Towards automated grain size mapping of gravel-bed river: UAV-based technique for grain size distribution assessment

Vers une cartographie automatisée de la taille des grains dans les rivières à lit de gravier : technique basée sur UAV pour l'évaluation de la distribution granulométrique

Ashraf MD[1], Miloš RUSNÁK[1]
[1]Geografický ústav SAV, Bratislava, Geogashr@savba.sk
[1]Geografický ústav SAV, Bratislava, Geogmilo@savba.sk

RÉSUMÉ

Des études récentes ont exploré l'analyse automatisée de la taille des grains à partir d'images de drones (UAVs) des bancs de gravier, offrant des alternatives efficaces aux méthodes de terrain traditionnelles pour comprendre l'hydraulique fluviale et les propriétés sédimentologiques. Ce travail compare le photosieving automatique d'orthophotos basées sur des drones de faible altitude (sUAS) avec des photographies de terrain des sédiments, traitées à l'aide de méthodes basées sur les objets telles que BASEGRAIN et PebbleCountsAuto. Ces méthodes ont également été évaluées, avec des degrés de précision variables par rapport aux mesures des échantillons de sédiments analysés en laboratoire pour la rivière à lit de gravier Ondava (Carpates occidentales, Slovaquie orientale). Ces approches UAV-SfM permettent une caractérisation rapide des tailles de grains avec une résolution spatiale et temporelle plus élevée que les méthodes traditionnelles, offrant des informations précieuses sur la dynamique sédimentaire et les processus fluviaux. Des paramètres d'habitats physiques peuvent être extraits à partir de modèles 3D détaillés, et la structure du lit du chenal ou le substrat des bancs de gravier est détectable. Un modèle prédictif de la relation entre les paramètres des images sUAS et les échantillons de terrain est proposé et appliqué à l'ensemble des orthophotos haute résolution de la zone d'étude. La technique met en évidence les capacités des images sUAS à haute résolution pour le traitement et l'analyse des paramètres de taille des grains dans le système fluvial. Nos résultats préliminaires montrent que les modèles statistiques calibrés sur la texture des images étaient presque très proches en comparaison avec les logiciels et l'approche UAV-SfM, et mettent en avant une approche potentielle pour accéder à la distribution granulométrique des rivières à l'avenir.

ABSTRACT

Recent studies have explored automated grain sizing analysis from UAVs imagery of gravel bars, offering efficient alternatives to traditional field methods to understand the river hydraulics and sedimentological properties. This work compares automatic photosieving of sUAS-based orthophotos with field photographs of sediments processed with object-based methods like BASEGRAIN, and PebbleCountsAuto, have also been evaluated, with varying degrees of accuracy compared to laboratory-analysed sediment samples measurements for gravel-bed river Ondava (Western Carpathians, Eastern Slovakia). These UAV-SfM approach enable rapid characterization of grain sizes at higher spatial and temporal resolution than traditional methods, providing valuable insight into sediment dynamics and river processes. Physical habitat parameters can be extracted from detailed 3D models and the channel bed structure or gravel bars substrate is detectable. A predictive model of the relationship between the sUAS image parameters and field samples is proposed and applied for whole high-resolution orthophotos of the study area. The technique showcases the capabilities of high-resolution sUAS images for processing and analysing grain size parameters of the river system. Our preliminary results shows that statistical models calibrated on image texture were almost very closed in comparison with software and the UAV-SfM approach and show potential approach to access the Grain size distribution of river in future.

KEYWORDS

Granulometry, LiDAR, Photosieving, Sedimentology, Uncrewed Aerial Vehicles (UAVs)
Granulométrie, LiDAR, Phototamisage, Sédimentologie, Véhicules aériens sans équipage (UAVs)

[1]MSc. Ashraf MD, Geografický ústav SAV, Štefánikova 49, 814 73 Bratislava, geogashr@savba.sk
[1]Miloš Rusnák, PhD. Geografický ústav SAV, Štefánikova 49, 814 73 Bratislava, geogmilo@savba.sk

