

# Using UAV and LIDAR data for gully geomorphic changes monitoring

Mihai Niculiță<sup>1</sup>, Mihai Ciprian Mărgărint<sup>1</sup>, Paolo Tarolli<sup>2</sup>

<sup>1</sup>Department of Geography, Faculty of Geography and Geology, Alexandru Ioan Cuza University of Iași, Carol I 20A, 700505, Iași (IS), Romania

<sup>2</sup>Department of Land, Environment, Agriculture and Forestry, University of Padova, Agripolis, viale dell'Università 16, 35020 Legnaro (PD), Italy

Submitted to the Book *Remote Sensing of Geomorphology*

(Elsevier book series Developments in Earth Surface Processes)

80 pages

Correspondence to: Mihai Niculiță ([mihai.niculita@uaic.ro](mailto:mihai.niculita@uaic.ro)), +40742824349 (Romania)

## **Abstract**

Gully formation and evolution represent an important aspect of landform evolution, but also of practical interest regarding hydrology and agriculture. The classic methodology of assessing the intensity of these erosion processes, and the volumes of sediments involved, is to use field measurements or classical/digital photogrammetry. These methods were recently completed by the use of high-resolution Digital Elevation Models (DEMs) derived from multitemporal LiDAR data and UAV images. In the Moldavian Plateau (north-eastern Romania) gullies are common landforms due to geologic, topographic, climatic and anthropic factors. Their episodic development and the relationship with high rainfall and/or snowmelt events constitute a key point in the deciphering the gully evolution. For this work we have chosen the case of four gullies developed in the lacustrine deposits of abandoned anthropic reservoirs and which presented an obvious dynamic in the last two decades on remote sensing images. A DJI Phantom 4 Pro UAV was flown over the study case areas and acquired images with 80% side and forward overlap at 20 MP resolution. The UAV point cloud was obtained using the Structure from Motion (SfM) technique in VisualSfM open source software from overlapping images and was georeferenced with ground control points. Georeferenced LiDAR point clouds acquired in winter 2012 were used as a reference dataset. The filtering of the point clouds for obtaining bare ground points was performed with the Multiscale Curvature Classification (MCC) algorithm. The point cloud ground data for both the sources and periods were used to interpolate a 0.25 m resolution bare earth DEMs for every gully. This LiDAR reference DEM was used together with the UAV SfM DEM for deriving the Dem of Differences (DoDs) using the Geomorphic Change Detection technique of Wheaton et al. (2010) implemented in SAGA GIS and R stat. The GCD was applied with both uniform and spatially variable thresholding, the threshold errors being derived from GCPs and from co-registration of the DEMs. Geomorphological mapping was performed for establishing the spatially variable thresholds and for assessing the sediment budget. The results highlighted the areas that were affected by erosion and deposition and allowed us to evaluate the process rate for every studied gully,

for every gully element and to derive a raw sediment budget, showing that LiDAR, UAV SfM and DoD are useful methods in geomorphological mapping and rate of process studies.

**Keywords:** LiDAR, high-resolution topography, DEM, gully erosion, UAV, SfM, NE Romania.

## 1. Introduction

A detailed knowledge of landform topography allows us varied and complex geomorphometric characterization, computation of different indices and also offer an enriched perspective on the history and processes that shaped the Earth surface (Tarolli, 2014). The large variety of new technologies used in geomorphology changed the face of this science (Inkpen, 2018), by shifts registered in the transition from poor to rich data, from field analysis to modeled reality and local surveys (Piegay et al., 2015), from analogue to digital technologies and the miniaturization and portability which changed the nature and the quantities of data recorded in the field (Viles, 2016). Among these technologies, airborne and terrestrial LiDAR (Light Detecting and Ranging), digital photogrammetry and Structure from Motion (SfM) provide a large spectrum of data in order to obtain accurate and low-cost Digital Elevation Models (DEM's). Due to their sub-meter resolution and the relatively high accuracy, the applications of these technologies are widespread in the analysis of many landforms which are characterized by fine fingerprints and whose evolution involved gradual processes (Passalacqua et al., 2015). This is the case of gully erosion which shows large year-to-year variation (Vanmaercke et al., 2016) and involves various processes (head retreat, bank retreat, scour, bank landslides, deposition) that creates a complex and fine morphology, that can be depicted on high-resolution DEMs.

Gully erosion is recognized as an important process of soil erosion and a source of sediments (Poesen, Vandaele and Wesemael, 1996, 1998; Poesen et al., 2003, 2006; Nagasaka et al., 2005), very often neglected in sediment budgets studies, but also of environmental and land degradation and economic losses for agricultural lands (Poesen et al., 2003, 2006). Gully

research is needed in order to fully conceptualize these complex phenomena that creates gully landforms in order to establish clear measures that can diminish their effects on land degradation (Heede, 1976; Bocco, 1991; Poesen et al., 2006; Bergonse and Reis, 2011). Gully monitoring evolved from topographic mapping (Ireland, Sharpe, and Eargle, 1939; Leopold and Miller, 1956; Schumm and Hadley, 1957; Tuckfield, 1964;), to photogrammetry (Giménez et al., 2009; Marzloff and Poesen, 2009) and remote sensing (Bocco and Valenzuela, 1993). Currently, not many research studies fully exploited the use of LiDAR and low-cost SfM, in characterizing gullies and in rate of process studies of gully erosion, with a few exceptions (Lannoeye et al., 2016; Gong et al., 2019). The studies dedicated to the usage of low cost DEMs were mainly focused on small areas and on proof of concept regarding the workflow, errors and gully features that can be modelled and mapped (Marzloff, Ries and Poesen, 2011; Peter et al., 2014; Stöcker, Eltner and Karrasch, 2015; Frankl et al., 2015; Liu et al., 2016; Koci et al., 2017; Glendell et al., 2017).

Our approach targets the usability of readily available datasets, like LiDAR and low-cost technology, like UAV SfM, coupled with DEM of Difference (DoD) analysis (Wheanton et al., 2010), to assess gully geomorphometry and rate of process.

## 1.1 LiDAR in geosciences

After experiments in the 60' and the 70', LiDAR acquiring topography technology became functional in the '80 and the '90, revolutionizing the elevation acquisition (Hickman and Hogg, 1969; Irish and White, 1998; Wehr and Lohr, 1999). In the '90 and early '00 bathymetry and topography LiDAR systems were used to map from regional areas through airborne systems to Solar System planets through satellite borne systems (Smith et al., 1997, 1999). Nowadays there is envisioned that in near future big swaths of Earth will be covered with accessible LiDAR data, and the application for the Earth's surface are very diverse, becoming a de-facto

tool in geosciences (Harpold et al., 2015), including geoscience education (Robinson et al., 2017).

LiDAR high resolution DEM's were successfully used in landslide detection and mapping (McKean and Roering, 2004; Guzzetti et al., 2012, Tarolli et al., 2012; Lin et al., 2013; Niculiță, 2016; Niculiță et al., 2016) and landslide dynamic and hazard assessment (Dewitte et al., 2008; Deron and Jaboyedoff, 2010; Schürch et al., 2011; Ventura et al., 2011; Jaboyedoff, 2012; Haas et al., 2012; Liu et al., 2018). In fluvial geomorphology the applications of LiDAR are various, from channel network initiation threshold mapping (Tarolli and Dalla Fontana, 2009; Passalacqua et al., 2010; Orlandini et al., 2011; Sofia et al., 2011), to channel bed morphology and dynamics (Cavalli et al., 2008; Notebaert et al., 2009; Trevisani et al., 2010; Cavalli and Tarolli, 2011; Tarolli et al., 2012; Sofia, Dalla Fontana and Tarolli, 2014). LiDAR technologies were also used in gully delineation and mapping (James et al., 2007; Momm et al., 2011, 2013; Xu et al., 2017; Wu et al., 2017) and the assessment of erosion rates (Evans and Lindsay, 2010; Perroy et al., 2010; Wang et al., 2016) or soil erosion (Eltner and Baumgart, 2015), both as TLS (Terrestrial Laser Scanning) or as ALS (Airborne Laser Scanning). Important results in the use of LiDAR were registered in the study of anthropic landform such as mining activities, agricultural terraces, farmlands, roads (Tarolli and Sofia, 2016; Sofia et al., 2016; Brown et al., 2017; Tarolli et al., 2017, 2019).

## 1.2 Digital photogrammetry and SfM in geosciences

After the emergence of low-cost computers and cameras, the close-range low-cost digital photogrammetry has become widely used to obtain high resolution representations of Earth surface known as Digital Terrain Models (DTMs) or even DEMs, where the elevation of the landforms is targeted (Barker et al., 1997; Aschenwald et al., 2001; Heimsath and Farid, 2002; Remondino and El-Hakim, 2006; Matthews, 2008; Fraser and Cronk, 2009; Eltner et al., 2016) in areas where dense vegetation is not present.

The Structure-from-Motion approach dates from back to the '80 and is based on the work done in computer vision in order to reconstruct the 3D position of the camera based on the unconnected elements in motion (Ullman, 1979; Longuet-Higgins, 1981), that are recognized in multiple views. The most used algorithm is Scale Invariant Feature Transform (SIFT) which is finding point features in each image and is invariant to image transformations (Lowe, 1999; 2001; 2004). After that, the point features between every pair of images are used for the estimation of a fundamental matrix for the pairs in terms of pixel locations (the most used is the RANSAC algorithm - Fischler and Bolles, 1981) which is later used to create tracks for every matched point across multiple images and of connectivity graphs (Snavely et al., 2008). The estimation of camera parameters (rotation, translation, focal length, radial distortions) is done in an iterative way in order to minimize the sum of distance between projections (Snavely et al., 2008) using an efficient algorithm for the five-point relative pose problem (Nistér, 2004) to find the solutions for relative camera pose between two calibrated views given five corresponding points. The camera locations and orientations are estimated in local x, y, z coordinates in order to create the jointly optimal 3D structure through bundle adjustment (Triggs et al., 2000; Snavely et al., 2008). The final result consists of a sparse point cloud and reconstructed camera poses. The sparse point cloud that contains only the recognized point features between pairs of images, needs to be densified, which is performed through depth-map merging methods (Micusik and Kosecka, 2009). These, compute individual depth maps for each image which are then combined into a single 3D model (e.g. Li et al., 2010). A depth map is an image representing the distance from the camera position viewpoint to the 3D scene objects (Carrivick et al., 2016).

The developments of image-based terrain extraction algorithms have made possible to achieve good quality topographic data in terms of accuracy and precision from any angle overlapping stereo-pairs (Chandler, 1999; Lane et al., 2000), through improvements of the methods to calibrate low cost DSLR cameras (Clarke and Fryer, 1998; Chandler et al., 2005; Remondino and Fraser, 2006). In this way any scientist could acquire good topographic data

for small areas, with a wide range of uses in geomorphology. Further, the low-cost UAV that can support low-cost cameras (Giordan et al., 2018), extended the spatial range and the quality of the topography reconstructions, since spatial settings similar and better than classic photogrammetric could be applied.

The application of digital photogrammetry and SfM techniques in geosciences (Westboy et al., 2012; Colomina and Molina, 2014; Carrivick et al., 2016) includes until now various geomorphology fields like (i) laboratory-scale landscape evolution models (Stojic et al., 1998; Hancock and Willgoose, 2001; Lane et al., 2001; Brasington and Smart, 2003; Rieke-Zapp and Nearing, 2005; Heng et al., 2010; Smith and Vericat, 2015; Momm et al., 2017), (ii) fluvial bed morphology (Heritage et al., 1999; Lane, 2000; Lane et al., 2000, 2001; Chandler et al., 2003; Brasington and Smart, 2003; Bird et al., 2010; Strick et al., 2018; Cucchiaro et al., 2018), (iii) river bank erosion (Barker et al., 1997; Pyle et al., 1997; Prosdocimi et al., 2015; Hamshaw et al., 2017), (iv) soil erosion (Eltner et al., 2013, 2014, 2015, 2017; Hänsel et al., 2016; Prosdocimi et al., 2017; Di Stefano et al., 2019), (v) gully erosion (Betts and DeRose, 1999; Marzloff and Poesen, 2009; Kaiser et al., 2014; Gómez-Gutiérrez et al., 2014; Gesch et al., 2015; Frankl et al., 2015; Vinci et al., 2015; Stöcker, Eltner and Karrasch, 2015; Glendell et al., 2017; Di Stefano et al., 2017; Castillo et al., 2015, 2018; Qin et al., 2019), (vi) glacier and proglacial surface change (Baltsavias et al., 2001; Keutterling and Thomas, 2006; Ely et al., 2016; Piermattei et al., 2016), (vii) geology mapping (Krosley et al., 2006; Sturznegger and Stead, 2009), (viii) rock slope stability analysis (Haneberg, 2008), (ix) landslide mapping and monitoring (Peppia et al., 2018), (x) agriculture (Tarolli et al., 2019), and (xi) anthropogenic landforms (Chen et al., 2015; Xiang et al., 2018).

## 2. Study Area: the reservoir bottom-gullies from Jijia Hills (Romania)

The Northeastern Romania lowland (Figure 1) is well known for its reservoir construction history, sedimentation and decommissioning during the last 500 years (Niculiță et al., 2019).

These reservoirs were in general small (under 1 million m<sup>3</sup>), shallow (4 – 8 m dam height with water depth of up to 5 m) and frequently dry during the summer or winter (Mărgărint and Niculiță, 2016; Niculiță, Mărgărint and Tarolli, 2017; Mărgărint et al., 2017). Their construction was requested by the dryness of the climate, the reservoirs being used for water storage, pisciculture, for cereals and fuller mills.

After reservoirs filling, the dam topography was kept and became smooth over time. The dams were cut in the principal spillway outlet area, in the auxiliary outlet area or in the median part of the dam, in order to evacuate/drain the groundwater, so that the reservoir bottom could be used as pasture. This anthropic intervention created a concentration of flow at high water discharges in the cut area, which allowed the evolution of gullies on the flat lacustrine bottom. In other case for the same effect, respectively groundwater draining, linear channels were cut along the median line of the reservoir bottom. In this case bank gullies developed and evolved on the flat lacustrine bottom, in areas where affluent discharge drained toward the anthropic channel. The reservoir sediments are predominantly silty, with layers of calcite duricrusts (Mărgărint et al., 2017).

In the Jijia Hills, North-Eastern Romania, Niculiță et al. (2019) identified 489 gullies, from which 68 showed changes in the aerial images from 2005 and 2010, and Google Earth high-resolution satellite imagery. From these 68 active gullies we have selected four gullies (Figure 1) that were surveyed in the late winter and the early spring of 2019. Two of the gullies are located south of Săveni City (Botoșani County, Romania) in the Ghițălăria catchment (20 km<sup>2</sup>), tributary to Sitna River, and the other two are located east of Șoldănești village (Botoșani County, Romania) in the Rogojeni catchment (61 km<sup>2</sup>), tributary to Jijia River. For simplicity the sites were labeled after the name of locality and the upstream or downstream location in the catchment.

Figure 1



## 3. Materials and methods

### 3.1. LiDAR data

LiDAR data was acquired at the end of 2012 with a Leica ALS60 system in geographic coordinates on the ETRS89 datum (EPSG:4258) by a company commissioned by Prut-Bârlad Water Administration. The point clouds (.las format v 1.1) were classified with an unspecified algorithm and software to ASPRS 1.1 format classes. The point clouds for the entire project (21708 km<sup>2</sup>) were georeferenced using a network of 387 geodetic points, measured both in ETRS89 and Stereo 70 Marea Neagră datums and for which a quasi-geoid model was computed. The vertical accuracy (expressed as RMSE of elevation difference) is 0.19 m, in line with data used in the literature (Adams and Chandler, 2002; Bowen and Waltermire, 2002; Hodgson and Bresnahan, 2004).

We used GDAL and proj4 to convert between EPSG:4258 to EPSG:3844 horizontal datum. No vertical datum conversion was performed since GPS coordinates were acquired in ETRS89 through the [www.rompos.ro](http://www.rompos.ro) differential correction service.

Because the algorithm of point cloud classification is not known, and because through remote sensing investigation (aerial imagery draped over the DEM and 3D views with the point cloud) we observed that especially the landform edges (gully bank and other scarps) are not correctly located (due to low vegetation identified on these edges) we have chosen to process ourselves the points clouds for bare earth extraction (Liu, 2008). The Multiscale Curvature Classification (MCC) algorithm (Evans and Hudak, 2007) was used since the study area has a low tree cover and the low grassy vegetation can be easily depicted by the curvature parameter used by this algorithm, due to the fact that the data was acquired in mid-winter, with low snow cover. Multiple runs with different parameters of the algorithm (scale parameters with values between 0.1 to 3 m and curvature parameter with values between 0.05 and 0.4) were assessed (Figure 2 – the DEMs were derived from the TIN interpolation of the point clouds; the highlighted DEM represents the run from which the values of the parameters were chosen). As we increased

the scale factor, more and more ground data was considered to be with a low vegetation cover and, as consequence was removed. The most affected areas are located on the edges of the gully banks and other scarps. The question that arose is what is acceptable: to lose information about the erosional morphology or to remove entirely the vegetation. In our case we argue that keeping morphology is important, since vegetation can be later removed from the DTM through filtering, or even manually, or as in our case is not so important since the gullies have important erosional surface, where there is very low vegetation cover. Finally, we have chosen as parameters for the MCC algorithm a scale of 0.5 and curvature of 0.1. We strongly advise others to use their own assessment in order to select the right parameters, since our gullies are in their majority free of vegetation during late autumn and winter (grasses decay after the very dry late summer and early autumn), when both the LiDAR and UAV data were acquired.

