Template for high-resolution river landscape mapping using UAV technology

Article in Measurement · October 2017
DOI: 10.1016/j.measurement.2017.10.023

4 authors, including:
Miloš Rusnák
Slovak Academy of Sciences
19 PUBLICATIONS 36 CITATIONS
See profile

Anna Kidova
Slovak Academy of Sciences
18 PUBLICATIONS 21 CITATIONS
See profile

Some of the authors of this publication are also working on these related projects:

- Quantification of morphological changes in river channels and its impact on flood risk (MORCHFLOOD - PA 05 Environmental Risks) View project
- Response of geomorphic-sedimentary connectivity/disconnectivity in fluvial system to environmental impacts View project

All content following this page was uploaded by Miloš Rusnák on 10 November 2017.
The user has requested enhancement of the downloaded file.
Template for high-resolution river landscape mapping using UAV technology

Miloš Rusnáka,⁎, Ján Sládekab, Anna Kidovǎa, Milan Lehotskýa

a Institute of Geography, Slovak Academy of Sciences, Štefánikova 49, 814 73 Bratislava, Slovakia
b GEOTECH Bratislava, s.r.o., Čermáikového 26, 851 01 Bratislava, Slovakia

ARTICLE INFO
Keywords:
UAV
Fluvial landscape mapping
Workflow
UAV photogrammetry
Data extraction

ABSTRACT
This paper presents the template for high-resolution mapping of a river landscape by Unmanned Aerial Vehicle (UAV) technology with the following five steps: (i) reconnaissance of the mapped site; (ii) pre-flight field work; (iii) flight mission; (iv) quality check and processing of aerial data; and (v) operations above the processed layers and landforms (objects) mapping (extraction). The small multirotor UAV (HiSystem Hexakopter XL) equipped with Sony NEX 6 camera with standard 16–50 mm lens provided image capture and workflow design applications. Images were processed by Agisoft PhotoScan software and georeferencing was ensured with 20 Ground Control Points (GCP) and 18 check points certifying accuracy assessment. Three imaging methods for 3D model creation of the study area were used: (i) nadir, (ii) oblique and (iii) horizontal. This minimized geometric error and captured topography under treetop cover and overhanging banks.

1. Introduction

Geomorphological mapping requires the collection of primary landform data and is dependent on scale and changes in the studied object’s attributes. Landform identification is normally based on the object classification framework using field work and remotely sensed data with temporal and spatial accessibility, flexibility and accuracy [1]. This methodology provides a very powerful tool for landform mapping [2–4]. River morphology is one of the most dynamic landscape entities, therefore it is essential in its mapping to generate the precise dataset and topography, required for linking processes, patterns and spatio-temporal volumetric changes [5–7]. Thus, remote sensing techniques combined with field survey provides the basic information source in modern fluvial geomorphology [8].

The last decade has seen rapid development in the use and availability of unmanned aerial vehicles (UAVs) for obtaining the earth surface spatial information [9,10], and various UAVs’ platforms are used in landscape research. While fixed wings systems are suitable for mapping of large areas, multicopters are superior for small, linear and narrow localities, and UAVs equipped with digital cameras and lidar, or these combined systems [11], are optimal for data acquisition in landscape research at resolutions from 0.5 to 2 cm [6,14–17]. Digital camera payload is commonly used in UAV technology, and development of easily applied commercial or open source software and inexpensive platforms enable high temporal and resolution topography reconstruction and monitoring [18].

Turner et al. [12] highlighted that UAV photogrammetry is the most suitable technology for real-time or near-real-time landscape monitoring and photogrammetrically-derived digital elevation model (DEM) is limited by its inability to capture surface topography beneath vegetation [19].

Technological advances in UAV enable production of a high quality elevation model and orthophotomosaic with spatial resolution up to 10 cm and vertical error to 50 cm (Table 1). UAV is therefore an ideal tool to assess riparian forest dynamics [20,32] and analyze post-flood river channel morphology [22,28], planform changes, meander neck cut-offs [27] and lateral channel shifts [21]. UAV photogrammetry generates the high resolution topographic data essential to detect morphological changes [18,26,28,35], bankfull stages [33], riparian vegetation dynamics and canopy height models [20,22,32]. While it provides excellent data quality, including data for grain size identification [34,36] and topographic reconstruction of submerged channels [6,23,29,30], evaluation of topographic accuracy and error range still requires validation.

Research has processed data acquisition from UAV images [24–26,30–32], and now an appropriate scheme encompassing all the aspects of flight mission logistics, data acquisition and processing and the nested, multi-scale and component aspects is required. Workflow approaches to UAV imaging and data processing consist of the following 6 main steps; (i) UAV preparation, (ii) its calibration, (iii)
Table 1
Rivers with different planform settings, which was studied by UAV technology with various platform types and dataset accuracy.