1. RIVER SEDIMENT ANALYSIS: CHALLENGES & TECHNOLOGICAL INNOVATIONS

Sediment is a fundamental component of river systems, shaping channel morphology, influencing flow dynamics, and acting as a vector for transporting nutrients and contaminants. About two gigatons of bed are transported annually through rivers on Earth (Syvitski et al., 2003). Sedimentation remains a critical challenge for river ecosystems worldwide. Research on 145 major rivers with consistent long-term sediment records reveals that approximately half of this river exhibits a statistically significant decline in flow trends attributable to sedimentation (willing and Fang,2003). However, it can also accumulate hazardous substances that may be remobilized during floods or human activities, leading to downstream contamination (Brils, 2008. While the European Union Water Framework Directives (WFD) initially neglected sediment's role, efforts by organizations like SedNet have highlighted its importance, with the Elbe River Basin pioneering the integration of sediment management into its River Basin Management Plan (RBMP) Förstner, 2008). Despite restoration efforts, many EU water bodies fails to meet WFD objectives due to chemical pollution and hydromorphological deficiencies, underscoring the need for simultaneous improvements in water and sediment quality (Carvalho et al., 2019). Recent WFD amendments now enable Member State to set Environmental Quality Standard (EQS) for sediment and biota, improving contamination management through advance monitoring tools (Förstner, 2008). Moving forward, integrating sediment management into policies, enhancing monitoring frameworks, and employing innovative analysis tools are essential for effective and evidence-based river basin management (Carvalho et al., 2019; Ramos et al., 2018). Based on Sumi and Hirose (2009) highlighted that the global reservoir gross storage capacity is estimated at around 6000 km3, with annual sedimentation reducing this by approximately 31km3 (0.52%). At this rate, it is projected that global reservoir storage could diminished by 50% up to 2100.

2 GRAIN SIZE DISTRIBUTION: EVOLVING FROM TRADITIONAL TO MODERN APPROACHES

Understanding and predicting fluvial processes rely on accurately quantifying the size distribution of riverbed particles (Detert & Weitbrecht, 2020. Over the past nearly a century, researchers have focused on river sediment analysis to understand sediment transport, hydraulics, and the evolution of river systems. Early reports on sediment measurement and analysis, laid the foundation for the study of sediment loads in streams. Traditional methods for obtaining grain size distribution (GSD), such as laboratory-based mechanical sieving and in-situ techniques like line sampling grid by numbers (René Fehr, 1987; Wolman, 1954), involve significant time labour costs and often disrupt the sample environment. These methods are further constrained by the spatial limitation and accessibility of sampling locations. Due to the advancement of the technology over the last three decades to address these challenges of GSD researchers introduced the photosieving technique, enabling grain size measurement from the photographs. Later, automated grain sizing approaches were developed, categorizing them into image-based and topography-based, like individual GSD from delineating grains, statistical GSD based on image or elevation metrics, and characteristics grain size, e.g. (D50, D84, & Dmean). The study of sediment transport (Lehotský et al., 2018) now requires multitemporal and multiscale approaches using advanced tools like precise imaging, 3D technology generation, elevation model, tracer particles analysis, ground-penetrating radar, and grain size analysis. Transitioning from local to catchment scale using high-resolution topographic datasets is a key challenge for identifying system linkages through numerical methods and an exhaustive inventory of sediment cascade processes (Rusnák et al., 2020). For decades, sieve analysis has been the standard for examining granular materials, particularly coarse ones.

2.1 Grain size distribution : Combine field data and UAV survey

This study integrates multiple approaches to analyse sediment variation of the river section and its systems. Initially, a small section of the riverbed was selected, where sediment samples were collected digitally, both photos (using high-resolution orthophotos from sUAS, LiDAR) and results of field sampling. The proposed approach combines the advantages of remote sensing techniques and drones for longer river reach with a detailed field survey. Finally, GSD distribution was compared with laboratory-processed data. During field survey, sediment distribution, was measured by application BASEGRAIN and PebbleCount photosieving software programs. While this provides detailed information about a localized area, understanding the Grain size distribution across the entire gravel bar required a broader analysis. To achieve this, data extracted from orthophotos, and UAV imagery were statistically analysed and compared with the field data, enabling a comprehensive assessment of grain size parameters across the study area.

The grain size distribution of the Ondava River was detected by a field survey in October 2023. A photographic area sampling method, also called photosieving, was implemented to identify the grain size of coarse sediments on the gravel bar. The method consists of photographing images of the gravel bar fill in a reference frame with well-defined dimensions. Overall, we selected 16 sites for the identification of photosieving GSD, and from 7 sites samples were collected for laboratory sieving analyses. Photosieving involves capturing images of sediment surfaces, which can be analysed to determine the grain size distribution (GSD) of particles. This method eliminates the need for field-based calibration data, which can be costly and logistically challenging to collect, especially in remote locations (Dugdale et al., 2010). Starting from the downstream to the upstream from Sample site (S1) to Sample site (S16). To extract the Grain size distribution (GSD) from the image processing procedure (tuned or automated) on different threshold, total 16 photos from the field (16 x 2 photographic analysis software) (i) BASEGRAIN (ii) PebblecountsAuto and having samples of sediment collected for lab sieving alternating site (S1, S3, S5, S7, S9, S11, and S14) from the field to compare and validate the results.