Figure 2

The description of the point cloud density and spacing before and after classification are reported in the Table 1.

Table 1 The details of LiDAR data for the areas of each gully

| ID | Name                  | Flight date | Density (points/m <sup>2</sup> ) | Mean spacing (m) | Density of ground points (points/m <sup>2</sup> ) | Mean spacing of ground points (points/m <sup>2</sup> ) |
|----|-----------------------|-------------|----------------------------------|------------------|---|--|
| 1  | Săveni downstream     | 01/21/2012  | 2.06                             | 0.35             | 1.98  | 0.35   |
| 2  | Săveni upstream       | 01/21/2012  | 3.68                             | 0.26             | 3.68  | 0.26   |
| 3  | Șoldănești downstream | 01/21/2012  | 1.81                             | 0.43             | 1.74  | 0.44   |

|   |                        |            |      |      |      |      |
|---|------------------------|------------|------|------|------|------|
| 4 | Șoldănești<br>upstream | 01/21/2012 | 1.16 | 0.81 | 1.16 | 0.81 |
|---|------------------------|------------|------|------|------|------|

### 3.2. UAV images

The Phantom 4 Pro quadcopter was used to capture the images in stereo pairs (models) as string and block photogrammetric flight path (Falkner and Morgan, 2002; Linder, 2016) with the help of PrecisionFlight pre-planning mobile application (<https://www.precisionhawk.com/precisionflight>). The altitude of flight was 50 m relative to the take-off location (close to the car that appears as reference in Figures 9-12), and side and forward (end) overlap of 80% (Falkner and Morgan, 2002). The camera acquired images at 20 MP resolution, in 3:2 Aspect Ratio with a size of 5472 × 3648 pixels per image. The nominal pixel size was of ~ 0.01157 m. The characteristics of the Phantom 4 Pro camera are: FOV 84° 8.8 mm/24 mm (35 mm format equivalent) and f/2.8 - f/11 auto focus at 1 m - ∞. Because the Phantom 4 Pro camera calibration parameters are not implemented in the used SfM software, the image were acquired in RAW format without geometric corrections of the software of the camera. The camera parameters were estimated by the SfM process. The ground control points were marked as targets in the field and measured using a Trimble R4 rover with the Rompos RTK correction (with centimetric accuracy, ±3 cm horizontal and ±6 cm vertical) in EPSG:3844 projection and ERTS89 vertical datum.

### 3.3. Structure-from-Motion

#### 3.3.1 SfM

The software used for the SfM technique was VisualSfM version 0.5.26 with the PMVS/CMVS tool chain (Wu et al., 2011; Wu, 2013; Shan et al., 2014; Wu, 2015; Zheng and Wu, 2015) which is free (<http://ccwu.me/vsfm/>). The software performs the classical SfM technique (Figure 3) through: (i) pairwise image matching through a Scale Invariant Feature Transform (SIFT), (ii) followed by full pairwise image matching, sparse reconstruction of the point cloud

based on the matched points between images with bundle adjustment (Snavely et al., 2006, 2008), (iii) GCPs identification and x,y,z setting for geometrical correction (scale and orientation) of the point cloud and (iv) finally the dense reconstruction of the point cloud by Clustering Views for Multi-view Stereo (CMVS) and Patch-based Multi-View-Stereo (PMVS) algorithms (Furukawa and Ponce, 2007; Furukawa et al., 2010; Furukawa and Ponce, 2010). Visual SfM is not so optimized like other proprietary software, but is giving good results in terms of cost and availability.

The SfM process allows the computation of the georeferencing errors as the difference between the true location of the GPS points and their estimated position after geometry correction. The values for every site are shown in Table 2 as RMSE values, the global RMSE being 0.1 for x, 0.16 for y and 0.11 for z.

**Table 2 The RMSE of GCPs after the SfM modelling for every study area**

| ID | Name                  | No of GCPs | x RMSE | y RMSE | z RMSE |
|----|-----------------------|------------|--------|--------|--------|
| 1  | Săveni downstream     | 10         | 0.061  | 0.085  | 0.331  |
| 2  | Săveni upstream       | 10         | 0.174  | 0.321  | 0.038  |
| 3  | Șoldănești downstream | 8          | 0.084  | 0.136  | 0.008  |
| 4  | Șoldănești upstream   | 7          | 0.056  | 0.085  | 0.012  |

Figure 3

### 3.3.2 Point cloud post-processing

The point clouds obtained through the SfM approach are much denser than the LiDAR points (Table 3) but can be processed in a similar manner. The MCC filtering is much more aggressive since there not as much points that cross to the vegetation canopy. Even in cases

with low vegetation cover like ours the results of the MCC filtering is not always good enough and manual editing is needed (Figure 4). Another type of error typical of SfM point clouds is the presence of point with low altitude (several meters under the point cloud), which were identified and deleted using the height above ground point (relative elevation) in CloudCompare (<https://www.danielgm.net/cc/>).

Figure 4

Table 3 The details of SfM point cloud data

| ID | Name                     | Flight date | Density<br>(points/<br>m <sup>2</sup> ) | Mean<br>spacing<br>(m) | Density of<br>ground<br>points<br>(points/m <sup>2</sup> ) | Mean spacing<br>of ground<br>points<br>(points/m <sup>2</sup> ) |
|----|--------------------------|-------------|---|------------------------|--|---|
| 1  | Săveni<br>downstream     | 02/17/2019  | 32.36                                   | 0.0000013              | 31.98  | 0.0000013   |
| 2  | Săveni<br>upstream       | 02/17/2019  | 32.11                                   | 0.0000013              | 31.73  | 0.0000013   |
| 3  | Șoldănești<br>downstream | 03/24/2019  | 77.12                                   | 0.0000009              | 76.93  | 0.0000009   |
| 4  | Șoldănești<br>upstream   | 03/24/2019  | 54.48                                   | 0.0000008              | 52.43  | 0.0000008   |

### 3.4. DEM generation

The quality of DEM's is highly influenced by the interpolation method, and by the density of the input data (Heritage et al., 2009). Regarding this, the density of data in the case of LiDAR and UAV photogrammetry is enough in order to depict morphologies with decimeter extent. The choice of interpolator is secondary to the data density, but in general TIN interpolators have the lowest errors (since every point is honored) and can represent linear features

(Heritage et al., 2009). Kriging was used with success (Lloyd and Atkinson, 2002) and is more statistical sounding, but it can give noise. While we agree with this statements, TIN algorithms create hard edges which are not seen in nature, especially in areas where the data density is lower, so we used a spline interpolator that has the characteristics that is able to allow the surface to pass through the input points (so it honours them like TIN) and to minimize spatially the bending of the surface, especially in case of dense spaced data (Niculiță, 2012). Of course, some overshooting is to be expected, but it should be restricted to areas where the density of elevation data is sparse.

DEM's were interpolated from the LiDAR and SfM point clouds with Multilevel B-spline (MBS) (Lee et al., 1997) at a resolution of 0.25 m. The chosen resolution was reflecting a compromise between data density, data coverage, image resolution, efficient data storage/ later processing requirements and surface representation. According to Hengl's (2006) specification, the point density is showing an optimum pixel size between 0.13 and 0.23 m, while the lowest mean distance between neighbor points is 0.26 points/m<sup>2</sup>. The 0.25 m value was considered a good trade-off.

MBS is an algorithm that well controls the spline interpolation, through the use of successive quadtree levels and generates relatively smooth data compared to a TIN interpolator (Niculiță, 2012) which will generate hard edges and planar surfaces, especially since the data density is good (the maximum distance between neighbor points is between 0.8 and 1.8 m). The MBS settings which control the degree of generalization of data are the maximum level of interpolation and the threshold of error allowed. Maximum level 14 allow for every point to influence the model, and we have chosen this value. A threshold error of 0.01 will smooth the surface more than a 0.001 error threshold. In Figure 5 several runs of these settings with variable values to show their influence are represented (the highlighted run represents the chosen parameters values).

For the studied sites the vertical accuracy of the LIDAR DEM versus the GCPs used for SfM georeferencing is 0.13 m. The vertical accuracy (expressed as RMSE of elevation difference) of the SfM DEMs computed for the 35 GCPs is 0.18 m.

**Table 4 The RMSE of the DEMs for every study area**

| ID | Name                  | No of GCPs | LiDAR DEM z RMSE [m] | SfM DEM z RMSE [m] |
|----|-----------------------|------------|----------------------|--------------------|
| 1  | Săveni downstream     | 10         | 0.363                | 0.405              |
| 2  | Săveni upstream       | 10         | 0.004                | 0.039              |
| 3  | Șoldănești downstream | 8          | 0.005                | 0.053              |
| 4  | Șoldănești upstream   | 7          | 0.026                | 0.116              |

Figure 5

### 3.5. Geomorphic Change Detection

Geomorphic Change Detection (GCD), a type of DEM differencing (Brassington et al., 2003) or DEM of Differences (Wheaton, 2008) was applied in our study. For the GCD analysis we have used the approach of Wheaton (2008), later extended in Wheaton et al. (2010) and Bangen et al. (2015). Instead of using the software provided by Riverscapes Consortium (<http://gcd.riverscapes.xyz/>), we have implemented ourselves the methodology in R stat (R Core Team, 2013) using various packages and SAGA (Conrad et al., 2015) software (Figure 6).

The Wheaton mixed approach (Wheaton et al., 2010) can be divided into three main steps: (i) the computation of raw differences between a reference and a later DEM, (ii) the error modelling, (iii) the error filtering and (iv) the construction of the sediment budget. The first step is straightforward and was implemented as a raster algebra difference. In the second step two uncertainty thresholding approaches were used: the 95% confidence interval of spatially

uniform standard deviation of raw differences (0.0355 m for Săveni downstream, 0.0212 m for Săveni upstream, 0.0193 m for Șoldănești downstream and 0.0167 m for Șoldănești upstream) and the probability of spatially variable error using fuzzy inference rules, in order to incorporate for non-uniform spatial errors. The second was based on a geomorphological mapping of the gully system in 2019, performed on the UAV SfM high-resolution DEM, its derivatives (slope, edge detection of slope, compound shading) and the orthoimage, a threshold of error was assigned for every digitized polygon in QGIS. The error was computed from the relatively flat areas of the reservoir bottom from around every polygon using descriptive statistics, areas which are stable from a geomorphological point of view. The values of the error were between  $\pm 0.1$  and  $\pm 0.5$  m, estimated based on the interquartile range. Further, the threshold error was filtered by probabilities that were assigned based on the point density of the LiDAR and UAV SfM data, slope (as in Wheaton et al., 2010) and vegetation cover assessment using fuzzy set rules (instead of 3D point quality of Wheaton et al., 2010). The fuzzy set rules were created with R stat package FuzzyR (Garibaldi et al., 2017). For point density and slope, trapezoidal membership function was used with left foot, left shoulder, right shoulder, right foot values defined based on the descriptive statistics of the input data (Figure 7 and Table 5), while for vegetation the singleton membership function was used. When the minimum, the lower whisker and Q1 were equal, Q1 was computed as half of the mean. This statistical setting of computing the trapezoidal function membership was chosen in order to standardize the fuzzy membership assignment.

The fuzzy inference system was of type Mamdani with minimum for AND and maximum for OR methods. The fuzzy rules are identical with those of Wheaton et al. (2010). The convolution filter for deriving the spatial contiguity index for erosion and deposition coherence was applied with the *focal* function of the *raster* R stat package (Hijmans, 2017) for the joined probabilities (uniform and spatially variable).



In the final stage, the sediment budget was computed for every type of process, using again the geomorphological map. Error assessment was performed only based on the uniform spatial filter, and as overall figure for erosion and deposition (Table 6).

Figure 6

Figure 7

Table 5 The values of the trapezoidal membership function (PD – point density, SL – slope, lw – lower whisker, uw – upper whisker)

| ID | Name                     | Year | Variable | min  | lw   | Q1   | mean  | sd    | Q3    | uw    | max   |
|----|--------------------------|------|----------|------|------|------|-------|-------|-------|-------|-------|
| 1  | Săveni<br>downstream     | 2012 | PD       | 0.00 | 0.00 | 1.00 | 1.98  | 1.14  | 3.00  | 6.00  | 8.00  |
|    |                          |      | SL       | 0.00 | 0.00 | 2.56 | 8.98  | 9.02  | 12.55 | 27.54 | 63.39 |
|    |                          | 2019 | PD       | 0.00 | 22   | 29   | 31.84 | 5.09  | 34    | 41    | 70    |
|    |                          |      | SL       | 0.00 | 0.00 | 2.36 | 8.57  | 8.78  | 11.71 | 25.74 | 86.46 |
| 2  | Săveni upstream          | 2012 | PD       | 0.00 | 1.00 | 2.32 | 1.99  | 2.67  | 3.48  | 5.22  | 57.38 |
|    |                          |      | SL       | 0.00 | 0.00 | 0.00 | 5.72  | 8.46  | 8.02  | 20.07 | 74.32 |
|    |                          | 2019 | PD       | 0.00 | 0.00 | 0.00 | 18.24 | 16.28 | 32.26 | 63.81 | 63.81 |
|    |                          |      | SL       | 0.00 | 0.00 | 0.00 | 4.96  | 7.97  | 6.43  | 16.08 | 72.56 |
| 3  | Șoldănești<br>downstream | 2012 | PD       | 0.00 | 0.00 | 0.00 | 0.83  | 0.97  | 2.00  | 5.00  | 5.00  |
|    |                          |      | SL       | 0.00 | 0.00 | 0.00 | 3.58  | 6.74  | 4.23  | 10.58 | 67.11 |
|    |                          | 2019 | PS       | 0.00 | 0.00 | 0.00 | 25.59 | 27.18 | 53.00 | 120   | 120   |
|    |                          |      | SL       | 0.00 | 0.00 | 0.00 | 3.93  | 7.17  | 4.85  | 12.12 | 73.89 |
| 4  | Șoldănești<br>upstream   | 2012 | PD       | 0.00 | 1.00 | 1.00 | 1.16  | 0.58  | 1.00  | 1.00  | 4.00  |
|    |                          |      | SL       | 0.00 | 0.00 | 1.38 | 6.83  | 7.26  | 9.46  | 21.59 | 62.17 |
|    |                          | 2019 | PD       | 0.00 | 61   | 73   | 78.03 | 8.49  | 81    | 93    | 169   |

|  |  |  |    |      |      |      |      |      |       |       |       |
|--|--|--|----|------|------|------|------|------|-------|-------|-------|
|  |  |  | SL | 0.00 | 0.00 | 2.49 | 7.69 | 7.57 | 10.14 | 21.61 | 80.68 |
|--|--|--|----|------|------|------|------|------|-------|-------|-------|

### 3.6 Geomorphological mapping

The geomorphological mapping was performed through a geomorphometric approach on the SfM DEM using as visual aid the orthoimagery. Slope, edge detection of slope and compound shading were the DEM derivatives used to identify the breaks in the morphology that corresponds with the visual information from the ortophotomap interpretation. The digitization was performed in QGIS v. 3.6, by creating polygons that correspond to elements of the gully, and by checking in 3D view the results, and refining if needed. Beside the 2019 data, aerial imagery from 2003 and 2010 at 0.5 m resolution and Google Earth time lapse imagery were used to check for the state of the geomorphological processes as well. This data was used to qualitatively assess the state of the bank erosion, channel deposition, landslide areas, vegetation cover and reservoir bottom lateral to the gully. According to the literature on gully morphology (Ireland, Sharpe, and Eargle, 1936, 1939; Heede, 1976; Imeson and Kwaad, 1980; Bettis III and Thompson, 1985; Geyik, 1986; Bocco, 1991; Farres et al., 1993; Poesen et al., 1996, 1998) the following elements of a continuous gully were delineated (Figure 8): edge, ridge, bank, terrace, bottom, channel and alluvial fan. The bank, the channel and the bottom were split into parts at the main branches of the main gully, at the knickpoints, at the headcuts and for bank gullies. Bank landslides (slumps) triggered by sloughing and incision were also separated. Piping was not identified as an important process along the investigated gully systems, although there are important systems of cracks in the silty sediments of the reservoirs through which water is moving. From this point of view most probably the hydrogeological factors involved in gully evolution is the presence of a groundwater body inside the reservoir sediments bounded by the old alluvial bed, sediment depth which also controls the depth of the gully (Mărgărint et al., 2017; Niculiță et al., 2019). These reservoir bottom gullies evolve from a small channel incision upstream the dam breach, by deepening from the initial reservoir bottom and head migration upstream when there is an overland flow

concentrating in the dam breach area. As the gully extends upstream, channel incision, slope wash and landslides generate the bank retreat and the gully will widen in the same time it will get deep. The episodes of incision happening along the gully, generate the presence of knickpoints and of sediments along the channel and the bottom, and even terraces. This situation is somehow similar to hillslope or valley gullies (Bocco, 1991), with the difference that the discontinuity of the process is not present. Instead, when the discharge is not present and vegetation grows on the banks and the bottom, the gully will stabilize. Later, when overland flow appear the gully might reactivate, especially in the head areas. The discontinuity is only present in the gully-channel system, some gullies continuing downstream with channels (Săveni gullies), others not (Șoldănești gullies) and the presence of gully fans is mainly characteristic for the ones which do not continue with a channel downstream (as is the case for Șoldănești upstream). These reservoir bottom gullies (Niculiță et al., 2019) have various forms (Imeson and Kwaad, 1980): linear, bulbous, dendritic or compound and are of type one or four.

Figure 8

## 4. Results

The results of the change detection between the 2012 LiDAR DEM and the 2019 UAV SfM DEM are represented in multiple ways. In Figures 9 to 12 for every investigated gully, the 2012 LiDAR DEM shading and the raw differences are represented side by side. Besides, the gully border, the ground control points and the location of the topographic sections are displayed.

