Mathews and Jensen 2013; Flynn and Chapra 2014; Kaneko and Seiich Nohara 2014), mapping and quantifying sediment and habitat parameters (Casado et al. 2015; Woodget 2015), quantifying changes in morphology, erosion and deposition (Wheaton et al. 2010; Lucieer et al. 2013; Smith and Vericat 2015; Tamminga et al. 2015; Stumpf et al., 2015) and many more. The particular value of the monitoring data lies in the combination of a high spatial and a moderate temporal resolution (Hering et al. 2010). Data acquisition and surface water mapping of aquatic habitats is critical to assess the conditions of lentic ecosystems as well as for planning. This approach demands intensive cooperation of engineers, ecologists and geomorphologists to determine the essential characteristics with sufficient accuracy (Rice et al. 2010).

This article describes the methodology and it`s application within the monitoring programme REFCOND_VOLGA, in the headwaters of the Volga.

RESEARCH AREA

Within the research expedition "Upper Volga 2005" an assessment of hydrological, hydrochemical and biological parameters was carried out in the Volga River upstream of Tver, including the main channel as well as major tributaries. This assessment revealed that the headwaters of the Volga River represent conditions which are either reference or least disturbed and stipulated the establishment of the monitoring programme "REFCOND_VOLGA", which is in operation since 2006 and includes stretches along the Volga River (Rzhev, Staritsa, Tver) as well as along the tributary Tudovka. This long-term monitoring includes assessments of hydrochemistry, as aquatic flora / fauna as well as hydromorphology (Schletterer et al. 2016). Therefore a detailed assessment, applying the structure from motion (SfM) technique as well as the establishment of 360°-panoramas, was carried out to supplement the environmental intelligence gathering at the monitoring sites.

MATERIAL & METHODS

Field work

Survey for SfM analyses

A standard camera (Canon EOS 600D) was used for generating the pictures. It uses a 18 Megapixel APS-C CMOS-Sensor with 18mm fixed focal length. Usually a UAV would be used for faster surveying at middle and low height. But as UAV flying is regulated and time consuming (dependence on weather conditions, flight planning), for the current study a ground-based survey was chosen. The photographer stood on one riverbank heading to the other bank in a 90° angle to the stream. Focusing the other bank, each photo should cover around 30% of the water surface and 70% of the bank and the terrain above and behind. This ensures that in the post-processing the software is able to find the water line and that it is covered in the whole model. After each photo is taken, the photographer takes a few steps to the side, focuses again and takes the next photo. The step should be the distance that ensures a total coverage of around 80% or more from photo to photo (Fig. 2). The process was continued until the total area of interest is covered, with a decent extra area in