<table>
<thead>
<tr>
<th>Study</th>
<th>River</th>
<th>Planform setting</th>
<th>UAV platform</th>
<th>Camera</th>
<th>Research</th>
<th>UAV accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lejot et al. [6]</td>
<td>Drôme River; Ain River (France)</td>
<td>Shifting gravel bed rivers</td>
<td>Pixy drone</td>
<td>Canon Powershot G5/Canon EOS 500 N Reflex</td>
<td>Bathymetric model of river bed</td>
<td>Spatial resolution 5–7 cm; vertical residuals ± 50 cm</td>
</tr>
<tr>
<td>Dunford et al. [20]</td>
<td>Drôme River (France)</td>
<td>Shifting gravel bed rivers</td>
<td>Pixy drone</td>
<td>Canon Powershot G5/Canon EOS 5D</td>
<td>Riparian forest automatic classification</td>
<td>Spatial resolution 6.8–21.8 cm</td>
</tr>
<tr>
<td>Vericat et al. [21]</td>
<td>Feshie River (Scotland UK)</td>
<td>Braided gravel bed</td>
<td>SkyHawk Helikite balloon</td>
<td>Ricoh Caplio R5</td>
<td>Generation photo-mosaics for river monitoring</td>
<td>Spatial resolution 5–10 cm; errors 25–5 cm</td>
</tr>
<tr>
<td>Hervouet et al. [22]</td>
<td>Drôme River (France)</td>
<td>Braided</td>
<td>Pixy drone/ULAV paraglider</td>
<td>Canon Powershot G5/Canon EOS 5D/Sony DSLR-A350</td>
<td>Vegetation dynamics</td>
<td>Spatial resolution 3–16 cm; RMSE 0.10 m</td>
</tr>
<tr>
<td>Flenner et al. [23]</td>
<td>Pulmanki River (Finland)</td>
<td>River bend with point bar</td>
<td>Minicopter Maxi-Joker 3DD/Align T-Rex 700E</td>
<td>Nikon D500/Nikon D5100</td>
<td>Creation seamless topography model by combination mobile lidar, UAV photography and optical bathymetric modeling</td>
<td>DEM: vertical 0.03/0.05 m (2010/2011), RMSE 0.0152/0.088 m; bathymetry: vertical 0.12/-0.5 m, RMSE 0.221/0.163 m</td>
</tr>
<tr>
<td>Flynn and Chapra [24]</td>
<td>The Clark Fork stream (US)</td>
<td>Meandering</td>
<td>DJI</td>
<td>GoPro Hero 3</td>
<td>Mapping aquatic vegetation – Cladophora</td>
<td>Spatial error 0.3 m</td>
</tr>
<tr>
<td>Javernick et al. [25]</td>
<td>Ahuriri River (New Zealand)</td>
<td>Braided</td>
<td>Robinson R22 helicopter</td>
<td>Canon + 28 mm lens</td>
<td>Complex DEM of river channel (ground and bathymetry)</td>
<td>Ground RMSE 0.20 m; bathymetry RMSE 0.31 m</td>
</tr>
<tr>
<td>Miříkovský and Langhammer [26]</td>
<td>Javôří Brook (Czech Republic)</td>
<td>Meandering</td>
<td>Mikrokopter HexaXL</td>
<td>Canon EOS 500D</td>
<td>Morphology changes of channel (volumetric changes)</td>
<td>Spatial resolution 2 cm; RMSE 3.7 cm</td>
</tr>
<tr>
<td>Miříkovský et al. [27]</td>
<td>Morava River (Czech Republic)</td>
<td>Meandering</td>
<td>Mikrokopter HexaXL</td>
<td>Canon EOS 500D</td>
<td>Monitoring cut-off of meander</td>
<td>Vertical RMSE 0.093 m</td>
</tr>
<tr>
<td>Tamminga et al. [28]</td>
<td>Elbow River (Canada)</td>
<td>Braided/wandering</td>
<td>Aeryon Scout quadcopter/elbe fixed-wing</td>
<td>Photo 3S camera/Canon IXUS 127 HS</td>
<td>Effect of floods to channel morphology (volumetric changes)</td>
<td>Spatial resolution 5/4 cm; RMSE(2012) 0.088 m (exposed)/0.098 m (submerged); RMSE(2013) 0.047 m/0.0952 m</td>
</tr>
<tr>
<td>Tamminga et al. [29]</td>
<td>Elbow River (Canada)</td>
<td>Braided/wandering</td>
<td>Aeryon Scout quadcopter</td>
<td>Photo 3S camera</td>
<td>Assessment reach scale habitat and morphology (DEM – exposed and submerged areas)</td>
<td>Vertical RMSE 8.8 cm (exposed areas), 11.9 cm (submerged)</td>
</tr>
<tr>
<td>Woodget et al. [30]</td>
<td>Arrow River; Coledale Beck River (UK)</td>
<td>Small stream</td>
<td>Draganflyer X6</td>
<td>Panasonic Lumix DMC-LX3</td>
<td>Quantitative assessment of submerged channel areas and topographic mapping</td>
<td>Mean error from -0.029 to 0.111 m</td>
</tr>
<tr>
<td>Casado et al. [31]</td>
<td>Dee River (Wales UK)</td>
<td>Meandering</td>
<td>QuestUA Q-200</td>
<td>Sony NEX 7/Panasonic Lumix DMC-LX7</td>
<td>Hydromorphological automatic classification of river channel</td>
<td>Spatial resolution 2.5/5/10 cm; RMSE 0.0451/0.1574/3.0574 m</td>
</tr>
<tr>
<td>Michez et al. [32]</td>
<td>Salm River; Houille River (Belgium)</td>
<td>–</td>
<td>Gatewing X100</td>
<td>Ricoh GR3</td>
<td>Riparian forest automatic classification</td>
<td>Reprojection error 0.72/0.86 pixel</td>
</tr>
<tr>
<td>Niedźwiedzki et al. [33]</td>
<td>Scinówka River (Poland)</td>
<td>Alluvial meandering with cutbanks</td>
<td>Swinglet Cam fixed-wing</td>
<td>Integrated RGB camera</td>
<td>Observing river stages</td>
<td>Resolution orthophoto 3 cm</td>
</tr>
<tr>
<td>Cook [18]</td>
<td>Daan River (Taiwan)</td>
<td>Bedrock gorge</td>
<td>DJI Phantom 2</td>
<td>Canon IXUS 135/Canon Powershot 4000IS</td>
<td>Topography identification and topography changes</td>
<td>Mean difference −0.9 cm/−0.85 cm; RMS difference 39.4 cm/45.9 cm</td>
</tr>
<tr>
<td>Langhammer et al. [34]</td>
<td>Javôří brook (Czech Republic)</td>
<td>Meandering</td>
<td>Mikrokopter HexaXL</td>
<td>Canon EOS 500D</td>
<td>Optical digital granulometry</td>
<td>Vertical RMSE 0.015/0.021 m</td>
</tr>
<tr>
<td>Marteau et al. [35]</td>
<td>Elen Giff stream (England UK)</td>
<td>–</td>
<td>DJI Phantom 1</td>
<td>GoPro Hero 3</td>
<td>Geomorphologic change detection for river restoration monitoring (volumetric analyses)</td>
<td>Orthophoto spatial resolution 0.025 m; error 0.025/0.030/0.017 m</td>
</tr>
<tr>
<td>Woodget and Austrums [36]</td>
<td>Coledale Beck River (UK)</td>
<td>Gravel bed river</td>
<td>Draganflyer X6</td>
<td>Panasonic Lumix DMC-LX3</td>
<td>Grain size relation to the image texture and topographic roughness</td>
<td>Spatial resolution 1 cm (orthophoto), 2 cm (DEM)</td>
</tr>
</tbody>
</table>
The aim of this paper is to compile a template for the application of UAV technology in riverine landscape mapping. Our illustrated example of a reach of braided-wandering river knickzone incorporates the fore-going concepts. This reach was selected because its landform and land cover diversity enable the combination of different methods in discriminating riverine landscape objects for scalar mapping and assessment.