Figure 9

Figure 10

Figure 11

Figure 12

The values from Table 6 show the areal extension of the gully systems from 2012 to 2019, split by erosion, deposition and no change, and the volumetric data with errors for the raw and for the thresholded data. The Săveni downstream gully has the biggest expansion, both in terms of surface and volumes of sediments, followed by Săveni upstream. Şoldăneşti downstream and upstream gullies have the lowest activity. The errors vary between 4 to 25% of the volumes.

**Table 6 The areal and volumetric GCD data for each gully**

|  |        | Săveni<br>downstream | Săveni<br>upstream | Şoldăneşti<br>downstream | Şoldăneşti<br>upstream |
|--|--------|----------------------|--------------------|--------------------------|------------------------|
| Area [m <sup>2</sup> ]                       | 2012   | 6,259                | 16,237             | 9,091                    | 8,534                  |
|  | 2019   | 8,340                | 19,190             | 9,806                    | 9,284                  |
| Area change [m <sup>2</sup> ] (%)            |        | 2,081 (33%)          | 2,953 (18%)        | 715 (8%)                 | 750 (9%)               |
| Erosion area<br>[m <sup>2</sup> ]            | Raw    | 5,077                | 7,219              | 3,929                    | 1,370                  |
|  | Thres. | 2,491                | 1,190              | 883                      | 854                    |
| Deposition<br>area [m <sup>2</sup> ]         | Raw    | 3,263                | 11,971             | 5,877                    | 7,914                  |
|  | Thres. | 783                  | 2,308              | 979                      | 4,628                  |
| No change<br>area [m <sup>2</sup> ] (%)      | Raw    | -                    | -                  | -                        | -                      |
|  | Thres. | 5,066 (61%)          | 15,692 (82%)       | 7,944 (81%)              | 3,802 (41%)            |
| Eroded volume<br>[m <sup>3</sup> ] (%)       | Raw    | 2474±180             | 1,598±153          | 699±76                   | 663±23                 |
|  | Thres. | 1,847±88             | 622±25             | 334±17                   | 548±14                 |
| Deposited<br>volume [m <sup>3</sup> ]<br>(%) | Raw    | 844±111              | 2,909±243          | 851±109                  | 652±127                |
|  | Thres. | 375±28               | 707±47             | 100±18                   | 410±74                 |
| Net volume<br>[m <sup>3</sup> ] (%)          | Raw    | 1631±69              | -1311±91           | -152±33                  | 11                     |
|  | Thres. | 1,472±61             | -85±22             | 234±1                    | 138±60                 |

In Figures 13, 16, 19 and 22 the filtered GCD final results are shown on the 2019 UAV SfM DEM shading, with the gully border, topographic sections (shown in Figures 14, 17, 20 and 23) and field photography (shown in Figures 15, 18, 21 and 24) locations. The histograms of the GCD raw and filtered results are shown in Figure 25, while the geomorphological mapping (Fig. 26) was used to separate the volumes for every gully element (Fig. 27).

The Săveni upstream gully (Fig. 15 P2) is showing important erosion by head retreat at the one branch along the main section (the one toward North-West), and at two branches that develop along the Iazul Mare valley, to North-East (Fig. 13 P1, Fig. 14 sections 2 and 4, and Fig. 15 P3, P4, P10). The banks outside the heads do not show important erosion processes (Fig. 13, Fig. 14 section 3, Fig. 15 P5-P10, and Fig. 27), but patches of basal accumulation due to erosion and landsliding at the upper part of the profile (Fig. 15 P3), and due to their length cumulate more amount of deposition than erosion (Fig. 27). The gully bottom and channels have the most important areas of deposition (Fig. 13, Fig. 14 sections 1 and 4, Fig. 15 P5-P9, and Fig. 27), downstream the gully heads and knickpoints (Fig. 15 P3, and Fig. 27). The incised channels, terraces and bottom from 2012 were covered by sediments until 2019 (Fig. 14 section 1 and 4, and Fig. 15 P5-P9). The first branch that develops toward North-West along the main valley at the contact with the hillslope (Fig. 13, and Fig. 15 P2) is inactive, affected by landslides at the hillslope side and by anthropic intervention (Fig. 26), the head being transformed in a small reservoir by damming (Fig. 13). The erosion and deposition are balanced (Fig. 25), over 600 m<sup>2</sup> both, with deposition slightly bigger (net deposition of approx. -85 m<sup>3</sup>) (Fig. 25). These results are showing that the gully is unable to evacuate all the sediments produced.

Figure 13

Figure 14

Figure 15

The Săveni downstream gully (Fig. 18 P3) is showing important erosion by head retreat at the main head and at two secondary heads (Fig. 16, Fig. 17 sections 1, 3, 4, and Fig. 18 P1, P2, P4 and P8), but also at two knickpoints on the main branch and on a secondary one (Fig. 16, Fig. 17 section 1 and 4 and, Fig. 18 P2, P4 and P6-7). The left bank of the main branch is also eroded along the section downstream of the knickpoint (Fig. 16, Fig. 17 section 2, and Fig. 18 P7, P9), while the channels are usually filled with sediments by deposition (Fig. 16, Fig. 17 sections 1 and 2, and Fig. 18 P2, P4, P7-9). The erosion is predominant (Fig. 25) and characterize the banks and the bottom with important landslides (Fig. 18 P9, and Fig. 27), but is more important on banks outside the heads. Deposition characterize the main channel and bottom with up to 1 m of sediments (Fig. 17 section 1 and 2). There is also human impact by deposition of the sediments of an anthropic mound (Fig. 10) at the bank of a secondary branch (Fig. 16, and Fig. 18 P6). The erosion is almost five times bigger than deposition, with a net erosion almost four times bigger than deposition (Fig. 25). These data are showing that the majority of the eroded data has been evacuated from the gully (80%).

Figure 16

Figure 17

Figure 18

The Șoldănești upstream gully is showing erosion by head and bank retreat along all the branches (Fig. 19, Fig. 20 sections 1 and 2, Fig. 21 P1-P3, and Fig. 27) and slight deposition along the channels (Fig. 19, Fig. 20 section 2, Fig. 21 P4-P5, and Fig. 27). The most interesting is that the main deposition is on the alluvial cone (Fig. 19, Fig. 20 section 3, Fig. 21 P4, and Fig. 27). A big proportion of this deposition happened on the gully fan, during a rain event in May 2018, and is visible on the ortophotoimage because vegetation didn't completely cover the sediments (Fig. 20 section 3, Fig. 21 P4, and Fig. 27). The erosion is slightly bigger than the deposition, with a net erosion of approx. 139 m<sup>3</sup> (Fig. 25), and both are quite important

considering the small size of the gully, which shows important activity. The difference in eroded sediment volume, of 25% was evacuated downstream the gully fan, out of the gully system.

Figure 19

Figure 20

Figure 21

The Şoldăneşti downstream gully is showing erosion mainly by head retreat and head landslides on the main branch and on a secondary one (Fig. 22, Fig. 23 section 2, Fig. 24, and Fig. 27). There is also erosion on the main bank (Fig. 27). There is slight deposition along the bottoms and channels (Fig. 22 P1, and Fig. 21 section 1), while landslides and slope wash generated accumulation at the base of the banks. The erosion is slightly bigger than the deposition, with a net erosion of approx. 234 m<sup>3</sup> (Fig. 25), showing that the 70% of the eroded volume was evacuated from the gully system.

Figure 22

Figure 23

Figure 24

Overall erosion is bigger than deposition for all the gullies, except for Săveni upstream, where deposition is slightly predominant (Fig. 25). This is showing us that the gully systems in general are able to evacuate between 25 to 80% of the produced sediments through erosion. Regarding the gully evolution, the change detection is showing us that the gully head are the main source of sediment and gully evolution, through erosion of the banks and landslides. The erosion of the banks outside the head areas, is in general of second importance, except for Săveni downstream gully, where is the most important in terms of eroded volumes. Deposition appears mostly as channel and bottom aggradation, but there are also important volumes of sediments deposited on the banks due to landslides or slope wash. The most active gullies in terms of evacuated sediments are those that have elongated main branches (Săveni

downtown and Șoldănești downstream). The most active areas of erosion are the non-vegetated ones (Fig. 15 P5-10, Fig. 18 P4-9, and Fig. 24), and the most active gullies in terms of both erosion and deposition are Săveni downstream and Șoldănești upstream.

Figure 25

Figure 26

Figure 27

## 5. Discussions

The comparison between LiDAR and photogrammetry/UAV SfM was performed in the literature qualitatively (Baltsavias, 1999) and quantitatively (Eltner et al., 2013; Eltner et al., 2014). While there are differences in regard to acquisition method and data density, these methods are able to precisely locate the topographic surfaces in the range of several centimeters (Eltner et al., 2014). Further, snow or vegetation can induce positional errors ranging from 10 to 50 cm, as we assessed in our case for the flat areas of the reservoir bottom around the gullies (Fig. 14 section 1-3, Fig. 17 sections 2-4, Fig. 15 P7-10, Fig. 18 P5-P9 and Fig. 21 P2). Beside these, the geometry of acquisition can introduce tilts, shifts and other deformations that are not necessarily linearly correlated. By analyzing the results of the raw differencing between the obtained DEMs (Fig. 9-12) it can be observed that the central area of the study cases has the negative values on the floodplain, while the edges have positive values, or vice-versa, situations which can be related to the distortion effect of the camera geometry and of the sampling network or to GCP sampling (James and Robson, 2012, 2014). These errors are visible especially due to the relatively flat area that is surveyed. Because in the majority of the studied areas the co-registration differences in elevation are very low (as can be seen in the topographic section from Fig. 14, 17, 20, 23) we did not perform co-registration of the point clouds as is done in some cases (Cucchiaro et al., 2018). The main differences between the points clouds are due to geomorphological processes and errors related to snow, vegetation and SfM deformation.



The LiDAR horizontal accuracy is mainly affected by positioning errors of the carrying platform, of the acquisition system, of the GPS base stations data used for georeferencing or of pre-processing (ASPRS, 2005) and it is several times greater than the vertical accuracy. The errors associated with the LiDAR data are split into four main groups: error per block, error per strip, error per GPS observation, and error per point (ASPRS, 2004, 2005, 2018). Beside the errors induced by the external factors, which are linear and can be dealt with by operations to the whole dataset, the errors induced by the operations of the platform and of the acquisition system are the most problematic, because will induce a variable level of error. The boresight error (misalignment between the laser sensor and the navigational and position al system) is variable to flight height, direction and scan angle and can be observed in areas with flat gradients, because affect differently the scan lines. In our case in Figures 9 to 12, on the shaded DEM from 2012 these errors can be seen in several areas (for example in Fig. 9 in the Western part of the DEM stripes with South-West to North-East orientation can be seen). As it can be seen in Fig. 1, for the channel downstream of the dam, these errors can be filtered, but sometimes this will remove also topography, which is why is preferable to be dealt with through the change detection approach. The difference between the striped ground and non-stripped ground is in the range of  $\pm 0.15$  m.

SfM is an affordable tool for obtaining high-resolution x,y,z point clouds (Carrivick et al., 2016), but some external factors can introduce errors that might hinder some types of analysis. The most problematic errors are those related to the geometry of acquisition, through which non-linear deformations are introduced. These errors are well discussed in the literature and even guidelines were produced for their minimization (Eltner et al., 2016; Wells, 2017; James et al., 2017, 2019). This includes the dishing or doming deformation (Carbonneau and Dietrich, 2017), which in our case has the effect for the geomorphic change detection by making the gully system to appear either too deep, or too shallow, on the SfM DEM compared with the LiDAR surface. Related to the processes, the effects will be that both erosion and deposition will be either under- or overestimated. The question is if this deformation is smaller enough in

magnitude than the change, in order not to influence it, and erosion to become deposition or vice-versa. In our case these deformations were under 25 cm in the gully area, and were removed by the use of GCD. This is visible and can be checked on the topographic sections from Fig. 14, 17, 20 and 23. In these sections it can be seen that the dry vegetation introduces more error than LiDAR and SfM techniques.

The GCPs are very important for reducing the acquisition errors (Javernick et al., 2014) and a sufficient number of GCPs with good distribution can overcome the inherent errors and produce good qualitative and quantitative estimations of the rate of change. The photogrammetry success also depends on the image texture (Fonstad et al, 2013).

The geomorphological mapping is very important for assessing the process rates and for interpreting the geomorphic change detection data. Even for relatively simple landforms, like gullies, the aerophoto-interpretation of the UAV orthoimagery is relevant in deciphering natural or anthropic processes. For example, the gully bottom which is a relatively flat area has a micro-topography created by the incised water flow or the deposition of sediment carried by the water flow at higher discharges and by the erosion or landsliding processes that affect the bank. Even the gully bank edge is sometimes very hard to be located, since erosion shapes its hard edges or landsliding or even the multi-step evolution of the gully incision is creating multiple morphometric edges (Figure 8).

The shape of these erosional features makes easier the assessment of positional errors in regard with the two DEMs used for change detection, which is not the case with complicated environments like braided rivers. The presence of erosion on one side, and of deposition on the other side, or of erosion/deposition of the flat areas around the landslide is an indicator of a misalignment, and can be easily found. The presence of water in the gully channel needs the evaluation of the depths through a reflection model (Dietrich, 2006) or other image enhancing techniques (Partama et al., 2018) to deal with water reflections.

Despite of these errors, the application of the complex Wheaton approach is able to filter the changes related to errors in LiDAR and SfM, or due to vegetation, and to show the meaningful changes that can be attributed to gully processes (Fig. 13 to 24). While the LiDAR and UAV photogrammetry have reasonable accuracy and precision (Tables 1 to 6), the characteristics of these method of topographic modelling affect the minimal unit of geomorphological change that can be derived. This can be problematic if we investigate processes with very low process rates or with very dense time frequency, for which the error rate is similar with the process rate, like for examples soil erosion (Hänsel et al., 2016).

The geomorphological mapping is a good opportunity to have a check on the field situation in order not misinterpret the results of the DoD (Kaiser, Erhardt and Eltner, 2018): for example, in the case of bank landslides, deposition can occur on steep banks, so mapping these landslides and allowing the negative value of raw DoD to pass through the uncertainty filtering is an approach that will highlight important processes, that otherwise might be filtered out.

## 6. Conclusions

The new methods of elevation acquisition like GPS, LiDAR and SfM are easy to use techniques for landform quantification, and their usage opened the possibility to perform analyzes of the rate of processes, both in a qualitative and quantitative way. We present such a case, where two different elevation acquisition methods are used to evaluate the rate of process for four reservoir bottom gully systems between two temporal frames.

The big temporal window (2012 to 2019) is overcome by the fact that these gullies evolves slowly mainly during late winter, early spring, or even during summer, during snowmelt or high rainfall events. The DoD approach is able to find and remove errors related to the deformations of the UAV SfM DEM and to the presence of dry vegetation on the LiDAR DEM, and to reveal the changes due to geomorphological processes.

The main gully geomorphological processes were identified and a raw sediment budget was established, although for detailed sediment budgets denser temporal surveys are needed in order to establish the seasonal evolution. Headwall and headbank erosion is the process through which these gullies extend. The main branches evolve through channel deepening and widening with important volume of sediments eroded from the banks and deposited along the channels and the bottoms. Landsliding is an important phenomenon affecting banks, especially in the head areas, which can be mapped and quantified using DoD approach.

The availability of the LiDAR data for extended areas is a positive factor, since the methods can be used to assess the state of the gully systems in the near past by UAV surveying and SfM DEMs. For further studies, UAV SfM is a promising tool that can be used to monitor the evolution of the gully systems in the near future. Detailed surveys (at least 2 flights per year) are planned for studying the model of evolution of these gullies from NE Romania.

## Acknowledgements

This work was supported by a grant of Ministry of Research and Innovation, CNCS – UEFISCDI, project number PN-III-P1-1.1-PD-2016-0154, within PNCDI III. We are grateful to Prut-Bârlad Water Administration who provided us with the LIDAR data. We have used the computational facilities given by the infrastructure provided through the POSCCE-O 2.2.1, SMIS-CSNR 13984-901, No. 257/28.09.2010 Project, CERNESIM (L4). Silviu Doru, Valeriu Stoilov-Linu and Georgiana Văculișteanu help with the field work is highly appreciated.