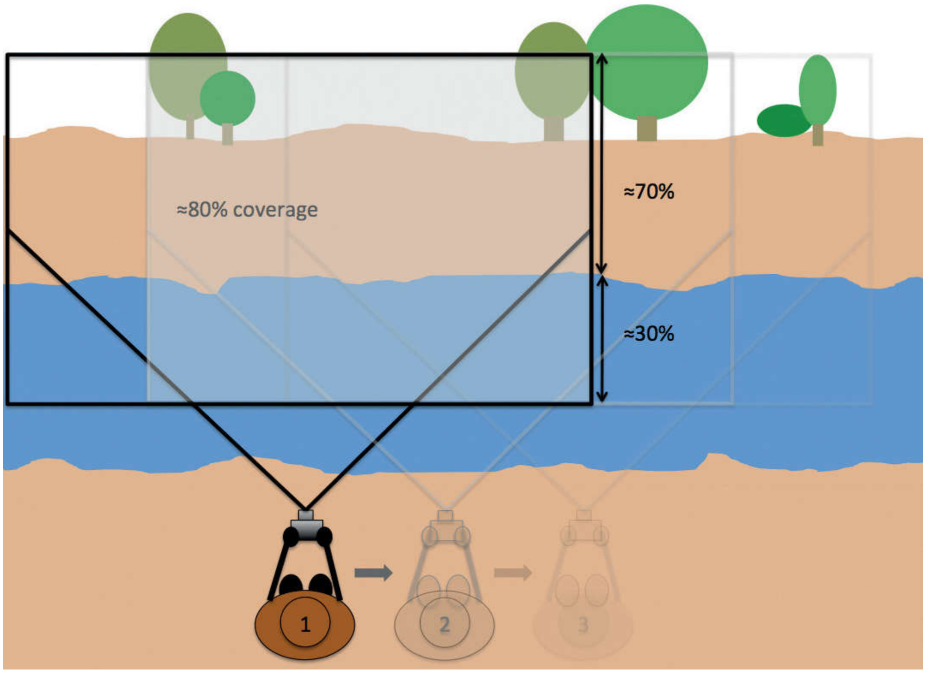

Fig. 2. Schematic drawing of terrestrial photographing of a river for SfM model purpose. The photographer takes one position and shoots a photo (1) and moves on to the next position (2) for shooting another photo with 80% total overlapping and so on (3).

the beginning and at the end (boundary conditions). After finishing one riverbank and screening the quality of the images in the field, the procedure was repeated from the other riverbank. These photos are used for SfM post-processing later on.

Virtual River (360° panorama)

Creating virtual spheres has certain requirements on the photo technique that are different to SfM requirements. While pictures taken for post-processing with SfM should contain motion, meaning angle and distance to the object of interest and therewith the position of shooting should vary between the captures, photos taken for virtual spheres should be made from one single point. Usually a tripod and a nodal point adapter are used in addition to the camera. The equipment is placed at point, which is identic to the viewers position the virtual tour later on, and the whole surrounding in all dimensions is captured with photos taken from this point without changing camera height and position. This procedure is repeated for different positions. In the post processing this points can be merged together to a tour, where the user can move from point to point. As no nodal point adapter and tripod was available during field trip for logistical reasons, photos were taken by hand, trying not to change position and height during the photos.

POST PROCESSING

SfM for high resolution topographic reconstruction

„Structure-from-Motion" (SfM) is a photogrammetric method for high resolution topographic reconstruction, which differs fundamentally from conventional photogrammetry as the geometry of the scene, camera positions and orientation is solved automatically (Westoby et al. 2012). The SfM approach uses a highly redundant, iterative bundle adjustment procedure based on a database of features automatically extracted from a set of multiple overlapping images (Snavely et al. 2008). The 3D point cloud generated through the SfM worklow is in a relative „image-space" coordinate system and has to be transformed to an absolute coordinate system (Fig. 3). Mostly achieved using a 3-D similarity transform based on a small number of known ground control points (GCPs) with known object-space coordinates, it is part of the post-processing after the SfM worklow described below.

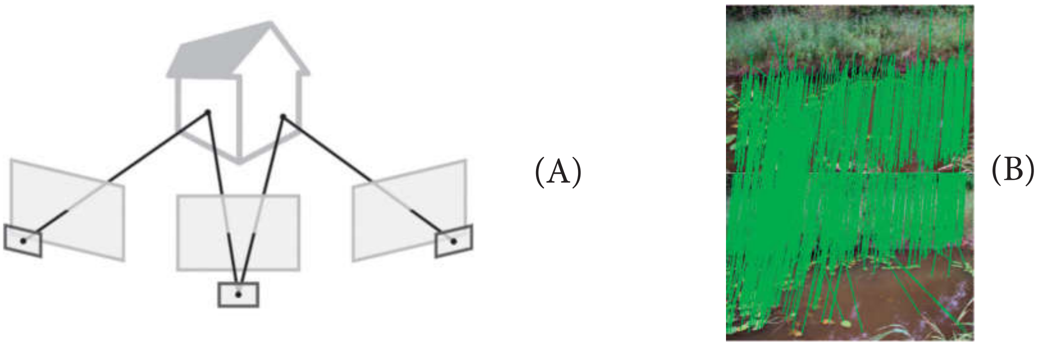

Fig. 3. (A) The SfM technology relates image coordinates (gained from different camera positions) with world coordinates, this approach is exemplified in (B) which shows the comparison of images in Visual SFM