2. Workflow design

Data acquisition for riverine landscape mapping using a low-cost UAV outlay is divided into 5 main steps (Fig. 1): (i) reconnaissance of the mapped site – identification of potential problems and dangers in flight mission, takeoff and landing points; (ii) pre-flight field work – the placement and targeting of ground control points (GCPs) for precise georeferencing; (iii) flight mission – aerial imaging of the study area; (iv) quality check and processing of aerial data – data accuracy assessment and software data processing and (v) operations above processed layers and landform (object) mapping (extractions) – comprising visualization, landform identification and morphometric analysis. The essential field research elements of legislative processes and UAV permission and regulations were certified prior to the flight; and these are designated step zero (0).
2.1. Step 0: Legislation and regulation

UAV mapping requires acceptance of legislation and the application of general field survey rules. These include survey permission in protected areas and private properties and specific requirements for areas such as designated military zones. Provision is also made for the various regulations affecting drone operation, including pilot training courses and licensing. Stöcker et al. [39] emphasize that UAV legal requirements are an integral part of the preparation phase for UAV flights and summarize different legislation applications in individual countries and national and international legislation in the following 6 main regulation spheres: (1,2) applicability and technical prerequisites that cover regulated UAV weight, range, control and safety systems; (3) operational limitations center on flight height, definition of 'non-flight zones', the line of sight and urban zone restrictions; (4) administration procedures involve flight permission, notification, approval from aviation authorities, registration number, insurance, image control by military authorities, company permission and appropriate license for aerial work; (5) human resource requirements include operator training and license and (6) ethical constraints for privacy and data protection. Different countries have varying regulations, it is essential to follow pre-flight instructions from aviation authorities and ensure that flight mission follows regulations set or order flight mission by relevant licensed companies and state institutions.
Fig. 4. Localization of (a) 6 take-off points and 6 sectors with image acquisition, (b) distribution of ground control points (GCP's) in the study area, (c) detailed GCP on the gravel bar and (d) GPS point targeting.