## References

- Adams, J.C., Chandler, J.H. 2002. Evaluation of lidar and medium scale photogrammetry for detecting soft-cliff coastal change. *Photogrammetric Record* 17, 99, 405–418. doi:10.1111/0031-868x.00195
- Aschenwald, J., Leichter, K., Tasserand, E., Tappeiner, U., 2001, Spatio-temporal landscape analysis in mountainous terrain by means of small format photography: A methodological approach: *IEEE Trans. Geosci. Remote Sensing* 39, 4, 885–893. doi:10.1109/36.917917
- ASPRS, 2004. Guidelines Vertical Accuracy Reporting for Lidar Data. V. 1.0, [https://www.asprs.org/a/society/committees/standards/Vertical\\_Accuracy\\_Reporting\\_for\\_Lidar\\_Data.pdf](https://www.asprs.org/a/society/committees/standards/Vertical_Accuracy_Reporting_for_Lidar_Data.pdf)
- ASPRS, 2005. LIDAR Guidelines: Horizontal accuracy reporting. V. 0.9. [https://www.asprs.org/a/society/committees/standards/Horizontal\\_Accuracy\\_Reporting\\_for\\_Lidar\\_Data.pdf](https://www.asprs.org/a/society/committees/standards/Horizontal_Accuracy_Reporting_for_Lidar_Data.pdf)
- ASPRS, 2018. ASPRS Guidelines on Geometric Inter-Swath Accuracy and Quality of Lidar Data. *Photogrammetric Engineering & Remote Sensing* 84, 3, 117-128. doi:10.14358/PERS.84.3.117
- Baltsavias, E.P., 1999. A comparison between photogrammetry and laser scanning. *ISPRS Journal of Photogrammetry & Remote Sensing* 54, 83–94. doi: 10.1016/S0924-2716(99)00014-3
- Baltsavias, E.P., Favey, E., Bauder, A., Bösch, H., Pateraki, M., 2001. Digital surface modelling by airborne laser scanning and digital photogrammetry for glacier monitoring. *The Photogrammetric Record* 17, 243–273. doi:10.1111/0031-868X.00182
- Bangen, S., Hensleigh, J., McHugh, P., Wheaton, J.M., 2016. Error modeling of DEMs from topographic surveys of rivers using Fuzzy Inference Systems. *Water Resources Research*. 52, 1176–1193. doi:10.1002/2015WR018299

- Barker, R., Dixon, L., Hooke, J., 1997. Use of terrestrial photogrammetry for monitoring and measuring bank erosion. *Earth Surf. Process. Landforms* 22, 13, 1217–1227. doi:10.1002/(SICI)1096-9837(199724)22:13<1217::AID-ESP819>3.0.CO;2-U
- Bergonse, R.V., Reis, E.J., 2016. Theoretical constraints to gully erosion research: time for a re-evaluation of concepts and assumptions? *Earth Surf. Process. Landforms* 36, 11, 1554–1557. doi:10.1002/esp.2188
- Bettis III, E.A., Thompson, D.M., 1985. Gully erosion. *Rangelands* 7, 2, 70-72.
- Betts, H.D., DeRose, R.C., 1999. Digital elevation models as a tool for monitoring and measuring gully erosion. *Journal of Applied Earth Observation and Geoinformation* 1, 91–101. doi:10.1016/S0303-2434(99)85002-8
- Bird, S., Hogan, D., Schwab, J., 2010. Photogrammetric monitoring of small streams under a riparian forest canopy. *Earth Surf. Process. Landforms* 35, 8, 952–970. doi:10.1002/esp.2001
- Bocco, G., 1991. Gully erosion: processes and models. *Progress in Physical Geography: Earth and Environment* 15, 4, 392-406. doi:10.1177/030913339101500403
- Bocoo, G., Valenzuela, C.R., 1993. Integrating satellite-remote sensing and geographic information systems technologies in gully erosion research, *Remote Sensing Reviews*, 7, 3-4, 233-240. doi:10.1080/02757259309532179
- Bowen, Z.H., Waltermire, R.G., 2002. Evaluation of light detection and ranging (lidar) for measuring river corridor topography. *Journal of the American Water Resources Association* 38, 1, 33–41. doi:10.1111/j.1752-1688.2002.tb01532.x
- Brasington, J., Smart, R.M.A., 2003. Close range digital photogrammetric analysis of experimental drainage basin evolution. *Earth Surf. Process. Landforms* 28, 3, 231–247. doi:10.1002/esp.480

- Brown, A.G., Tooth, S., Bullard, J.E., Thomas, D.S.G., Chiverrell, R.C., Plater, A.J., Murton, J., Thorndycraft, V.R., Tarolli, P., Rose, J., Wainwright, J., Downs, P., Aalto, R., 2017. The Geomorphology of The Anthropocene: Emergence, Status and Implications. *Earth Surf. Process. Landforms* 42, 71–90. doi:10.1002/esp.3943
- Carbonneau, P.E.; Dietrich, J.T., 2017. Cost-Effective Non-Metric Photogrammetry from Consumer-Grade sUAS: Implications for Direct Georeferencing of Structure from Motion Photogrammetry. *Earth Surf. Process. Landforms* 43, 3, 473-486. doi:10.1002/esp.4012
- Carrivick, J., Quincey, D., Smith, M., 2016. Structure from motion in the geosciences. *New analytical methods in earth and environmental science*. Wiley Blackwell, 197.
- Castillo, C., James, M. R., Redel-Macías, M. D., Pérez, R., Gómez, J. A., 2015. SF3M software: 3-D photo-reconstruction for nonexpert users and its application to a gully network. *Soil* 1, 583–594. doi:10.5194/soil-1-583-2015
- Castillo, C., Marín-Moreno, V.J., Pérez, R., Muñoz-Salinas, R., Taguas, E.V., 2018. Accurate automated assessment of gully cross-section geometry using the photogrammetric interface FreeXSapp. *Earth Surf. Process. Landforms* 43, 8, 1726–1736. doi:10.1002/esp.4341
- Cavalli, M., Tarolli, P., 2011. Application of lidar technology for rivers analysis. *Italian Journal of Engineering Geology and Environment Special Issue* 1, 33–44. doi:10.4408/IJEGE.2011-01.S-03
- Cavalli, M., Tarolli, P., Marchi, L., Dalla Fontana, G., 2008. The effectiveness of airborne LiDAR data in the recognition of channel-bed morphology. *Catena* 73, 3, 249–260. doi:10.1016/j.catena.2007.11.001
- Chandler, J.H., 1999. Effective application of automated digital photogrammetry for geomorphological research. *Earth Surf. Process. Landforms* 24, 1, 51–63. doi:10.1002/(SICI)1096-9837(199901)24:13.0.CO;2-H

- Chandler, J., Ashmore, P., Paola, C., Gooch, M., Varkaris, F., 2003. Monitoring river channel change using terrestrial oblique digital imagery and automated digital photogrammetry. *Annals of the Association of American Geographers* 92, 4, 631–644. doi:10.1111/1467-8306.00308
- Chandler, J.H., Fryer, J.G., Jack, A., 2005. Metric capabilities of low cost digital cameras for close range surface measurement. *The Photogrammetric Record* 20, 109, 12–26. doi:10.1111/j.1477-9730.2005.00302.x
- Chen, J., Li, K., Chang, K.-J., Sofia, G., Tarolli, P., 2015. Open-pit mining geomorphic feature characterization, *International Journal of Applied Earth Observation and Geoinformation*, 42, 76-86. doi:10.1016/j.jag.2015.05.001
- Clarke, T.A., Fryer, J.G., 1998. The development of camera calibration methods and models. *The Photogrammetric Record* 16, 91, 51–66. doi:10.1111/0031-868X.00113
- Colomina, I., Molina, P., 2014. Unmanned aerial systems for photogrammetry and remote sensing: A review. *ISPRS Journal of Photogrammetry and Remote Sensing* 92, 79–97. doi:10.1016/j.isprsjprs.2014.02.013
- Conrad, O., Bechtel, B., Bock, M., Dietrich, H., Fischer, E., Gerlitz, L., Wehberg, J., Wichmann, V., Böhner, J., 2015. System for Automated Geoscientific Analyses (SAGA) v. 2.1.4. *Geosci. Model Dev.* 8, 1991-2007. doi:10.5194/gmd-8-1991-2015
- Cucchiaro, S., Cavalli, M., Vericat, D., Crema, S., Llana, M., Beinat, A., Marchi, L., Cazorzi, F., 2018. Monitoring topographic changes through 4D-structure-from-motion photogrammetry: application to a debris-flow channel, *Environmental Earth Sciences*, 77, 632. doi:10.1007/s12665-018-7817-4
- Derron, M.-H., Jaboyedoff, M., 2010. Preface "LIDAR and DEM techniques for landslides monitoring and characterization". *Nat. Hazards Earth Syst. Sci.* 10, 1877–1879, doi:10.5194/nhess-10-1877-2010



- Dewitte, O., Jasselette, J.-C., Cornet, Y., Van Den Eeckhaut, M., Collignon, A., Poesen, J., Demoulin, A., 2008. Tracking landslide displacements by multi-temporal DTMs: A combined aerial stereophotogrammetric and LIDAR approach in western Belgium. *Engineering Geology* 99, 1-2, 11-22. doi:10.1016/j.enggeo.2008.02.006
- Di Stefano, C., Ferro, V., Palmeri, V., and Pampalone, V., 2017. Testing the use of an image-based technique to measure gully erosion at Sparacia experimental area, *Hydrol. Process* 31, 3, 573–585. doi:10.1002/hyp.11048
- Di Stefano, C., Palmeri, V., Pampalone, V., 2019. An automatic approach for rill network extraction to measure rill erosion by terrestrial and low-cost UAV photogrammetry. *Hydrol. Process.* 33, 13, 1883-1895. doi:10.1002/hyp.13444
- Dietrich, J.T., 2016. Bathymetric Structure-from-Motion: extracting shallow stream bathymetry from multi-view stereophotogrammetry. *Earth Surf. Process. Landforms* 42, 2, 355–364. doi:10.1002/esp.4060
- Eltner, A., Mulsow, C., Maas, H-G., 2013. Quantitative measurement of soil erosion from TLS and UAV data. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XL-1/W2*: 119–124. doi:10.5194/isprsarchives-XL-1-W2-119-2013
- Eltner, A., Baumgart, P., Maas, H-G., Faust, D., 2014. Multi-temporal UAV data for automatic measurement of rill and interrill erosion on loess soil. *Earth Surf. Process. Landforms* 40, 741–755. doi:10.1002/esp.3673
- Eltner, A., Baumgart, P., 2015. Accuracy constraints of terrestrial Lidar data for soil erosion measurement: Application to a Mediterranean field plot. *Geomorphology*, 245, 243-254. doi:10.1016/j.geomorph.2015.06.008

- Eltner, A.; Baumgart, P.; Maas, H.-G.; Faust, D., 2015. Multi-temporal UAV data for automatic measurement of rill and interrill erosion on loess soil, *Earth Surface Processes and Landforms*, 40, 6, 741-755. doi:10.1002/esp.3673
- Eltner, A., Kaiser, A., Castillo, C., Rock, G., Neugirg, F., Abellán, A, 2016. Image-based surface reconstruction in geomorphometry – merits, limits and developments, *Earth Surf. Dynam* 4, 359–389. doi:10.5194/esurf-4-359-2016
- Eltner, A., Kaiser, A., Abellan, A., Schindewolf, M., 2017. Time lapse structure-from-motion photogrammetry for continuous geomorphic monitoring. *Earth Surf. Process. Landforms* 42, 14, 2240–2253. doi:10.1002/esp.4178
- Ely, J.C., Graham, C.; Barr, I.D., Rea, B.R., Spagnolo, M., Evans, J., 2016. Using UAV acquired photography and structure from motion techniques for studying glacier landforms: application to the glacial flutes at Isfallsglaciären. *Earth Surf. Process. Landforms* 42, 6, 877–888. doi:10.1002/esp.4044
- Evans J. S., Hudak, A.T., 2007. A Multiscale Curvature Algorithm for Classifying Discrete Return LiDAR in Forested Environments. *IEEE Transactions on Geoscience and Remote Sensing* 45, 4, 1029–1038. doi: 10.1109/TGRS.2006.890412
- Evans, M., Lindsay, J.B., 2010. High resolution quantification of gully erosion in upland peatlands at the landscape scale. *Earth Surf. Process. Landforms* 35, 8, 876-886., doi:10.1002/esp.1918
- Falkner, E., Morgan, D., 2002. *Aerial mapping. Methods and applications*, Ild edition, CRC Press, Boca Raton.
- Farres, P., Poesen, J., Wood, S., 1993. Soil erosion landscapes. *Geography Review* 6, 38–41.

- Fischler, M.A., Bolles, R.C., 1981. Random sample consensus: a paradigm for model fitting with applications to image analysis and automated cartography. *Communications of the ACM CACM* 24, 6, 381-395. doi: 10.1145/358669.358692
- Fonstad, M.A., Dietrich, J.T., Courville, B.C., Jensen, J.L., Carbonneau, P.E., 2013. Topographic structure from motion: A new development in photogrammetric measurement. *Earth Surf. Process. Landforms*. 38, 4, 421–430. doi:10.1002/esp.3366
- Frankl, A., Stal, C., Abraha, A., Nyssen, J., Rieke-Zapp, D., De Wulf, A., Poesen, J., 2015. Detailed recording of gully morphology in 3D through image-based modelling. *Catena* 127, 92-101. doi: 10.1016/j.catena.2014.12.016
- Fryer, J.G., Brown, D.C., 1986. Lens distortion for close-range photogrammetry. *Photogram. Eng. Remote Sens.* 52, 51–58.
- Fraser, C.S., Cronk, S., 2009. A hybrid measurement approach for close-range photogrammetry. *ISPRS Journal of Photogrammetry and Remote Sensing* 64, 3, May 2009, 328-333. doi: 10.1016/j.isprsjprs.2008.09.009
- Furukawa, Y., Ponce, J., 2007. Accurate, Dense, and Robust Multi-View Stereopsis. *IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR 2007)* 1, 1–8. doi:10.1109/CVPR.2007.383246
- Furukawa, Y., Ponce, J., 2010. Accurate, Dense, and Robust Multi-View Stereopsis. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 32, 8, 1362–1376. doi:10.1109/TPAMI.2009.161
- Furukawa, Y., Curless, B., Seitz, S.M., Szeliski, R., 2010. Towards Internet-scale Multi-view Stereo. In: 2010 IEEE Computer Society Conference on Computer Vision and Pattern Recognition 1–8, 13-18 June 2010, San Francisco, CA, USA. doi:10.1109/CVPR.2010.5539802

- Garibaldi, J., Chen, C., Razak, T., 2017. FuzzyR: Fuzzy Logic Toolkit for R. R package version 2.1. <https://CRAN.R-project.org/package=FuzzyR>
- Gesch, K.R., R.R. Wells, R.M. Cruise, H.G. Momm, Dabney, S.M., 2015. Quantifying uncertainty of measuring gully morphological evolution with close-range digital photogrammetry. *Soil Science Society of America Journal* 79, 2, 650–659. doi:10.2136/sssaj2014.10.0396.
- Geyik, M.P., 1986. FAO watershed management field manual. Gully Control. FAO Conservation guide 13/2 Rome.
- Giménez, R., Marzloff, I., Campo, M.A., Seeger, M., Ries, J.B., Casalf, J., Álvarez-Mozos, J., 2009. Accuracy of high-resolution photogrammetric measurements of gullies with contrasting morphology, *Earth Surf. Process. Landforms*, 34, 14, 1915-1926. doi: 10.1002/esp.1868
- Giordan, D., Nex, F.C., Hayakawa, Y., Remondino, F., Tarolli, P. 2018. The use of remotely piloted aircraft systems (RPASs) for natural hazards monitoring and management. *Nat. Hazards Earth Syst. Sci.* 18, 1079–1096. doi:10.5194/nhess-18-1079-2018
- Glendell, M., McShane, G., Farrow, L., James, M.R., Quinton, J., Anderson, K., Evans, M., Benaud, P., Rawlins, B., Morgan, D., Jones, L., Kirkham, M., DeBell, L., Quine, T.A., Lark, M., Rickson, J., Brazier, R.E. 2017. Testing the utility of structure-from-motion photogrammetry reconstructions using small unmanned aerial vehicles and ground photography to estimate the extent of upland soil erosion. *Earth Surf. Process. Landforms* 42, 12, 1860–1871. doi:10.1002/esp.4142
- Gómez-Gutiérrez, A., Schnabel, S. Berenguer-Sempere, F., Lavado- Contador, F., Rubio-Delgado, J., 2014. Using 3D photo-reconstruction methods to estimate gully headcut erosion. *Catena* 120, 91–101, 2014. doi:10.1016/j.catena.2014.04.004

- Gong, C., Lei, S., Bian, Z., Liu, Y., Zhang, Z., Cheng, W., 2019. Analysis of the Development of an Erosion Gully in an Open-Pit Coal Mine Dump During a Winter Freeze-Thaw Cycle by Using Low-Cost UAVs, *Remote Sensing*, 1, 11, 1356. doi:10.3390/rs11111356
- Guzzetti, F., Mondini, A.C., Cardinali, M., Fiorucci, F., Santangelo, M., Chang, K.-T., 2012. Landslide inventory map: new tools for an old problem. *Earth-Science Reviews* 112, 42–66, doi:10.1016/j.earscirev.2012.02.001
- Hänsel, P., Schindewolf, M., Eltner, A., Kaiser, A., Schmidt, J., 2016, Feasibility of High-Resolution Soil Erosion Measurements by Means of Rainfall Simulations and SfM Photogrammetry. *Hydrology*, 3(38), 16. doi:10.3390/hydrology3040038
- Haas, F., Heckmann, T., Hilger, L., Becht, M. 2012. Quantification and modelling of debris flows in the proglacial area of the Gepatschferner, Austria, using ground-based LiDAR. In *Erosion and Sediment Yields in the Changing Environment*, Proceedings of a symposium held at the Institute of Mountain Hazards and Environment, CAS-Chengdu, China, 11–15 October 2012, IAHS Publ. 356, 293–302.
- Hamshaw, S.D., Bryce, T., Rizzo, D.M., O'Neil-Dunne, J., Frolik, J., Dewoolkar, M.M., 2017. Quantifying streambank movement and topography using unmanned aircraft system photogrammetry with comparison to terrestrial laser scanning. *River Research and Applications* 33, 8, 1354–1367. doi:10.1002/rra.3183
- Hancock, G.R., Willgoose, G.R., 2001. The production of digital elevation models for experimental model landscapes. *Earth Surf. Process. Landforms* 26, 5, 475–490. doi:10.1002/esp.187
- Haneberg, W.C., 2008. Using close range terrestrial digital photogrammetry for 3-D rock slope modeling and discontinuity mapping in the United States. *Bulletin of Engineering Geology and the Environment* 67, 4, 457–469. doi:10.1007/s10064-008-0157-y