The flight campaign was performed in October 2023 with DJI Phantom Pro4 equipped with FC6310 (8.8 mm) camera. Dataset areas covered approximately 600 m in width and 2.1 km in length. Overall, 40 ground control points (GCP) were used for spatial referencing. Overall, 1,708 images were successfully processed. The first step was photo aligning and tie point generation. In the last step, the software created orthophotomosaics of a final resolution of 2.08 cm/pix. For model generation, 20 GCPs with root mean square error (RMSE) 0.0084 m were used and 20 checkpoints for accuracy verification with RMSE 0.0288 m. Lidar datasets were obtained by DJI Agras T30 with payload Riegl VUX-1. LiDAR scanner recorded 395,671,882 points with point density: all returns 493.58 per square meter and 355.88 per square meter for ground points.

In the upper section of the river data from (S16 to S12), coarser sediments were prevalent. Particularly large cobbles. For example, at S12, D50 values reached a maximum of 76.9 mm (BASEGRAIN), and D90 exceeded 160 mm (PebbleCounnt), signifying the dominance of larger gravel and cobbles. The cobble sizes observed in this section were mostly in the range of small and medium cobbles (65-128 mm), with some large cobbles (129-256 mm) at S12 and S14. Grain size distribution varied significantly across the river’s length. In the downstream section (S1 to S5), coarser materials dominated, with larger gravel and cobble sizes predominating. At S1, the D50 values from pebbleCounts, BASEGRAIN, and lab sieving were 58.5 mm and 62.1 mm, respectively, reflecting the presence of course gravel. As one moved upstream (S6 to S12), a noticeable decrease in sediment size was observed, particularly in S5, where the D50 values dropped to 31.4 mm (PebbleCounts), 23.9 mm (BASEGRAIN), and 14.63 (lab sieving), indicating a higher proportion of fine gravel and some medium gravel.

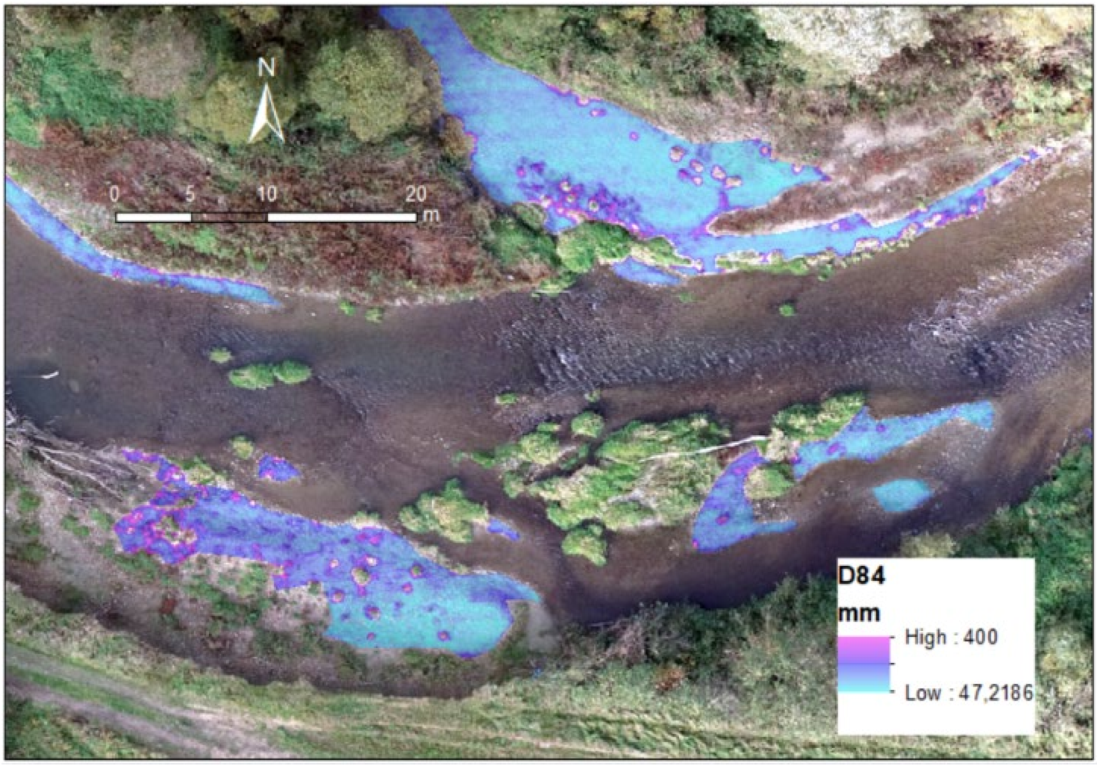

Figure 1 Figure 1 D84 Grain size estimation in selected area by regression model between point cloud geometry characteristics and field measurement. (Surface point cloud elevation variability with 30 cm window)

Finally, results obtained from the field survey (photosieving and lab sieving) were compared with image-based metrics of grain size from SfM photogrammetry orthophotomosaics and topography-based metrics from UAV LiDAR datasets. Testing different images and point cloud metrics helps to establish UAV-assisted grain size estimation and reported R2 values between 0.65 and 0.71 for UAV datasets.

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