Fig. 5. Vectorisation and identification of objects in the 3-level database with its 3 main components: braidplain, floodplain and terrace (level 1). Objects specification at level 2 (braidplain area, the most specific part of the fluvial landscape). The database was completed by land cover information at level 3.
2.2. Step 1: Reconnaissance of the mapped site

Study area field reconnaissance and visual assessment identify the flight course, obstacles and takeoff and landing sites. The area to be mapped and UAV technical limitations in operation time and line-of-sight determine the numbers of flight sectors and number of take-off/landing points. Electrical wiring and vegetation create fixed obstacles and shielded GPS signal, so the visual survey identifies potential urban and economic risk areas and helps the operator select the type of flight mode: autonomous/manual, if this is not nationally predefined.

2.3. Step 2: Pre-flight field work

Ground control points (GCPs) distribution and accuracy are key factor in precise UAV mapping [13, 40–42], because this technique is 5–10 times more accurate than direct georeferencing by internal GNSS of the UAV [37]. Three or more GCPs may be required for georeferencing [43–45], as errors increase with limited GCP number and distance from the GCP [17,46]. PhotoScan software requires at least 10 GCPs for model referencing [47] and these should not be distributed in lines or create regular patterns; such as equilateral triangles [48]. A further relevant condition for GCP placement is their arrangement at different vertical level; including river banks, in-channel structures, floodplain benches, terraces and bluffs. The next paramount feature of pre-flight work is defining the settings used for UAV and camera parameters based on flight plan design. Here, Miřiovský and Langhammer [26] recorded the calculation equations for flight height, focal length, scale and ground sample distance. Camera parameters are particularly important, and these must be set for shutter speed in prevailing light conditions to produce sharp images of approximately 1/1000. Camera can be pre-calibrated prior to the flight or self-calibrated in software processing. Difficulties, however, are invited by low number of images, strip-imaging and sole use of nadir photography because these can lead to model deformation and the ‘doming’ effect due to radial distortion [40,49,50]. All these parameters must be considered in flight planning and control to ensure the accuracy of the final topography.

2.4. Step 3: Flight mission

Nadir, oblique and horizontal imagery is recommended to combine in manual or autonomous flights to achieve precision and model texture quality (Fig. 2). This combination improves self-calibration and model precision, thus minimizing model deformation [40,50]. The oblique photographs provide conjunction between nadir and horizontal imaging from ground or low UAV flight paths and ensure the capture of overhanging river-banks and bank topography obscured by treetop cover. Sunlight illumination and water surface reflectance also influence successful flight mission planning and timing.

Fig. 6. The five classes identified by (a) automatic supervised maximum likelihood classification (MLC), (b) result of post-classification processing: noise and mis-classification removal by application of the focal statistics tool, boundary clean toolset and removing small isolated regions of pixels, (C) reference data source for quality assessment (POMC) and (d) spatial distribution of automatic classification errors on orthophotomosaic .
2.5. Step 4: Quality check and processing of aerial data

Image quality control prevents the occurrence of unexpected and inaccurate results from the data processing and 3D processing failure by inadequate flight line and images overlap. It is firstly necessary to inspect the general coverage and image exposure and sharpness quality after each flight mission and secondly quality check-level then ensures software detection of criss-cross image overlap by recording the number of identical point visible in different images. The final check level identifies optical and motion blurring, as does the image blurry analysis in Agisoft PhotoScan [47]. Sieberth et al. [51] have previously presented automatic detection methods for identifying blurred images in sets. Low quality images must therefore be excluded from geometric model analysis. The accepted set of photographs then undergo photogrammetric software processing.

Advances in technology and image analysis enable user-friendly black-box operation and model generation [49,50]. Specialized research has described process of image analysis, SfM photogrammetry, multi-view stereopsis techniques and model geometry generation with image alignment, dense point cloud generation, geometry, texture building and georeferencing [9,13,25,50]. In addition SfM software from open source or commercial or on-line solutions are now available for data processing, including Bundler, PMVS, Pix4D Mapper, Agisoft PhotoScan, Photosynth or ARC3D.