- Harpold, A. A., Marshall, J. A., Lyon, S. W., Barnhart, T. B., Fisher, B. A., Donovan, M., Brubaker, K. M., Crosby, C. J., Glenn, N. F., Glennie, C. L., Kirchner, P. B., Lam, N., Mankoff, K. D., McCreight, J. L., Molotch, N. P., Musselman, K. N., Pelletier, J., Russo, T., Sangireddy, H., Sjöberg, Y., Swetnam, T., and West, N., 2015. Laser vision: lidar as a transformative tool to advance critical zone science. *Hydrol. Earth Syst. Sci.* 19, 2881-2897. doi:10.5194/hess-19-2881-2015.
- Heede, B. H., 1976. Gully development and control: the status of our knowledge. USDA Forest Service Research Paper RM-169, Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Fort Collins, Colorado 80521.
- Heng, B.C.P., Chandler, J.H., Armstrong, A., 2010. Applying close-range digital photogrammetry and soil erosion studies. *The Photogrammetric Record* 25, 131, 240–265. doi:10.1111/j.1477-9730.2010.00584.x
- Hengl, T., 2006. Finding the right pixel size. *Computers & Geosciences* 32, 9, 1283–1298. doi:10.1016/j.cageo.2005.11.008
- Heritage, G.L., Fuller, I.C., Charlton, M.E., Brewer, P.A., Passmore, D.P., 1999. CDW photogrammetry of low relief fluvial features: accuracy and implications for reach-scale sediment budgeting. *Earth Surf. Process. Landforms* 23, 13, 1219–1233. doi:10.1002/(SICI)1096-9837(199812)23:13<1219::AID-ESP927>3.0.CO;2-R
- Heritage, G.L., Milan, D.J., Large, A.R.G., Fuller, I.C., 2009. Influence of survey strategy and interpolation model on DEM quality. *Geomorphology* 112, 334–344. doi:10.1016/j.geomorph.2009.06.024
- Heimsath, A.M., Farid, H., 2002. Hillslope topography from unconstrained photographs. *Mathematical Geology*, 34, 8, 929–952. doi:10.1023/A:1021364623017

- Hickman, G. D., & Hogg, J. E., 1969. Application of an airborne pulsed laser for near shore bathymetric measurements. *Remote Sensing of Environment* 1, 1, 47–58. doi:10.1016/s0034-4257(69)90088-1
- Hijmans, R.J., 2017. raster: Geographic Data Analysis and Modeling. R package version 2.6-7. <https://CRAN.R-project.org/package=raster>
- Hodgson, M.E., Bresnahan, P., 2004. Accuracy of Airborne Lidar- Derived Elevation: Empirical Assessment and Error Budget, *Photogram. Eng. Remote Sens.*, 70, 331–339. doi:10.14358/PERS.70.3.331
- Imeson, A.C., Kwaad, F.J.P.M., 1980. Gully types and gully prediction. *Geografisch Tijdschrift* 14, 5, 430-441.
- Inkpen, R. 2018. New technologies and the political economy of geomorphology. *The Canadian Geographer/Le Géographe canadien*, 1–12, doi:10.1111/cag.12455
- Ireland, H.A., Sharpe, C.F.S., Eargle, D.H., 1939. Principles of gully erosion in the Piedmont of South Carolina. Technical Bulletin No. 633, U.S. Department of Agriculture, Washington, D.C., 1-143.
- Irish, J.L., White, T.E., 1998. Coastal engineering applications of high-resolution lidar bathymetry. *Coastal Engineering* 35, 1-2, 47–71. doi:10.1016/s0378-3839(98)00022-2
- Jaboyedoff, M., Oppikofer, T., Abellán, A., Derron, M.-H., Loye, A., Metzger, R., Pedrazzini, A., 2012. Use of lidar in landslide investigations: a review. *Natural Hazards* 61, 5–28, doi:10.1007/s11069-010-9634-2
- James, A., Watson, D.G., Hansen W.F. 2007. Using LIDAR Data to Map Gullies and Headwater Streams under Forest Canopy: South Carolina, USA, *Catena*, 71, 1, 132–144, doi:10.1016/j.catena.2006.10.010

- James, M.R., Robson, S., 2012. Straightforward reconstruction of 3-D surfaces and topography with a camera: Accuracy and geoscience application, *J. Geophys. Res.* 117, F03017. doi:10.1029/2011JF002289
- James, M.R., Robson, S., 2014. Mitigating systematic error in topographic models derived from UAV and ground-based image networks *Earth Surf. Process. Landforms* 39, 10, 1413–1420. doi:10.1002/esp.3609
- James, M.R., Robson, S., Smith, M.W., 2017. 3-D uncertainty-based topographic change detection with structure-from-motion photogrammetry: precision maps for ground control and directly georeferenced surveys. *Earth Surf. Process. Landforms* 42, 12, 1769–1788. doi:10.1002/esp.4125
- James, M.R., Chandler, J.H., Eltner, A., Fraser, C., Miller, P.E., Mills, J.P., Noble, T., Robson, S., Lane, S.N., 2019. Guidelines on the use of structure-from-motion photogrammetry in geomorphic research. *Earth Surf. Process. Landforms*. doi:10.1002/esp.4637
- Javernick, L., Brasington, J., Caruso, B., 2014. Modeling the topography of shallow braided rivers using Structure-from-Motion photogrammetry. *Geomorphology* 213, 166–182. doi:10.1016/j.geomorph.2014.01.006
- Kaiser, A., Neugirg, F., Rock, G., Müller, C., Haas, F., Ries, J.B., Schmidt, J., 2014. Small-Scale Surface Reconstruction and Volume Calculation of Soil Erosion in Complex Moroccan Gully Morphology Using Structure from Motion. *Remote Sensing* 6, 7050–7080. doi:10.3390/rs6087050
- Kaiser, A., Erhardt, A., Eltner, A., 2018. Addressing uncertainties in interpreting soil surface changes by multi-temporal high resolution topography data across scales. *Land Degradation & Development*, 29(8), 2264-2277. doi:10.1002/ldr.2967



- Keutterling, A., Thomas, A., 2006. Monitoring glacier elevation and volume changes with digital photogrammetry and GIS at Gepatschferner glacier, Austria. *International Journal of Remote Sensing* 27, 4371–4380. doi:10.1080/01431160600851819
- Koci, J., Jarihani, B., Leon, J.X., Sidle, R.C., Wilkinson, S.N., Bartley, R., 2017. Assessment of UAV and Ground-Based Structurefrom Motion with Multi-View Stereo Photogrammetry in a Gullied Savanna Catchment, *International Journal of Geo-Information*, 6, 328, 23. doi:10.3390/ijgi6110328
- Krosley, L.K., Shaffner, P.T., Oerter, E., Ortiz, T., 2006. Digital ground-based photogrammetry for measuring discontinuity orientations in steep rock exposures. *Proceedings of the 41st U.S. Symposium of Rock Mechanics (USRMS)*, 17-21 June, Golden, Colorado, 1–13.
- Lane, S.N., 2000. The measurement of river channel morphology using digital photogrammetry. *The Photogrammetric Record* 16, 96, 937–961. doi:10.1111/0031-868X.00159
- Lane, S.N., James, T.D., Crowell, M.D., 2000. Application of digital photogrammetry to complex topography for geomorphological research. *The Photogrammetric Record* 16, 95, 793–821. doi:10.1111/0031-868X.00152
- Lane, S.N., Chandler, J.H., Porfiri, K., 2001. Monitoring river channel and flume surfaces with digital photogrammetry. *Journal of Hydraulic Engineering* 127, 10, 871–877. doi:10.1061/(ASCE)0733-9429(2001)127:10(871)
- Lannoeye, W., Stal, C., Guyassa, E., Zenebe, A., Nyssen, J., Frankl, A., 2016. The use of SfM-photogrammetry to quantify and understand gully degradation at the temporal scale of rainfall events: an example from the Ethiopian drylands, *Physical Geography*, 37, 6, 430-451. doi:10.1080/02723646.2016.1234197

- Lee, S.J., Wolberg, G., Shin, S., 1997. Scattered data interpolation with multilevel B-splines. *IEEE Transactions on Visualization and Computer Graphics* 3, 3, 228–244. doi: 10.1109/2945.620490
- Leopold, L.B., Miller, J.P., 1956. Ephemeral streams. Hydraulic factors and their relation to the drainage net. US Geological Survey PP 282-A.
- Li, J., Li, E., Chen, Y., Xu, L., Zhang, Y., 2010. Bundled depth-map merging for Multi-View Stereo. In: 2010 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR), June 13–18, 2010, pp. 2769–2776. San Francisco, CA. doi:10.1109/CVPR.2010.5540004
- Lin, C.W., Tseng, C.-M., Tseng, Y.-H., Fei, L.-Y., Hsieh, Y.-C., Tarolli, P., 2013. Recognition of large scale deep-seated landslides in forest areas of Taiwan using high resolution topography, *Journal of Asian Earth Sciences*, 62, 389-400. doi:10.1016/j.jseaes.2012.10.022
- Linder, W., 2016. *Digital Photogrammetry. A Practical Course*. Springer Berlin Heidelberg. doi:10.1007/978-3-662-50463-5
- Liu, X., 2008. Airborne LiDAR for DEM generation: some critical issues. *Progress in Physical Geography* 32, 1, 31–49. doi:10.1177/0309133308089496
- Liu, K., Ding, H., Tang, G., Na, J., Huang, X., Xue, Z., Yang, X., Li, F., 2016. Detection of Catchment-Scale Gully-Affected Areas Using Unmanned Aerial Vehicle (UAV) on the Chinese Loess Plateau, *ISPRS Int. J. Geo-Inf.* 5, 238, 21. doi:10.3390/ijgi5120238
- Liu, C., Shao, X., Wu, H., Li, N., Qu, T., Dotta, G., & Huang, Y., 2018. Giant landslide displacement analysis using a point cloud set conflict technique: a case in Xishancun landslide, Sichuan, China. *International Journal of Remote Sensing*, 1–20. doi:10.1080/01431161.2018.1541331

- Lloyd, C.D., and P.M. Atkinson, 2002. Deriving DSMs from lidar data with kriging. *International Journal of Remote Sensing* 23, 12, 2519–2524. doi:10.1080/01431160110097998
- Lohr, U., 1998. Digital elevation models by laser scanning, *Photogrammetric Record* 16, 91, 105–109. doi:10.1111/0031-868X.00117
- Longuet-Higgins, H.C. (1981) A computer algorithm for reconstructing a scene from two projections. *Nature* 293, 133–135. doi:10.1038/293133a0
- Lowe, D.G., 1999. Object recognition from local scale-invariant features. In: *Proceedings of the Seventh IEEE International Conference on Computer Vision*, September 20–27, 1999, pp. 1150–1157, Corfu, Greece. doi:10.1109/ICCV.1999.790410
- Lowe, D.G., 2001. Local feature view clustering for 3D object recognition. In: *Proceedings of the 2001 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, CVPR 2001*, 8-14 Dec. 2001, 7 pp, Kauai, Hawaii. doi: 10.1109/CVPR.2001.990541
- Lowe, D.G., 2004. Distinctive image features from scale-invariant keypoints. *International Journal of Computer Vision* 60, 91–110. doi:10.1023/B:VISI.0000029664.99615.94
- Mărgărint, M.C., Niculiță, M., 2016. Using high resolution LIDAR DEM to reconstruct historical network of lakes and wetlands in the Northern part of the Moldavian Plateau, NE Romania, *Georeview – Scientific Annals of Ștefan cel Mare University of Suceava, Geography Series*, 26, 2. doi:10.4316/GEOREVIEW.2016.0.0.336
- Mărgărint, M.C., Niculiță, M., Nemeth, A., Cristea, I., 2017. Topographic and depositional signature of old anthropic lakes in northern part of the Moldavian Plateau (NE Romania), 19th EGU General Assembly, EGU2017, 23-28 April, 2017 in Vienna, Austria., p.12206, 2017EGUGA..1912206C.
- Mărgărint, M.C., Niculiță, M., Doru, S., Necula, N., Cristea, I., 2017. Old anthropic dams, lacustrine deposits, and gullies from Șoldănești village. In: Niculiță, M., Mărgărint, M.C.

- (eds.), Proceedings of Romanian Geomorphology Symposium, vol. 1. Alexandru Ioan Cuza University of Iași Press, Iași, 137-141. doi:10.15551/prgs.2017.133.
- Marzloff, I., Poesen, J., 2009. The potential of 3D gully monitoring with GIS using high-resolution aerial photography and a digital photogrammetry system, *Geomorphology*, 111, 1-2, 48-60. doi:10.1016/j.geomorph.2008.05.047
- Marzloff, I., Ries, J.B., Poesen, J., 2011. Short-term versus medium-term monitoring for detecting gully-erosion variability in a Mediterranean environment. *Earth Surf. Process. Landforms* 36, 12, 1604–1623. doi:10.1002/esp.2172
- Matthews, N.A., 2008. Aerial and close-range photogrammetry technology: providing resource documentation, interpretation, and preservation. Technical Note 428. U.S. Department of the Interior, Bureau of Land Management, National Operations Center, Denver, Colorado, 42 pp.
- McKean, J., Roering, J., 2004. Objective landslide detection and surface morphology mapping using high-resolution airborne laser altimetry. *Geomorphology* 57, 3-4, 331–351. doi:10.1016/S0169-555X(03)00164-8
- Micusik, B., Kosecka, J., 2009. Piecewise planar city 3D modeling from street view panoramic sequences. In: 2009 IEEE Conference on Computer Vision and Pattern Recognition (CVPR 2009), June 20–25, 2009, pp. 2906–2912. Miami, FL. doi: 10.1109/CVPR.2009.5206535
- Momm, H.G., Bingner, R., Wells, R., Dabney, S., 2011. Methods for Gully Characterization in Agricultural Croplands Using Ground-Based Light Detection and Ranging. In *Sediment Transport - Flow and Morphological Processes*, Faruk Bhuiyan (ed.), 101–124, IntechOpen, doi: 10.5772/21360

- Momm, H.G., R.L. Bingner, R.R. Wells, S.M. Dabney, and L.D. Frees, 2013. Effect of Terrestrial LiDAR Point Sampling Density in Ephemeral Gully Characterization. *Open Journal of Modern Hydrology*. 3, 38–49. doi: 10.4236/ojmh.2013.31006
- Momm, H.G., Wells, R.R., Benett, S.J., 2017. Disaggregating soil erosion processes within an evolving experimental landscape. *Earth Surf. Process. Landforms* 43, 2, 543–552. doi: 10.1002/esp.4268
- Nagasaka, A., Yanai, S., Sato, H., Hasegawa, S., 2005. Soil erosion and gully growth associated with cultivation in southwestern Hokkaido, Japan, *Ecological Engineering*, 24, 503-508. doi:10.1016/j.ecoleng.2005.01.008
- Niculiță, M., 2012. Realizarea unui cadru de lucru pentru analiza geomorfometrică a reliefului reprezentat pe modelele numerice ale suprafeței terenului (A framework for geomorphometric analysis of landforms from DEMs). Unpublished PhD, Alexandru Ioan Cuza University of Iasi, Iasi, 211 pp. Available at: [http://www.geomorphologyonline.com/teza\\_doctorat\\_Mihai\\_Niculita\\_2012\\_Analiza\\_geomorfometrica\\_a\\_reliefului.pdf](http://www.geomorphologyonline.com/teza_doctorat_Mihai_Niculita_2012_Analiza_geomorfometrica_a_reliefului.pdf) (in Romanian)
- Niculiță, M., 2016. Automatic landslide length and width estimation based on the geometric processing of the bounding box and the geomorphometric analysis of DEMs. *Nat. Hazards Earth Syst. Sci.*, 16, 2021–2030. doi:10.5194/nhess-16-2021-2016
- Niculiță, M., Mărgărint, M.C., Santangelo, M. 2016. Archaeological evidence for Holocene landslide activity in the eastern Carpathian lowland. *Quat. Int.* 2016, 415, 175–189. doi:10.1016/j.quaint.2015.12.048
- Niculiță, M., Mărgărint, M.C., Tarolli, P., 2017. Historical reservoir construction: potential hotspot of anthropogenic induced sediments in lowland Northeastern Romania, 19th EGU General Assembly, EGU2017, proceedings from the conference held 23-28 April, 2017 in Vienna, Austria., p.11922, 2017EGUGA..1911922N.