The SfM workflow presented herein is common for a number of open-source applications, which are implemented e.g. in VisualSFM (Wu 2011) as well as in the application bundle SFMToolkit3 (Astre 2010). VisualSFM is a freely availaible GUI application using structure from motion for 3D reconstruction. This system integrates SiftGPU, a multicore bundle adjustment and for processing of a dense cloud the Clustering View or Multi-view Stereo (CMVS) and Patch-based Multi-view Stereo is implemented (Wu 2007; 2011). The bundle SFMToolkit3 includes SiftGPU (Lowe 2004), Bundler (Snavely et al. 2008), CMVS and PMVS2 (Furukawa and Ponce 2007; Furukawa et al. 2010). The input data are pre-calibrated images which have been undistorted, thus this is a user-friendly procedure to a sparse and dense point cloud, which is the basis for a digital terrain model (DTM) with different resolutions (Fig. 4).

The initial processing step of the SfM workflow is feature extraction on every image in the photoset. There are different methods existing for automated detection of feature points, but most commonly used, the scale-invariant feature transform (SIFT) proved to be very robust against rotation and scaling and is partially invariant to illumination changes and view point variation. After the creation of a feature descriptor, matching of the extracted features is performed between all images. A detailed description of the SIFT algorithm is shown in Lowe (2004). The relative camera orientation between pairs of images is estimated with the established feature correspondences between images. The bundle adjustment system used in Bundler (Snavely et al. 2008) estimates camera pose and reconstructs the 3D scene by generating a sparse point cloud. Therefore,

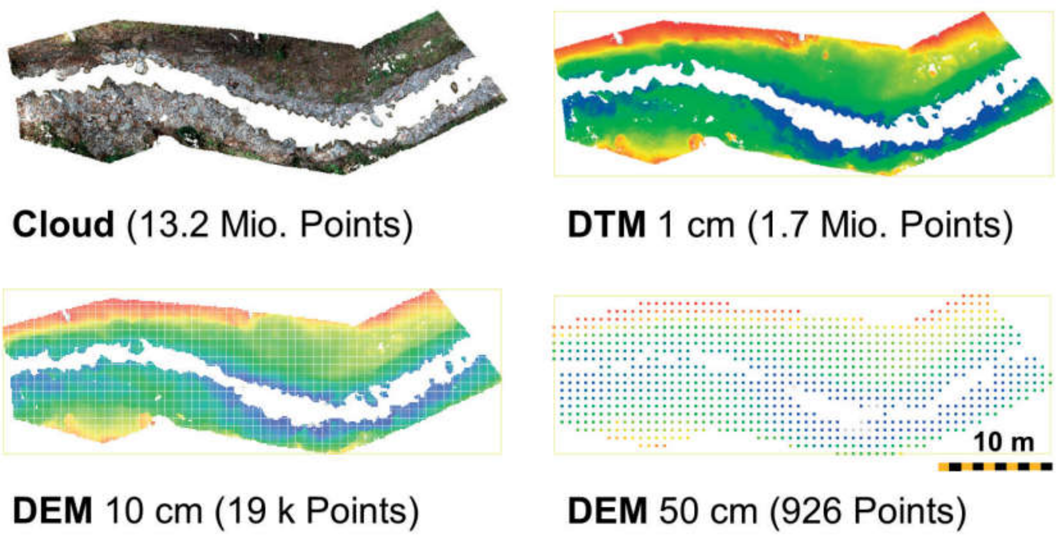

Fig. 4. Example on different processing steps from the dense cloud towards DTM (digital terrain model) and DEM (digital elevation model) and the related number of points (graphic from J.A. Tuhtan)

approximate nearest neighbour (Arya et al. 1998) and Random Sample Consensus (RANSAC; Fischler and Bolles 1987) are used. Feature correspondences place constraints on camera pose orientation, which is reconstructed using a similarity transformation and the minimisation of errors is accomplished by a non-linear least-square solution (Szeliski and Kang 1994; Nocedal and Wright 1999). Triangulation of 3D feature points is used for reconstructing scene geometry in a relative coordinate system.