It is crucial to assess precision and accuracy following the final 3D model geometry computation. This is essential for topographic models to undergo successful modeling and volumetric changes computation. The reference sources for spatial DEM accuracy are used terrestrial laser scanner (TLS) data [18,42,52,53]; lidar data [9,14,17]; and total station, DGPS and RTK GPS check points [12,13,16,21,37,54].

2.6. Step 5: Operations above processed layers and landform (object) mapping (extractions)

The final step requires processing data generated in orthophotomosaics, raster, TIN DEM and point cloud formats. In fluvial geomorphology, it is also necessary to identify topographical surfaces under vegetation. Combined 2D and 3D datasets enable the use of classification techniques and point cloud filtration for precise object identification. This especially includes banks under tree canopies, overhanging banks and vertical structures. The final operations here are strongly influenced by the study aims and the nature of the study objects. In fluvial studies, UAV generated topography models detect morphology changes [18,26,28,35], identify submerged area topography [6,23,25,30], vegetation dynamic [22,32], classify object from orthophotomosaic [20,24,31] and analyze optical granulometry [34,36].

3. Workflow application: case study area and technical equipment

Imaging data of the 1.6 km long knickzone reach of the braided-wandering Belá River in the northern part of Slovakia (Fig. 3) was chosen to illustrate the template’s individual steps. This reach has a system of bars with a well developed main channel, bedrock outcrop, vertically diverse forested banks, forested floodplain with side arms, a terrace, 30 m high undercut bluff and variable land cover.

The small multirotor UAV (HiSystem Hexakopter XL, Fig. 1e) equipped with Sony NEX 6 camera and standard 16–50 mm lens was used for images capturing. All images were taken at 16 mm focal length providing 82° field-of-view. The UAV was equipped with First Person View (FPV) to image targets and visually check the flight path. This provides live-view for transmitting video from either the traditional camera or small CCD camera UAV board to the ground station with external monitor and Google maps for position localization. Agisoft PhotoScan software running on standard 4 core workstation Intel i7
equipped with 32 GB RAM and 2 GB graphic card then processed the images.

4. Methods

4.1. Image acquisition and processing

Field reconnaissance ensured successful location of six take off and landing sites on the valley floor at the top of gravel bars centers. These provided the best conditions for UAV visual flight control, with

---

**Table 2**

Confusion matrix and accuracy measures (classification accuracy, overall classification accuracy and KAPPA index) between classified and reference data for supervised Maximum Likelihood Classification.

<table>
<thead>
<tr>
<th>Class</th>
<th>Reference data</th>
<th>Classification accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water area</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>Bar surface</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Vegetation</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Woody debris</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>Bare surface</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Overall classification accuracy: 0.81 (81.39%).
Kappa index of agreement: 0.62.

---

Fig. 8. (a) Photorealistic colorized point cloud landscape model in the study area, (b) classified point cloud (water – blue, ground – grey, vegetation – green, LWD – orange), and (c) point cloud of surface model containing only ground and water classes. Raster generated (d) envelope surface model (DSM) with vegetation, or (e) terrain digital elevation model (DTM) and (f) DEM of differences between these models. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
maximal direct visual contact for flights over floodplain forest and terraces and the accompanying six imaging sectors highlighted in Fig. 4a. A total of 38 GCPs were measured by RTK GPS of GG03 antenna and Leica Zeno 5 with 1–2 cm accuracy were measured (Fig. 4b–d). Images were obtained by Sony NEX6 camera with automatically computed aperture, and the exposure time was set at shutter speeds of 1/1200 in good sunlight and 1/800 in cloudy conditions. The autonomous flight mode of Hexakopters for take-off, landing and waypoint flight stabilized by GPS could not be used for imaging because GPS signal were shielded by tree canopy.

Nadir, oblique and horizontal imaging were used for 3D model creation over the 75 min flights. Nadir imaging was realized in all sectors with the average flight height (AGL – above ground level) 80 m and 50 m above terrace surface in sector 4. Oblique imaging at 30–45° was applied in sectors 2, 3 and 4, where treetops covered the banks and bank line. AGL at 20 m was used for oblique imaging of sector 2 and 3, while sector 4 (bluff imaging) was performed at 80 m, 60 m, 50 m AGL. The Orthogonal and oblique imaging was complemented by horizontal one which provided ground level photos of river banks under tree canopies and bluffs by UAV from 30 m and 20 m AGL. Aerial image data was processed by Agisoft PhotoScan with 2413 aerial images and S_JTSK (the unified trigonometric cadastral network) coordinates of 20 GCP’s. The remaining 18 points served as check points for accuracy assessment. Thus, data exported form PhotoScan provided the textured point cloud, RGB orthophotomosaic in red, green and blue bands with pixel resolution 5 cm and digital elevation model of channel and floodplain with 6.46 cm resolution.