- Niculiță, M., Mărgărint, M.C., Tarolli, P., (2019) Gully erosion of lowland old anthropic lakes beds (in preparation).
- Nistér, D., 2004. An efficient solution to the five-point relative pose problem. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 26, 756–777. doi: 10.1109/TPAMI.2004.17
- Notebaert, B., Verstraeten, G., Govers, G., Poesen, J., 2009. Qualitative and quantitative applications of lidar imagery in fluvial geomorphology. *Earth Surf. Process. Landforms* 34, 2, 217–231. doi:10.1002/esp.1705
- Orlandini, S., Tarolli, P., Moretti, G., Dalla Fontana, G., 2011. On the prediction of channel heads in a complex alpine terrain using gridded elevation data. *Water Resources Research* 47, 1–12, doi:10.1029/2010WR009648
- Partama, I.G.D.Y., Kanno, A., Ueda, M., Akamatsu, Y., Inui, R., Sekine, M., Yamamoto, K., Imai, T., Higuchi, T., 2018. Removal of Water-Surface Reflection Effects with a Temporal Minimum Filter for UAV-Based Shallow-Water Photogrammetry. *Earth Surf. Process. Landforms* 43, 12, 2673-2682. doi:10.1002/esp.4399
- Passalacqua, P., Tarolli, P., Foufoula-Georgiou, E., 2010. Testing space-scale methodologies for automatic geomorphic feature extraction from lidar in a complex mountainous landscape. *Water Resources Research* 46, 1, 1–17. doi:10.1029/2009WR008812
- Passalacqua, P., Belmont, P., Staley, D.M., Simley, J.D., Arrowsmith, R., Bode, C.A., Crosby, C., DeLong, S.B., Glenn, N.F., Kelly, S.A., Lague, D., Sangireddy, H., Schaffrath, K., Tarboton, D.G., Wasklewicz, T., Wheaton, J.M., 2015. Analyzing high resolution topography for advancing the understanding of mass and energy transfer through landscapes: A review. *Earth-Science Reviews* 148, 174 - 193. doi:10.1016/j.earscirev.2015.05.012

- Peppas, M.V.; Mills, J.P.; Moore, P.; Miller, P.E.; Chambers, J.E., 2018. Automated co-registration and calibration in SfM photogrammetry for landslide change detection. *Earth Surf. Process. Landforms* 44, 1, 287–303. doi:10.1002/esp.4502
- Perroy, R.L., Bookhagen, B., Asner, G.P., Chadwick, O.A., 2010. Comparison of gully erosion estimates using airborne and ground-based LiDAR on Santa Cruz Island, California. *Geomorphology* 118, 3-4, 288–300, doi:10.1016/j.geomorph.2010.01.009
- Peter, K.D., d'Oleire-Oltmanns, S., Ries, J.B., Marzloff, I., Ait Hssaine, A., 2014. Soil erosion in gully catchments affected by land-levelling measures in the Souss Basin, Morocco, analysed by rainfall simulation and UAV remote sensing data, *catena*, 113, 24-40. doi:10.1016/j.catena.2013.09.004
- Piegay, H., Kondolf, G. M., Minear, J. T., Vaudor, L. 2015. Trends in publications in fluvial geomorphology over two decades: A truly new era in the discipline owing to recent technological evolution? *Geomorphology* 248, 489–500, doi:10.1016/j.geomorph.2015.07.039
- Piermattei, L., Carturan, L., de Blasi, F., Tarolli, P., Dalla Fontana, G., Vettore, A., Pfeifer, N., 2016. Suitability of ground-based SfMMVS for monitoring glacial and periglacial processes, *Earth Surf. Dynam.* 4, 425–443. doi:10.5194/esurf-4-425-2016
- Poesen, J., Vandaele, K., Van Wesemael, B., 1996. Contribution of gully erosion to sediment production on cultivated lands and rangelands. In *Erosion and Sediment Yield: Global and Regional Perspectives, Proceedings of the Exeter Symposium, July 1996, IAHS Publ. no 236*, 251-266.
- Poesen J., Vandaele K., van Wesemael B., 1998. Gully Erosion: Importance and Model Implications. In: Boardman J., Favis-Mortlock D. (eds) *Modelling Soil Erosion by Water. NATO ASI Series (Series I: Global Environmental Change)*, vol 55. Springer, Berlin, Heidelberg. doi:10.1007/978-3-642-58913-3\_22

- Poesen, J., Vanwalleghem, T., de Vente, J., Knapen, A., Verstraeten, G., Martínez-Casasnovas, J.A., 2006. Gully erosion in Europe, in *Soil Erosion in Europe*, J. Boardman and J. Poesen (eds.), Wiley, 515-536.
- Poesen, J., Nachtergaele, J., Verstraten, G., Valentin, C., 2003. Gully erosion and environmental change: importance and research needs, *Catena*, 50, 91–133. doi:10.1016/S0341-8162(02)00143-1
- Prosdocimi, M., Calligaro, S., Sofia, G., Dalla Fontana, G., Tarolli, P., 2015. Bank erosion in agricultural drainage networks: new challenges from structure-from-motion photogrammetry for post-event analysis. *Earth Surf. Process. Landforms* 40, 14, 1891–1906. doi:10.1002/esp.3767
- Prosdocimi, M., Burguet, M., Di Prima, S., Sofia, G., Terol, E, Rodrigo Comino J., Cerdà, A., Tarolli, P., 2017. Rainfall simulation and Structure-from-Motion photogrammetry for the analysis of soil water erosion in Mediterranean vineyards. *Science of the Total Environment*, 574, 204-215. doi:10.1016/j.scitotenv.2016.09.036.
- Pyle, C.J., Richards, K.S., Chandler, J.H., 1997. Digital photogrammetric monitoring of river bank erosion. *The Photogrammetric Record* 15, 89, 753–764. doi:10.1111/0031-868X.00083
- Qin, C., Wells, R.R., Momm, H.G., Zu, X., Wilson, G.V., Zheng, F., 2019. Photogrammetric analysis tools for channel widening quantification under laboratory conditions. *Soil & Tillage Research*, 191, 306–316. doi:10.1016/j.still.2019.04.002
- R Core Team, 2013. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL <http://www.R-project.org/>.
- Remondino, F., El-Hakim S., 2006. Image-based 3D Modelling: A Review. *The Photogrammetric Record*, 21, 15, 269–291. doi:10.1111/j.1477-9730.2006.00383.x



- Rieke-Zapp, D.H., Nearing, M.A., 2005. Digital close range photogrammetry for measurement of soil erosion. *The Photogrammetric Record* 20, 109, 69–87. doi:10.1111/j.1477-9730.2005.00305.x
- Robinson SE, Bohon W, Kleber EJ, J Arrowsmith R, Crosby C.J., 2017. Applications of high-resolution topography in Earth science education. *Geosphere* 13, 6. doi:10.1130/GES01236.1
- Schumm, S.A., Hadley, R.F., 1957. Arroyos and the semi-arid cycle of erosion (Wyoming and New Mexico), *American Journal of Science*, 255, 161-174. doi:10.2475/ajs.255.3.161
- Schürch, P., Densmore, A.L., Rosser, N.J., Lim, M., McArdell, B.W., 2011. Detection of surface change in complex topography using terrestrial laser scanning: Application to the Illgraben debris-flow channel. *Earth Surf. Process. Landforms*, 36, 14, 1847–1859. doi:10.1002/esp.2206
- Shan, Q., Wu, C., Curless, B., Furukawa, Y., Hernandez, C., Seitz, S. M., 2014. Accurate Geo-Registration by Ground-to-Aerial Image Matching. In: 2014 2nd International Conference on 3D Vision, 8-11 Dec. 2014, Tokyo, Japan. doi:10.1109/3DV.2014.69
- Smith, D.E., Zuber, M.T., Neumann, G.A., Lemoine, F.G., 1997. Topography of the Moon from the Clementine lidar. *Journal of Geophysical Research* 102, E1, 1591-19611.
- Smith, D. E., Zuber, M.T., Solomon, S.C., Phillips, R.J., Head, J.W., Garvin, J.B., Banerdt, B.W., Muhleman, D.O., Pettengill, G.H., Neumann, G.A., Lemoine, F.G., Abshire, J.B., Aharonson, O., Brown, D.C., Hauck, S.A., Ivanov, A.B., McGovern, P.J., Zwally, J.H., Duxbury, T.C., 1999. The Global Topography of Mars and Implications for Surface Evolution. *Science* 284, 5419, 1495–1503. doi:10.1126/science.284.5419.1495
- Smith, M.W., Vericat, D. 2015. From experimental plots to experimental landscapes: topography, erosion and deposition in subhumid badlands from structure-from-motion

- photogrammetry, *Earth Surf. Process. Land.* 40, 12, 1656–1671, 2015. doi:10.1002/esp.3747
- Snaveley, N., Seitz, S.M., Szeliski, R., 2006. Photo Tourism: Exploring image collections in 3D. *ACM Transactions on Graphics*, 25, 3, 835–846. doi:10.1145/1141911.1141964
- Snaveley, N., Seitz, S.M., Szeliski, R., 2008. Modeling the World from Internet Photo Collections. *International Journal of Computer Vision*, 80, 2, 189–210. doi:10.1007/s11263-007-0107-3
- Sofia, G., Tarolli, P., Cazorzi, F., Dalla Fontana, G., 2011. An objective approach for feature extraction: distribution analysis and statistical descriptors for scale choice and channel network identification. *Hydrology and Earth System Sciences* 15, 1387–1402. doi:10.5194/hess-15-1387-2011
- Sofia, G., Dalla Fontana, G., Tarolli, P., 2014. High-resolution topography and anthropogenic feature extraction: testing geomorphometric parameters in floodplains, *Hydrological Processes*, 28, 2046-2061. doi:10.1002/hyp.9727.
- Sofia, G., Bailly, J., Chehata, N., Tarolli, P., Levavesseur, F., 2016. Comparison of Pleiades and LiDAR Digital Elevation Models for terraces detection in farmlands, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 9(4), 1567-1576. doi:10.1109/JSTARS.2016.2516900.
- Stöcker, C., Eltner, A., Karrasch, P., 2015. Measuring gullies by synergetic application of UAV and close range photogrammetry - A case study from Andalusia, Spain. *Catena*, 132, p. 1-11. doi:10.1016/j.catena.2015.04.004.
- Stojic, M., Chandler, J.H., Ashmore, P., Luce, J., 1998. The assessment of sediment transport rates by automated digital photogrammetry. *Photogrammetric Engineering and Remote Sensing* 64, 5, 387–395.

- Strick, R.J.P., Ashworth, P.J., Sambrook Smith, G.H., Nicholas, A.P., Best, J.L., Lane, S.N., Parsons, D.R., Simpson, C.J., Unsworth, C.A., Dale, J., 2019. Quantification of bedform dynamics and bedload sediment flux in sandy braided rivers from airborne and satellite imagery. *Earth Surf. Process. Landforms* 44, 4, 953–972. doi:10.1002/esp.4558
- Sturznegger, M., Stead, D., 2009. Close-range terrestrial digital photogrammetry and terrestrial laser scanning for discontinuity characterization on rock cuts. *Engineering Geology* 106, 3-4, 163–182. doi:10.1016/j.enggeo.2009.03.004
- Tarolli, P., 2014. High-resolution topography for understanding Earth surface processes: Opportunities and challenges, *Geomorphology*, 216, 295–312. doi:10.1016/j.geomorph.2014.03.008
- Tarolli, P., Dalla Fontana, G., 2009. Hillslope-to-valley transition morphology: new opportunities from high resolution DTMs, *Geomorphology*, 113, 47-56. doi:10.1016/j.geomorph.2009.02.006
- Tarolli, P., Sofia, G., Dalla Fontana, G., 2012. Geomorphic features extraction from high-resolution topography: landslide crowns and bank erosion, *Natural Hazards*, 61, 65-83. doi:10.1007/s11069-010-9695-2
- Tarolli, P., Calligaro, S., Cazorzi, F., Dalla Fontana, G., 2013. Recognition of surface flow processes influenced by roads and trails in mountain areas using high-resolution topography, *European Journal of Remote Sensing*, 46, 176–197. doi:10.5721/EuJRS20134610.0.1029/2017EO069637
- Tarolli, P., Sofia, G., Calligaro, S., Prosdocimi, M., Preti, F., Dalla Fontana, G., 2015. Vineyards in terraced landscapes: new opportunities from lidar data, *Land Degradation & Development*, 26, 92-102. doi:10.1002/ldr.2311

- Tarolli, P., Sofia, G., 2016. Human topographic signatures and derived geomorphic processes across landscapes, *Geomorphology*, 255, 140–161. doi:10.1016/j.geomorph.2015.12.007
- Tarolli, P., Sofia, G., Ellis, E., 2017, Mapping the topographic fingerprints of humanity across Earth. *Eos*, 98. doi:/10.1029/2017EO069637.
- Tarolli, P., Cavalli, M., Masin, R., 2019. High-resolution morphologic characterization of conservation agriculture. *Catena*, 172, 846–856, doi: 10.1016/j.catena.2018.08.026.
- Tarolli, P., Cao, W., Sofia, G., Evans, D., Ellis, EC. 2019. From features to fingerprints: a general diagnostic framework for anthropogenic geomorphology. *Progress in Physical Geography: Earth and Environment*, 43, 95–128, doi:10.1177/0309133318825284
- Trevisani, S., Cavalli, M., Marchi, L., 2010. Reading the bed morphology of a mountain stream: a geomorphometric study on high-resolution topographic data. *Hydrology and Earth System Sciences* 14, 393–405. doi:10.5194/hess-14-393-2010
- Triggs, B., McLauchlan, P.F., Hartley, R.I. & Fitzgibbon, A.W. (2000) Bundle adjustment – a modern synthesis. In: B. Triggs, A. Zisserman & R. Szeliski (eds), *Vision Algorithms '99*, LNCS 1883, pp. 298–372. Springer-Verlag, Berlin Heidelberg.
- Tuckfield, C.G., 1964. Gully erosion in the New Forest, Hampshire, *American Journal of Science*, 262, 795-807. doi: 10.2475/ajs.262.6.795
- Ullman, S. 1979. *The Interpretation of Structure from Motion*. The Royal Society. *Proceedings Biological Sciences*, 203, 1153, 405–426. doi:10.1098/rspb.1979.0006
- Viles, H., 2016. Technology and geomorphology: Are improvements in data collection techniques transforming geomorphic science? *Geomorphology* 270: 121–133. doi:10.1016/j.geomorph.2016.07.011
- Vanmaercke, M., Poesen, J., Van mele, B., Demuzere, M., Bruynseels, A., Golosov, V., Rodrigues Bezerra, J.S., Bolysov, S., Dvinskih, A., Frankl, A., Fuseina, Y, Teixeira

- Guerra, A.J., Haregeweyn, N., Ioniță, I., Makanzu Imwangana, F., Moeyersons, J., Moshe, I., Nazari Samani, A., Niacșu, L., Nyssen, J., Otsuki, O., Rădoane, M., Rysin, I., Ryzhov, Y.V., Yermolaev, O., 2016. How fast do gully headcuts retreat? *Earth-Science Reviews*, 154, 336-355. doi:10.1016/j.earscirev.2016.01.009
- Ventura, G., Vilardo, G., Terranova, C., Bellucci Sessa, E., 2011. Tracking and evolution of complex active landslides by multi-temporal airborne LiDAR data: The Montaguto landslide (Southern Italy). *Remote Sensing of Environment* 115, 12, 3237-3248. doi: 10.1016/j.rse.2011.07.007
- Vinci, A., Brigante, R., Todisco, F., Mannocchi, F., Radicioni, F., 2015. Measuring rill erosion by laser scanning. *Catena* 124, 97–108, doi:10.1016/j.catena.2014.09.003.
- Wang, R., Zhang, S., Pu, L., Yang, J., Yang, C., Chen, J., Guan, C., Wang, Q., Chen, D., Fu, B., Sang, X., 2016. Gully Erosion Mapping and Monitoring at Multiple Scales Based on Multi-Source Remote Sensing Data of the Sancha River Catchment, Northeast China. *ISPRS Int. J. Geo-Inf.*, 5, 200, 1–17. doi:10.3390/ijgi5110200
- Wells, R.R., Momm, H.G., Castillo, C., 2017. Quantifying uncertainty in high-resolution remotely sensed topographic surveys for ephemeral gully channel monitoring. *Earth Surf. Dynam* 5, 347–367. doi:10.5194/esurf-5-347-2017
- Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J., Reynolds, J. M., 2012. 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology* 179, 300–314. doi:10.1016/j.geomorph.2012.08.021
- Wheaton J.M., 2008. Uncertainty in morphological sediment budgeting of rivers. Unpublished PhD, University of Southampton, Southampton, 412 pp. Available at: <http://www.joewheaton.org/Home/research/projects-1/phdthesis>

- Wheaton, J.M., Brasington, J., Darby, S.E., Sear, D., 2010. Accounting for Uncertainty in DEMs from Repeat Topographic Surveys: Improved Sediment Budgets. *Earth Surf. Process. Landforms*. 35, 2, 136–156. doi:10.1002/esp.1886
- Wehr, A., Lohr, U., 1999. Airborne laser scanning – An introduction and overview, *ISPRS Journal of Photogrammetry and Remote Sensing* 54, 2-3, 68–82. doi: 10.1016/S0924-2716(99)00011-8
- Wu, C., Agarwal, S., Curless, B., Seitz, S.M. 2011. Multicore bundle adjustment. In *IEEE Computer Vision and Pattern Recognition (CVPR)*, Colorado Springs. <https://grail.cs.washington.edu/projects/mcba/poster-mcba.pdf>
- Wu, C., 2013. Towards linear-time incremental structure from motion. 2013 International Conference on 3D Vision (3DV 2013), Proceedings of a meeting held 29 June - 1 July 2013, Seattle, Washington, USA, 127, 1–8.
- Wu, C., 2015. P3.5P: Pose estimation with unknown focal length. In: 2015 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 7-12 June 2015, Boston, MA, USA. doi:10.1109/CVPR.2015.7298858
- Wu, H., Zu, X., Zheng, F., Qin, C., He, X., 2017. Gully morphological characteristics in the loess hilly-gully region based on 3D laser scanning technique. *Earth Surf. Process. Landforms* 43, 8, 1701–1710. doi:10.1002/esp.4332
- Xiang, J., Chen, J., Sofia, G., Tian, Y., Tarolli, P., 2018. Open-pit mine geomorphic changes analysis using multi-temporal UAV survey, *Environmental Earth Sciences*, 77, 220, doi:10.1007/s12665-018-7383-9.
- Xu, Y., Yue, D., He, P. 2017. Point Cloud Segmentation of Gully Based on Characteristic Difference using Airborne LiDAR Data, *ISPRS Archives*, XLII-2/W7. doi:10.5194/isprs-archives-XLII-2-W7-307-2017

Zheng, E., Wu, C., 2015. Structure from Motion Using Structure-less Resection. In: 2015 IEEE International Conference on Computer Vision (ICCV), 7-13 Dec. 2015, Santiago, Chile.  
doi:10.1109/ICCV.2015.240

## Figure captions

Fig. 1 Jijia Hills and the study cases: 1 – Săveni upstream, 2 – Săveni downstream, 3 - Şoldăneşti upstream, 4 - Şoldăneşti downstream.