The described SfM approach from feature extraction to the accurate 3D scene reconstruction is fully automated. The use of Clustering View or Multi-view Stereo (CMVS) (Furukawa and Ponce 2007; Furukawa et al. 2010) and Patch-based Multi-view Stereo (PMVS2) algorithms (Furukawa and Ponce 2007) is an additional process which provides an enhanced density point cloud.

VIRTUAL RIVER (360° PANORAMA)

After checking the photos on quality, the post-processing can be started. The proprietary software Kolor Panotour (www.kolor.com/panotour/) was used for creating the spheres. The single photos were merged and projected to a 360-degree sphere, which is displayed flattened on the computer screen. With this first product, and overview of problems occurring between the different pictures can be estimated. The most obvious mistake in the merged photo were blurred parts that result from objects moving in between two photos, for example clouds, people and water. For this moving objects, the status of a single photo has to be decided to be weighted hundred percent in the merging process, meaning only this object occurring after merging process. The so created spheres were again merged to a virtual tour, linking the individual spheres, depending on their position to each other, together in a row. Also tools for zooming and switching between the spheres were implemented.

RESULTS

The application of the SfM approach based on terrestrial photography turned out to be applicable for the different streams and rivers in the research area, i.e. it was shown that: (I) Monitoring sites along small to mid-sized rivers, like the Tudovka River, can be assessed quite well using terrestrial photography. However it turned out that at some locations vegetation is a limiting factor. (II) Large rivers can be analyzed well, however as images are taken from the right bank to the left bank and vice versa – in this case it turned out to be very difficult to bring both models (for both banks) into one single model. (III) A promising approach to get a model for a large river is taking images taken from a bridge, i.e. the model displays a "cross-section" (e.g. Volga at Rzhev, (Fig. 5).

The quality of a SfM-model is related texture and resolution of the images used to create the model, i.e. high resolution images with complex structures enable higher accuracy in the model. Variation in lightning and individual scenes can influence the texture and quality. It has to be considered that the method is not yet feasible for measurements

Fig. 5. View from the bridge at Rzhev upstream: original image (left) and combination of model and the image (right)