4.2. Data analysis and processing

Orthophotomosaic provided manual classification of land cover categories and landforms in ArcGIS software (Fig. 5). On the first level, landforms were classified in three main braidplain, floodplain and terrace geomorphic components. Second level classification then gave the braidedplain in water area, bar area and islands categories and land cover was classified in: water area, bedrock, gravel bar, low vegetation, shrub vegetation, tree vegetation, and large woody debris categories. Process-oriented manually classified layer (POMC) with 2 landform levels and 7 land cover categories was the result.

The photogrammetrically derived point cloud created a surface envelope, and the vegetation cover used in creating the surface topography required identification and filtering. Unfortunately, since the classification process with high density photogrammetrically derived points was based on digital camera imaging with only one “return” from the screened object, it was impossible to use the filtering algorithm with the first and last returns supplies by airborne lidar. The photogrammetrically derived point cloud classification is therefore based on the inspections of radius angles and the height between classified points by several iterations. The quasi-vertical bank, bluff, landslide surface classification results prove unreliable without operator input.

The Terrasolid-TerraScan extension in Microstation software for semi-automatic point cloud classification filtered the following six vegetation cover classes: (1) high vegetation (> 5 m); (2) middle vegetation (1.5–5 m); (3) low vegetation (0.2–1.5 m); (4) ground; (5) water and (6) LWD have been identified. This classification of vegetation cover was harmonized with American Society for Photogrammetry and Remote Sensing (ASPRS) classification standards. Woody debris was included into the low vegetation class, and therefore extraction was based on the previous manually-vectorised woody debris land cover class in the POMC layer. The water area points were also difficult to classify by automatically methods because the flat water surface was
deformed by rippling water. This led to classification of the water surface as ground or small vegetation or noise, and the water areas were therefore classified similarly to the woody debris class based on polygons created from the POMC layer. Class corrections were verified by the moving profile method in all study area.

The RGB orthophotomosaic was classified in ArcGIS software by supervised Maximum Likelihood Classification (MLC). Here training sites signatures identified the five water area, bar surface, vegetation, LWD and bare surface land-covers. ISO cluster analysis and dendrogram tools tested, separated and validated the potential number of classification categories and training samples were manually digitized via spectral RGB diversity into five author-predefined classes. Final post-classification processing to reduce noise and mis-classification comprised in focal statistics filtering, smoothing by the boundary clean toolset and removing small isolated regions of pixels (Fig. 6).

5. Results

5.1. UAV data: accuracy and precision

Fig. 7 highlights that the high resolution of UAV orthophotomosaic combined with nadir, oblique and horizontal imaging provided landforms and land cover vectorization with one dimension greater than 10 cm. This included vertically oriented bluffs and banks with overhanging tree canopy. Aligned GCP’s precision computed by Agisoft PhotoScan was 0.336 pixel (0.08 m) and the average rate of root mean square errors (RMSE) of all GCPs after alignment was 0.01915 m (z = 0.10093 m; x = 0.01474 m; y = 0.02272 m). The mean difference in check points was 0.02642 m and the RMSE vertical coordinates were 0.02836 m and 0.02459 m for the X coordinate and 0.02812 m for Y.

Fig. 10. Woody debris accumulation identification (a) on the orthophotomosaic and digital elevation model with (b) 3 cross-section plotted on woody debris. Statistical distribution (c) of values calculated form 516 woody debris spots and (d) spatial distribution of woody debris accumulation in the study area.
The point cloud was exported to RGB point information which provided photorealistic 3D visualization (Fig. 8a) and the class information for terrain, vegetation and separately defined classes (Fig. 8b and c). Filtering gave the DSM for combined all classes points (Fig. 8d) and also DTM with only ground-point classes (Fig. 8e). Vertical differences between DTM and DSM for vegetation cover height varied from −4.38 to +34.09 m, dependent on floodplain tree cover (Fig. 8f). With exception of islands, the braided area has small vegetation from 50 cm to 1 m providing a less precise topography model because of the low number of points remaining after filtering vegetation points.

5.2. Automatic supervised classification

The accuracy of the MLC supervised classification of RGB characteristics was assessed by the combination toolset and cross-tabulation with the manually-classified POMC reference layer dataset. POMC was adjusted here by merging the data in the equal 5 classes: (1) water areas; (2) bar surface; (3) vegetation; (4) woody debris; (5) bare surface. Accuracy assessment results are presented in the Table 2 confusion matrix, which provided overall accuracy of 81.39% and 0.62 KAPPA index of agreement. While proficient automated classification was achieved for the “vegetation” and “gravel bar” classes when spatial error distribution in Fig. 6d was considered, close observation of the water areas class provided lower accuracy due to vegetation class cover overhanging the bank line, visible bedrock under the water level classified in the bare-surface class and the gravelled channel. Here, the bare surface and woody debris classes also exhibited low accuracy. The spatial distribution of error matrix at study area margins was characterized by lower image quality, especially in areas with visible bottom channel bed structure and in the vegetation-channel and water area-bar surface contact zones (Fig. 6d).