Fig. 2 Multiscale Curvature Classification (MCC) algorithm results and the chosen values (the corresponding image is bolded)

Fig. 3 SfM workflow

Fig. 4 Post-processing workflow of point clouds

Fig. 5 MBS interpolations settings and their results

Fig. 6 The GCD workflow

Fig. 7 The fuzzy set membership computed based on descriptive statistics of data thresholds

Fig. 8. The geomorphological mapping of the gully elements shown on topographic sections (top), on 2D (middle) and 3D shading (bottom).

Fig. 9 Săveni upstream, GCP location, topographic sections location and GCD raw raster.

Fig. 10 Săveni downstream, GCP location, topographic sections location and GCD raw raster.

Fig. 11 Şoldăneşti upstream, GCP location, topographic sections location and GCD raw raster.

Fig. 12 Şoldăneşti downstream, GCP location, topographic sections location and GCD raw raster.

Fig. 13 Săveni upstream change detection results.

Fig. 14 Săveni upstream topographic and change detection sections (the red and blue lines represent the raw positive and negative change detection, while the orange and the cyan interrupted lines represent the final filtered positive and negative change detection results).



Fig. 15 Săveni upstream field photos (taken 24.03.2019 – photo number location is shown in Fig. 13)

Fig. 16 Săveni downstream change detection results.

Fig. 17 Săveni downstream topographic and change detection sections.

Fig. 18 Săveni downstream field photos (taken 24.03.2019 – photo number location is shown number in Fig. 16)

Fig. 19 Șoldănești upstream change detection results.

Fig. 20 Șoldănești upstream topographic and change detection sections.

Fig. 21 Șoldănești upstream field photos (taken 24.03.2019 – photo number location is shown number in Fig. 19)

Fig. 22 Șoldănești downstream change detection results.

Fig. 23 Șoldănești downstream topographic and change detection sections.

Fig. 24 Șoldănești downstream field photos (taken 24.03.2019 – photo number location is shown number in Fig. 22)

Fig. 25 Histograms of the raw (grey) and filtered change detection volumes (orange and blue) for the four studied gullies.

Fig. 26 The geomorphological maps of the studied gullies.

Fig. 27 The balance of change detection volumes for every studied gully by geomorphological unit.