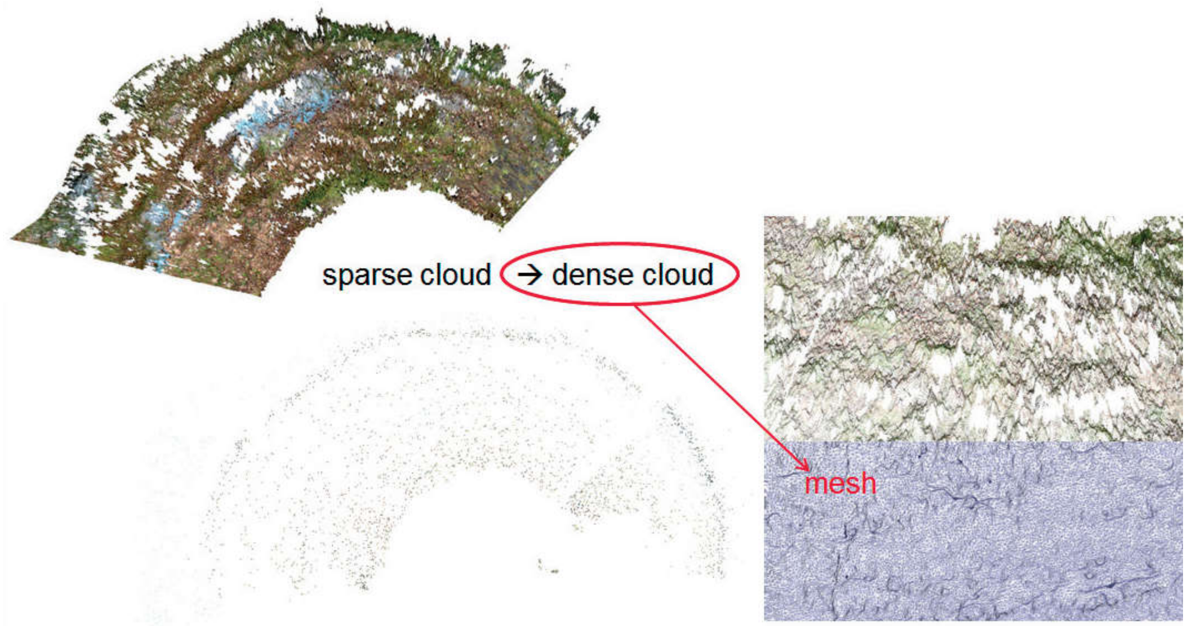

Fig. 6. Example of SFM-analyses of a river bank near Staritsa, which allow detailed assessment of the monitoring sites on macro and micro scale

below the water surface and this application is also limited to transparent shallow water bodies. As the rivers in the research area are lowland systems with an influence of mires, the water surface is the border for the model. However, it enables to assess non-wetted areas with high accuracy (Fig. 6), thus the application of this methodology during the summer low flow period in the headwaters of the Volga is a promising approach for detailed assessments of the river banks along the monitoring sites.

As photos for the virtual tour were not taken using a nodal point adapter, creation of full 360-degree spheres was almost impossible. This problem could be party solved by splitting the spheres into several parts. In the cases were spheres could be created or for the parts of the spheres, photo quality was very good and high resolution was possible. This virtual tour – with the possibility of zooming into scenery, seeing the virtual actual position within space on a map and the moving from sphere to sphere – supports the documentation of certain environmental conditions, such as flow patterns, vegetation, etc. (online supplementary material). Also it is an feasible tool "to come back to field (during analyses in the laboratory)", to check the conditions during a certain sampling campaign, for model validation or to display the environment to project partners who were not able to participate in the field trip.

CONCLUSION AND OUTLOOK

The application of structure from motion (SfM) technique is very useful for the characterisation of riverine systems as

- point clouds and surface models of non-wetted areas

and

- high-resolution (1-10 cm/px) imagery

provide a baseline for modelling and mapping hydromorphology, as local conditions and their change over time (seasonal, after extreme events).

Our study revealed that the methodology can be applied for ground based surveys (especially for small to mid-sized rivers and "cross sections" made from a bridge). However for large scale surveys areal investigations are needed: Civil applications of unmanned aerial vehicles (UAVs) have grown rapidly over the past years. Thus we`d like to highlight their use of remote sensing observations: current applications are archaeology, geography, mining, as well as civil engineering and ecology. UAVs can be leveraged to rapidly create high resolution (up to 1 cm/px) maps of river landscapes and thus have the advantage of being both lean and agile. A lightweight multi-camera system specially designed for

UAVs was tested, generating total coverage spectral imagery. Another advantage is the possibility spectral imagery is mapping of macrophyte stands. High resolution maps of the Normalized Differenced Vegetation Index (NDVI) can be generated using near infrared (NIR) imagery gathered by a multi camera system. This hybrid approach allows for detailed study of the interactions between hydromorphological conditions and aquatic as well terrestrial vegetation.