5.3. Channel landforms mapping and woody debris volume calculation

Classified elevation models identified study area landforms and their vertical diversity. DTM longitudinal profiles then determined vertical differentiations in the abandonment arms which are approximately 60–100 cm higher than the main channel water level (Fig. 9), and DTM also provided information on the secondary channel incision which is approximately 150 cm compared to the main channel in the southern part of the knickzone accompanied by outcrop of claystones. In addition, the combined DTM and high precision orthophotomosaic identified bar vertical diversity (Fig. 9c). The point bar’s three levels (Fig. 9e) define three accretion stages which differ in deposited material grain size (Fig. 9d). The oldest level, No. 3, has 706.256 m a.s.l. average altitude and is stabilized by low vegetation cover and sandy deposits, while bar level 2 has average 705.671 m a. s. l. altitude and the youngest bar level 1 elevation is 705.001 m a.s.l. The orthophotomosaic also highlights that the youngest bar level surface is formed by finer material than level 2.

In addition to vertical landform differentiation, point cloud enables woody debris volume calculation (Fig. 10); and this calculation example is chosen because woody debris has a very important role in braided channel development. High resolution orthophotomosaic and point cloud give precise debris identification, including calculation of its length, study area location and orientation to water flow (Fig. 10a). The elevation model determines vertical profiles of roots and trunks (Fig. 10b), which create flow obstruction; the point cloud captures woody debris with height 30 cm (profile 1), 10 cm high trunk (profile 2), and 1 m high root and woody debris bulk (profile 3); and this corresponds to the actual terrain situation. The total air and wood mass volume in the woody debris was computed by the ‘cut method’ volume analysis tool in Topolyst software. A total of 516 woody debris accumulations with 931 m³ volume were registered in the study area (Fig. 10d); with 134.9 m² maximum accumulation, 1.8 m³ average and 0.0195 m³ median. This highlights that 75% of all accumulations was less than 0.319 m³ (Fig. 10c).

It is essential in woody debris estimation to quantify wood mass volume by identifying wood/air volume ratio in the different types of accumulated material; isolated wood pieces, jams of logs, branches, root boles and twigs and shrubs and whole trees. An appropriate approach for estimation of woody debris accumulation mass, calculation of the density index for woody debris and air proportion estimation in log jams and shrubs derived from aerial photography were developed by Thévenet et al. [55] and presented by Piégay et al. [56] or Wyżga and Zawiejska [57].

6. Discussion

6.1. Workflow design

The template for UAV technology application to riverine landscape mapping consists of five steps. These encompass complying with UAV regulations, reconnaissance of the mapped site, data processing and landform mapping/object classification. Universally applied UAV technology describes the process of image acquisition and processing, including description of the UAV platform, technical parameters, number of images, camera settings, software processing and the specialized work involved in the use of UAV as the best tool for case study data acquisition. Research also emphasizes problems involved in methods used for final data post-processing, especially in image classification [31], vegetation segmentation and classification [32], re- fraction correction [30] and submerged topography model generation [23,25]. Other reports highlight photogrammetric processing, the calibration process, GCP distribution and parameters setting for accuracy assessment in UAV derived models [13,37,38,40,41]. Further articles then describe legislation and regulations mandated in the image data acquisition phase. Here, Tonkin et al. [16] recorded aviation authority requirements in line-of-sight, while Flynn et al. [24] conducted flights in accordance with the Model Aircraft Operating Standards Advisory Circular, and Cassado et al. [31] described data collection under UK Civil Aviation Authority regulation. Rango and Laliberte [58] then detailed UAV flight planning required by US Federal Aviation Administration law (FFA) in the National Airspace System and Stöcker et al. [39] provided wide overview of UAV regulations in 19 countries with the common goal of minimizing risks in UAV operations. The development of workflow template as an appropriate tool for mapping objects in riverine landscape requires familiarization with all complexities involved in UAV application to this process, and it ensure check systems for identifying and controlling all steps in model creation. Workflow design must cover the multi-component aspects of field data acquisition and all technical requirements in order to achieve precise data generation.

Advances in UAV image processing and progress in multi-view stereopsis techniques with universal availability and low-cost UAV outlay as an easy data collection source led to UAV photogrammetry black-box technology data generation. Combination of the following essential steps is fundamental in UAV mapping; (i) data collection under legislative and regulatory frameworks to minimize risks, (ii) photogrammetric processing with high accuracy GCP, combined nadir/ oblique imaging and geometric model accuracy assessment and (iii) final data processing methodology.