Environmental intelligence gathering can be applied to increase the scope of scientific surveillance, which reveals new opportunities to detect and quantify complex ecological interactions across a wide spectrum of scales. As the applied imagery methodologies have huge potential for environmental variable classification, future developments will concentrate on information extraction from multispectral imagery as well as feature acquisition and processing in real-time.

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Philipp Thumser is co-founder and managing director of I AM HYDRO GmbH, with its main competence in Investigation And Monitoring of HYDROsystems for better data and to improve understanding of environmental processes. Philipp has an academical background in hydrology and meteorology from the TU Dresden. Philipp also lead and participated in several projects and studies in Europe and abroad. Since 2016 he is also external lecturer at Stuttgart University at the Department of Hydraulic Engineering and Water Resources Management.

Vyacheslav V. Kuzovlev, candidate of technical sciences, associate professor. In 1994 he graduated from Tver State Polytechnic Institute (Russia) in «Open pit mining» and in 2002 he defended his thesis on «Development of Methods for the Environmental Evaluation of the Wise Use of Peatlands». Since 2000 he is working at Tver State Technical University. Research interests: evaluation of the impact of natural landscapes on the hydrochemical regime of riverine systems. Since 2011 he is also the head of the Laboratory of Environmental Monitoring of the Tver Center for Hydrometeorology and Environmental Monitoring (ROSHYDROMET division in Tver region).

Kyrill Y. Zhenikov graduated in 2011 from Tver State Technical University (Russia) with a degree in «Environmental protection and rational use of natural resources». Research interests are focused in the following areas: hydrochemistry and hydrology of surface water, marsh drains, the resources of peat and sapropel ecosystems. Since 2014 he is a postgraduate student at Tver State Technical University and works in international scientific projects.

Prof. Dr. Yuri N. Zhenikov graduated in 1973 at the Kalinin Polytechnic Institute (Russia), with the specialty «Technology and complex mechanization of peat deposits». In 2000 he defended his doctoral thesis «Geoecological basis for the rational use of peat bog resources of the Upper Volga Region». Since 1996 he works in international scientific projects. Research interests are focused in the following areas: the interaction of peat bogs and the environment, the composition and properties of the surface water as well as environmental impact assessment. Since 1973 he is working at Tver State Technical University, in 2004 he became head of the Chair of Nature Management and Ecology (Кафедра Природообустройства и экологии). He also supervises the department of Geology, exploration and technological design of the East European Institute of Peat Business (www.instorf.ru).

Maximilian Boschi, economics student at Leopold-Franzens University in Innsbruck (Austria) and managing director of droneproject.at, an Austrian-based unmanned aerial vehicle (UAV) company founded in 2012. In collaboration with his twin brother Peter Boschi they focus on dynamic aerial based filming as well as on photogrammetric surveys.

Peter Boschi, student of Applied Geosciences at Montanuniversiät Leoben (Austria) and self-employed running a film production company since 2015. His bachelor thesis outlines the UAV-based applications in geosciences.

Dr. Martin Schletterer studied biology, with a focus on zoology and limnology, at the University of Innsbruck (Austria) and graduated in 2007. He obtained his doctoral degree (PhD) for his research on "Benthic Invertebrates and Reference Conditions in East European Running Waters: Case study in the headwaters of Volga River (Tver Region, Russia) and adjacent water bodies" in 2010. He was working on national and international scientific projects since 2003 and his research interests are concentrated in the following areas: monitoring, biodiversity (zoobenthos and other aquatic quality components), investigation of anthropogenic stressors at large spatial scales and in the context of environmental factors as well as river basin management. Since 2009 he is working at TIWAG – Tiroler Wasserkraft AG (Hydropower Planning Department) as head of the group "Ecology" and in this role he is responsible for planning and management of ecological aspects as well as R&D projects. Additionally, Dr. Schletterer has teaching assignments at the Institute for Modelling Hydraulic and Environmental Systems at University of Stuttgart (Germany), the University of Vienna (Austria) as well as at the Universidade de Lisboa (Portugal).