6.2. Advantages and limitation of UAV riparian landscape mapping

New developments of UAV technology have enabled the creation of high precision models of the actual landscape with appropriate information density and position referencing, especially in the vertical dimension [59]. Míříkovský and Langhammer [26] emphasize the great reliability of UAV in fluvial geomorphologic research and illustrate differences between standard schematization of study area during
classic field research with errors from subjective observation and UAV mapping. This new mapping platform ensures less time-consuming data acquisition, and its greatest advantages include real-time capture of the landscape state and subsequent changes elucidated by time series data. This determines the actual processes involved in these changes and is especially applicable in capturing and monitoring flood events and landslide movements. The precise results record small objects with a few centimeters resolution, thus improving data identification, extraction and classification, with additional benefit from both vertical data information and improved spatial data processing analysis.

A further advantage of this technology is coupling several data models generated from the one flight. Three hours UAV mapping of six flights with 12 min duration and approximately 1 h GCP targeted on the Belá River, together with DEMs, orthophotos, point cloud and nadir or tilted aerial photos for complex modeling of landscape have thus been generated. While UAV mapping is less expensive, it is better operational and has equal spatial information density than airborne lidar [15], its optical data acquisition cannot penetrate the vegetation cover and receive the signals from terrain topography [12]. Its technology is also limited by surface envelope vegetation cover, where significant errors are especially recorded in landscape covered by small trees and shrubs [15], vegetated areas [17] and areas continuously covered by low vegetation which cannot be classified or removed from the surface [19]. In contrast, highly precise DTM can capture ground terrain in sparsely vegetated areas by optical sensors after point cloud filtering.

Ground level for data classifications in our study area involves non-densely, sparsely vegetated, or bare surfaces, so classified point cloud greatly improves topographic surface model accuracy. Its precise compilation of a sparsely point cloud covered floodplain plays a crucial role in landforms mapping. However, interpolation during DTM generation is impossible when the floodplain is covered by dense vegetation, so geodynamics analysis with UAV photogrammetry is essential to study vegetation effect on vertical errors. While it is possible to use UAV lidars [11] for point cloud acquisition in the areas where we need to hit the ground under the vegetation canopy. Disadvantage of small UAV lidar are their relatively high price and weigh more than 2 kg that limits to use on small UAV platforms.

6.3. UAV technology in riparian landscape of Belá River

Multiple imaging by classic nadir images combined with oblique and horizontal ground imaging is crucial in mapping bank height, bank line, bluffs and valley walls. Point cloud combined with calculation of woody debris volume provides precise data for high spatial resolution in land cover class classification. Here, debris below the planar surface and buried in gravel is excluded, so wood debris volume is calculated by differences between woody debris classified points and the planar surface.

The Belá River is subdivided into two reaches; (1) the northern reach dominated by gravel bar and island areas with woody debris accumulated in abandonment arms created by material accumulation up to 1 m above present river flow and (2) the reach in the lower part is affected by anthropogenic creation of a small hydropower plant and artificial channel with evident secondary channel incision [60]. This river has a riverine landscape with floodplain tree cover so it is essential here to use the multiple imaging of classic orthogonal and oblique and ground horizontal imaging. This provides workflow advantages in identifying the bank lines and surface under tree canopies overhanging the river banks. The accuracy of the applied classic approaches to bank delimitation from aerial photos in both models and orthophotos is severely affected when the banks are inclined at an angle rather than forming a vertical cliff. It is therefore important to create a methodology which applies landforms delimitation in 3-dimensional space; employing 3D assessment of landscape objects rather than classic planar geoscience analysis in GIS.

7. Conclusion

The presented template for the application of UAV technology in riverine landscape mapping encompasses all technical aspects of flight mission logistics, data acquisition and processing. It also includes the nested, multiscale and multi-component aspects of riverine landscape object discrimination and their scalar mapping and assessment which further provide a successful tool for researching this landscape type. Our proposed five step workflow comprises (0) legislation and regulation control, (i) reconnaissance of the mapped site, (ii) pre-flight field work, (iii) flight mission, (vi) quality check and processing of aerial data, (v) operations above processed layers and landform (object) mapping (extractions). The combination of all these essential steps is fundamental in UAV mapped identification of bank lines and morphological changes.

Finally, it is of outmost importance to recognize that the accuracy of the applied classic approaches to bank delimitation from aerial photos and UAV orthophotos is compromised where banks are inclined at an angle rather than forming a vertical cliff. This, however, can be successfully counteracted by methodology which applies landform delimitation in 3-dimensional space, thus employing 3D assessment of landscape objects.

Acknowledgments

This research was supported by Science Grant Agency (VEGA) of the Ministry of Education of the Slovak Republic and the Slovak Academy of Sciences; 02/0020/15. Flight mission was accomplished by collaboration with GEOTECH Bratislava s.r.o. and the orthoimage aerial was provided by EUROSENSE Slovakia, s.r.o. The authors are grateful to R. Marshall for manuscript language review.

References