Figures

Fig. 1

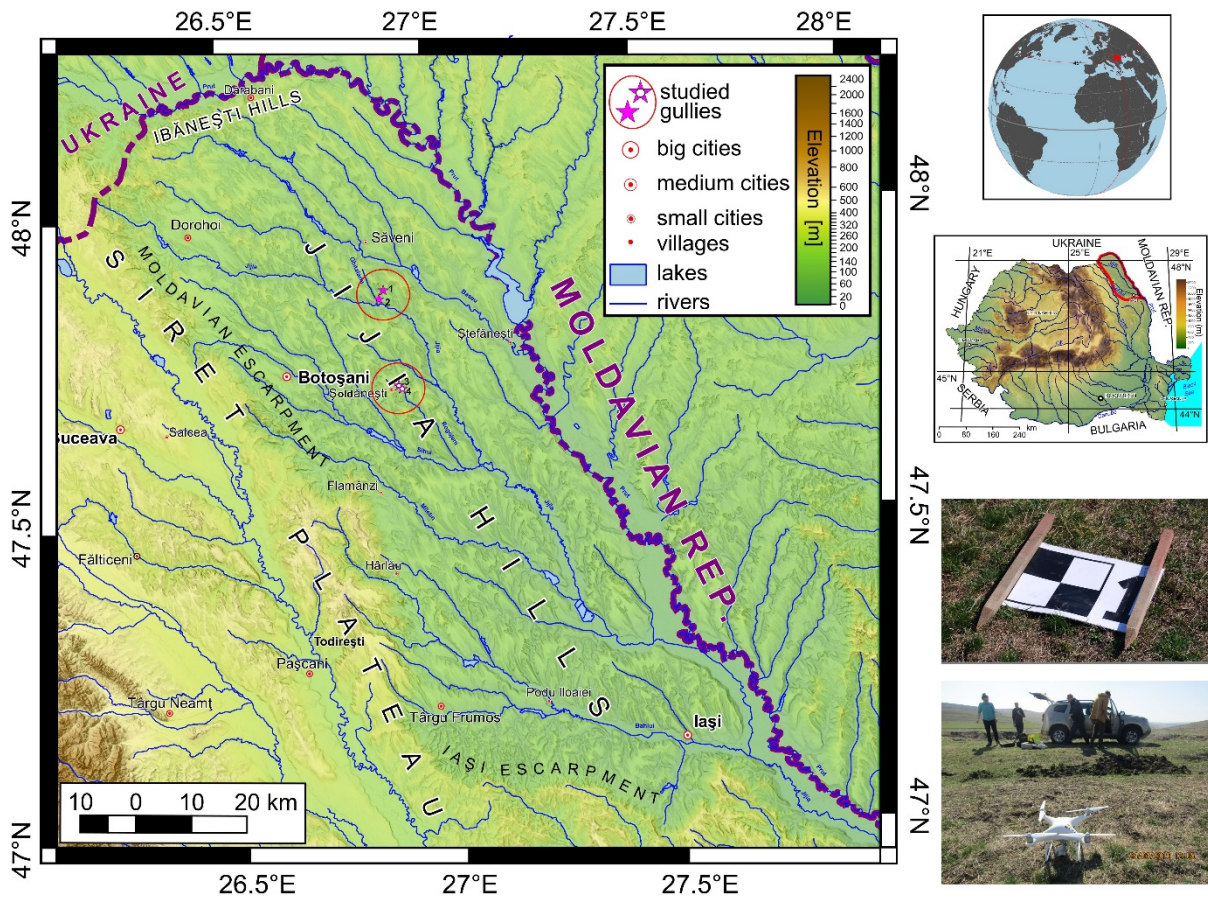


Fig. 2

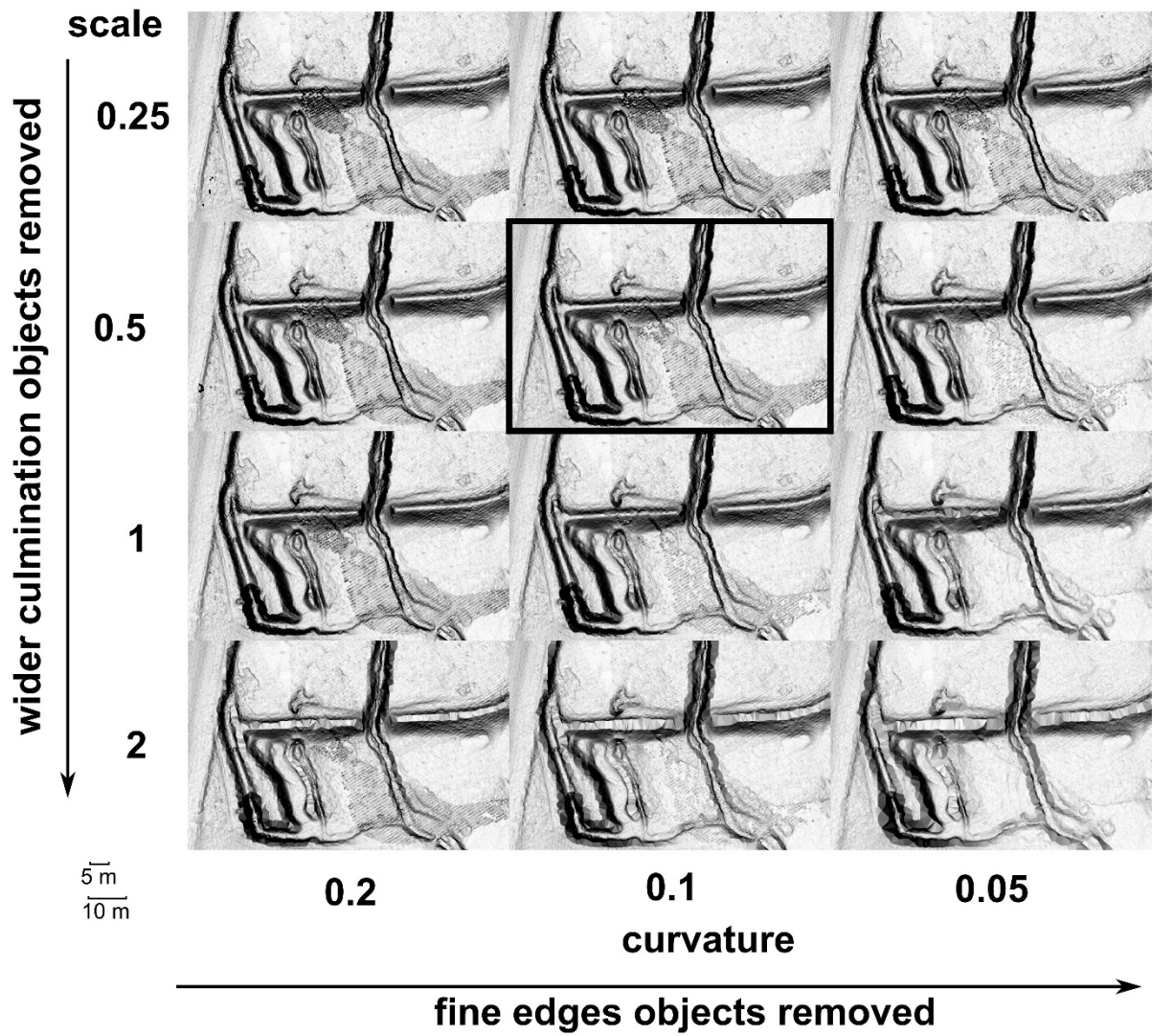


Fig. 3

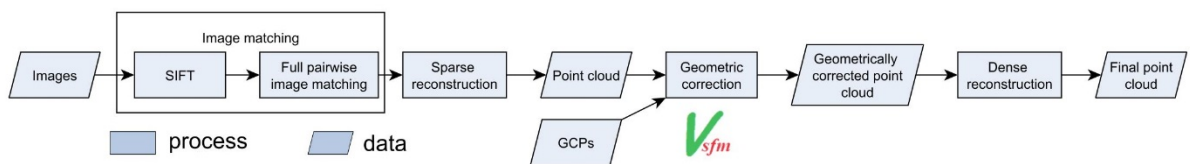


Fig. 4

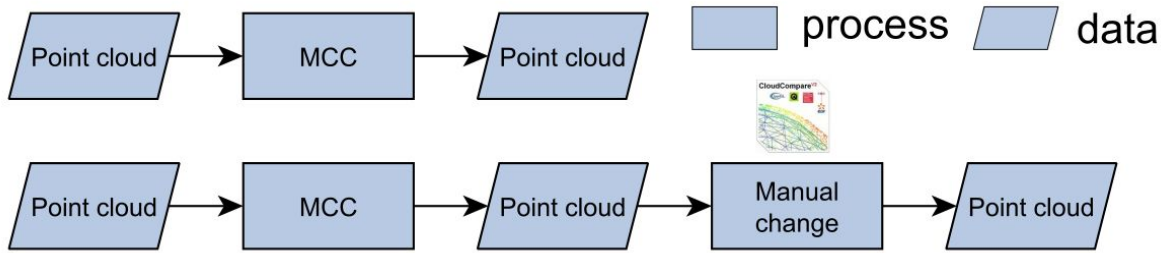


Fig. 5

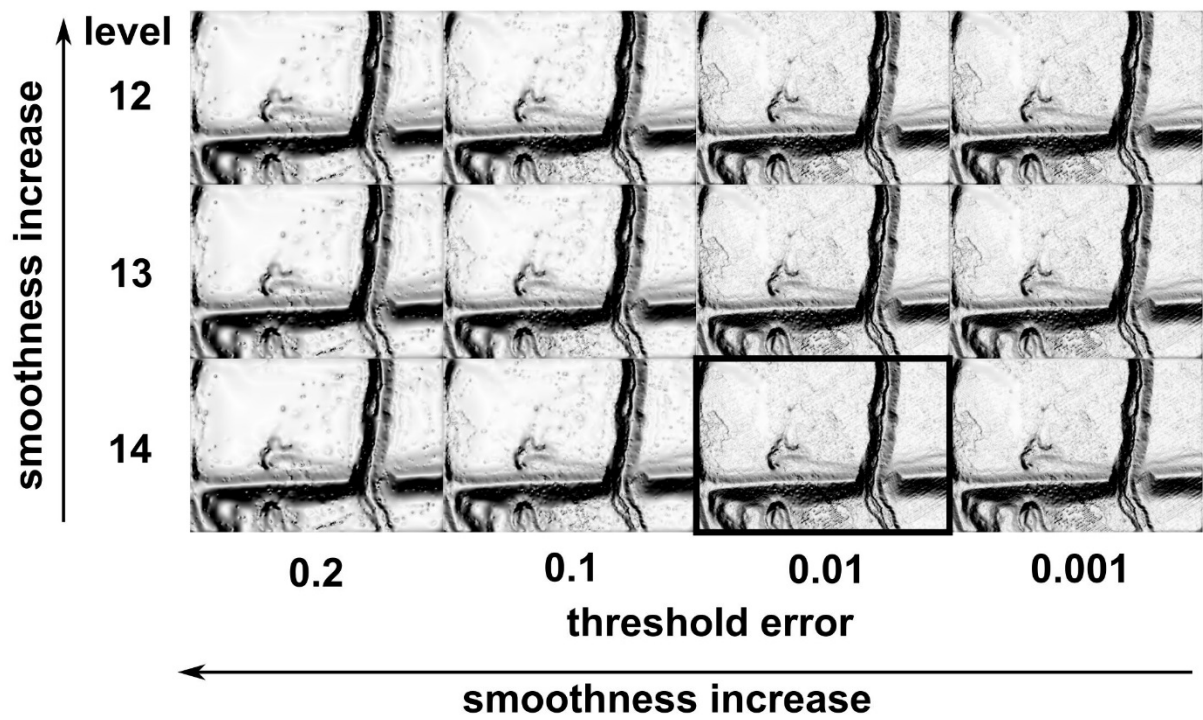


Fig. 6

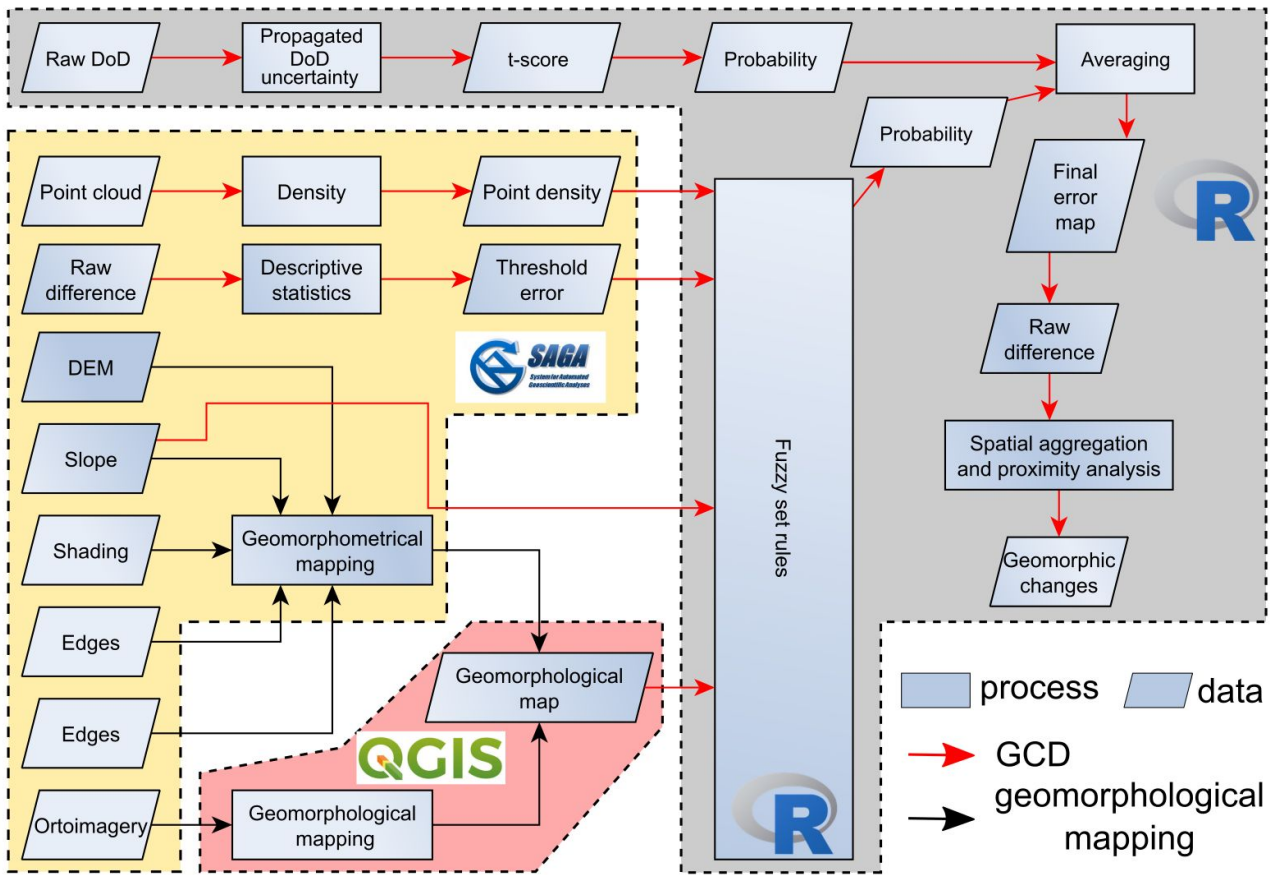


Fig. 7

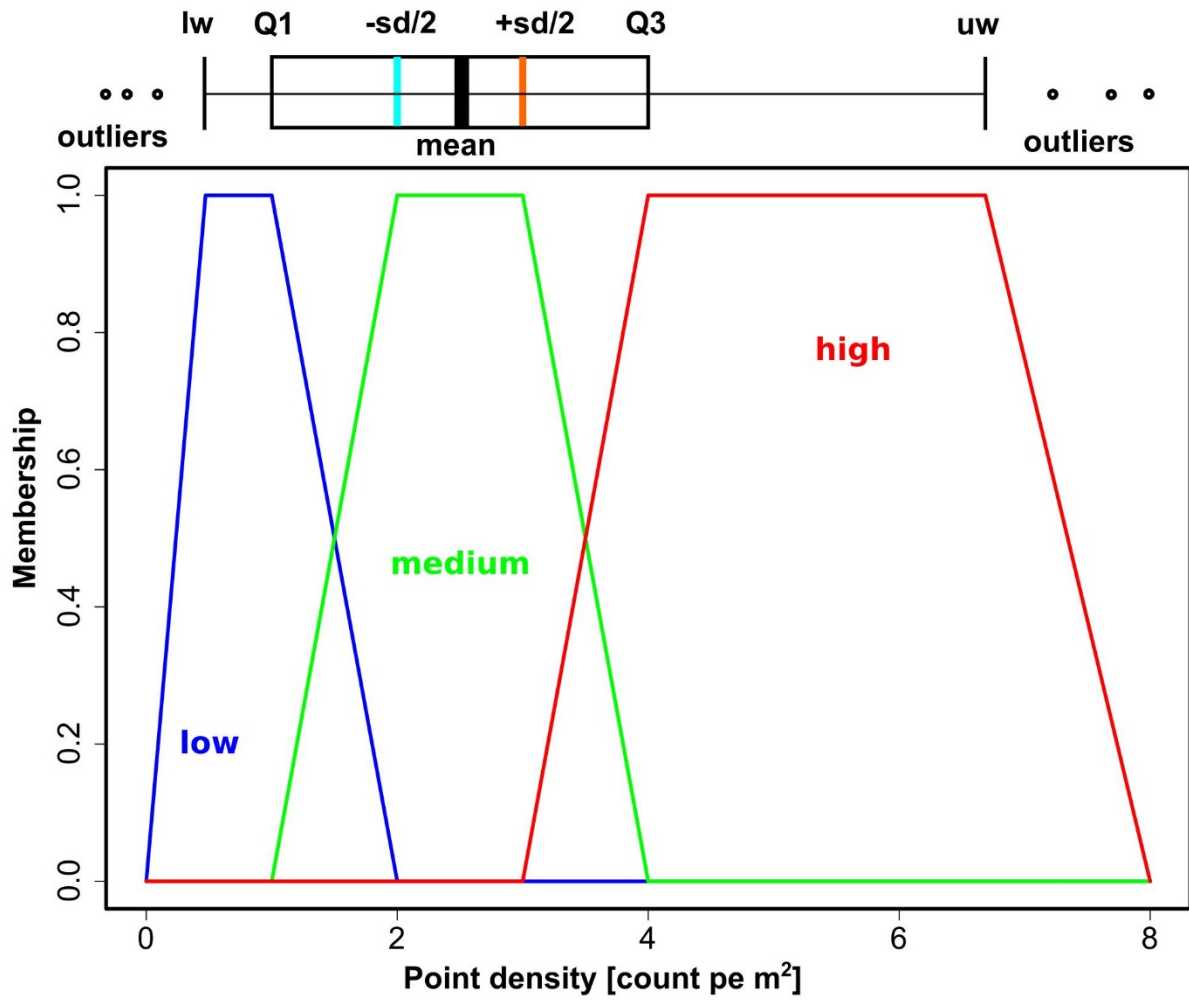


Fig. 8

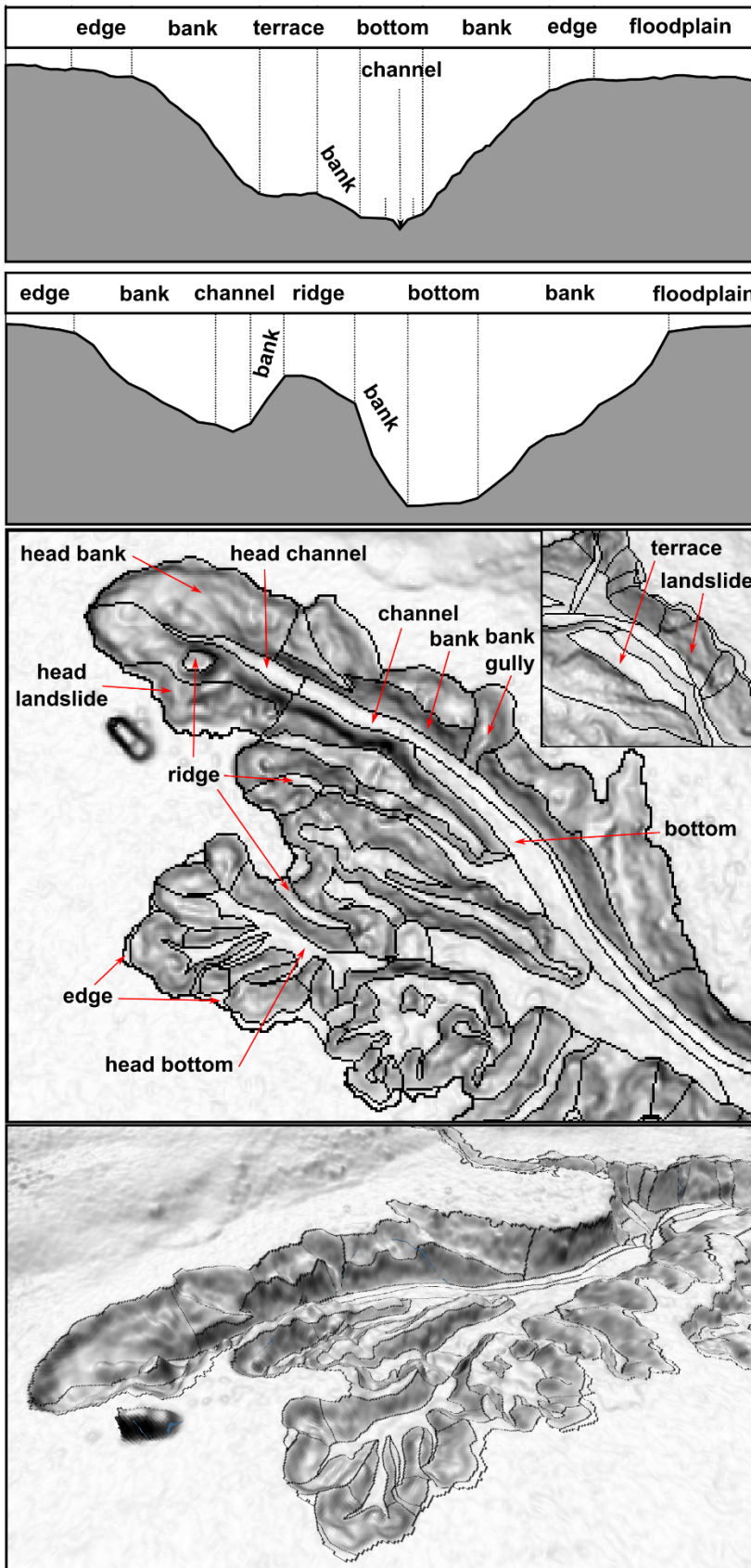


Fig. 9

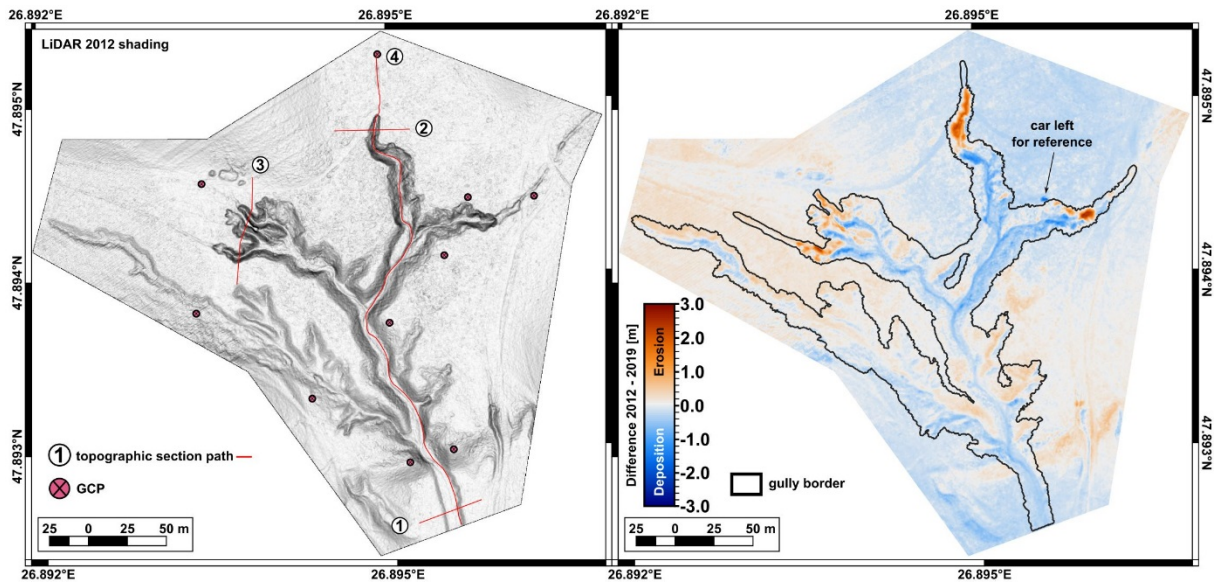


Fig. 10

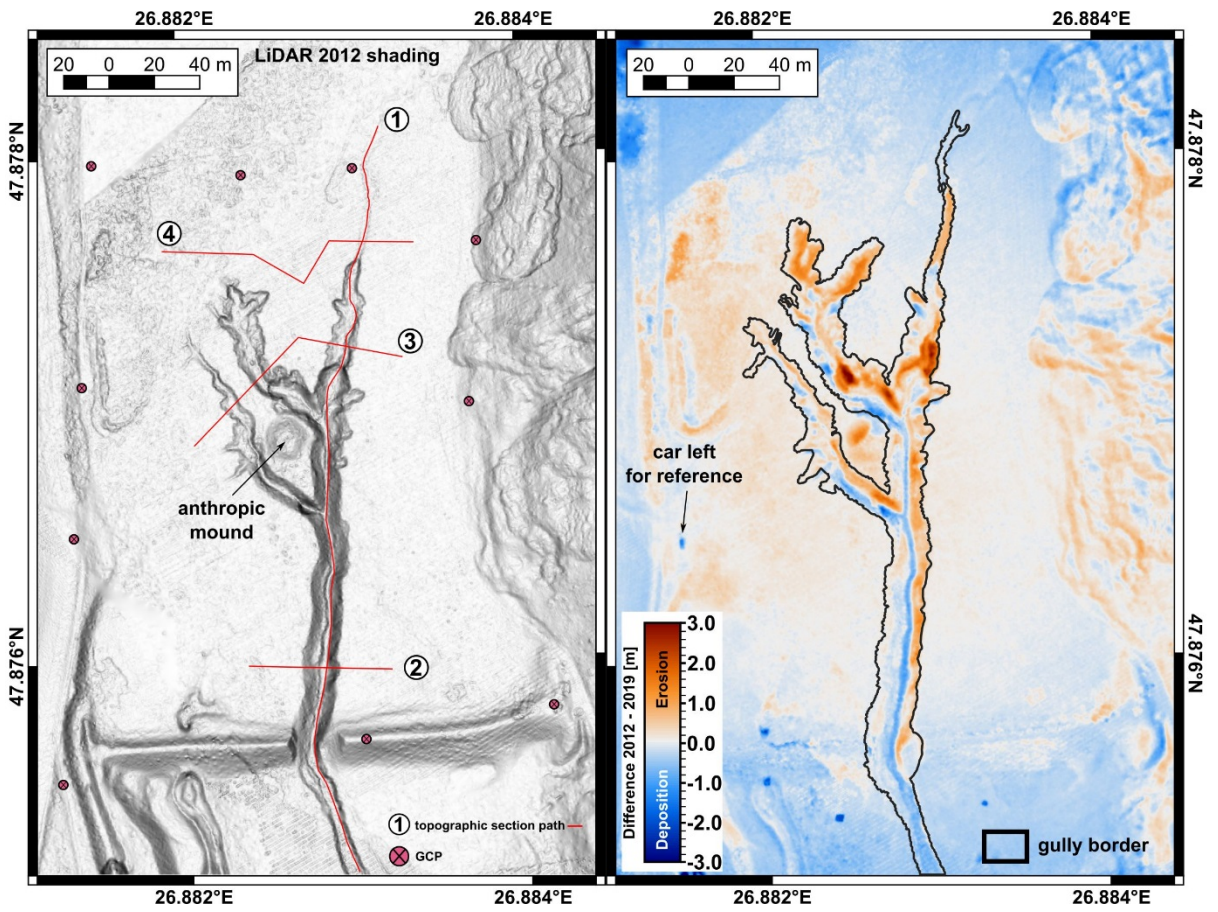




Fig. 11

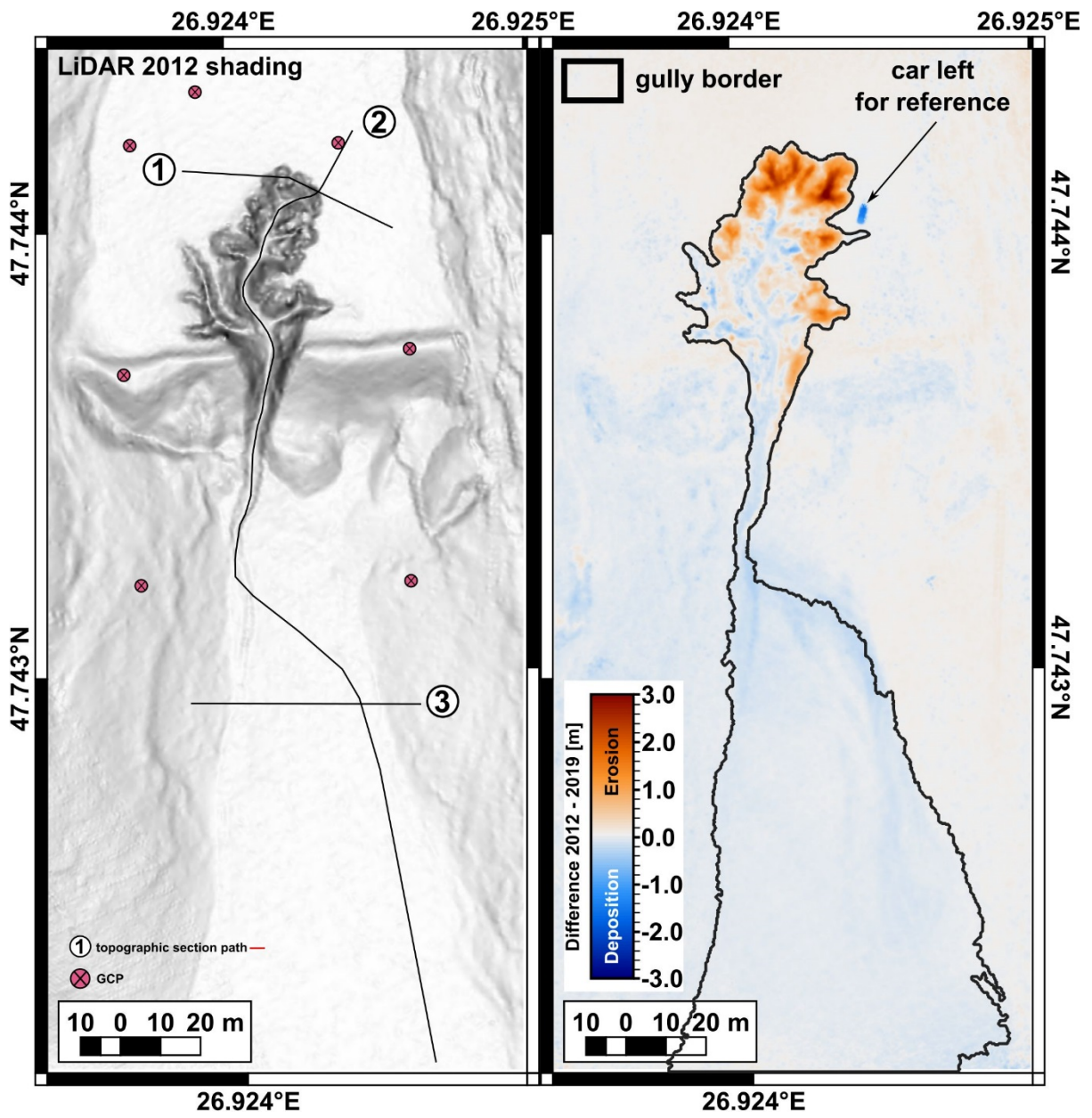


Fig. 12

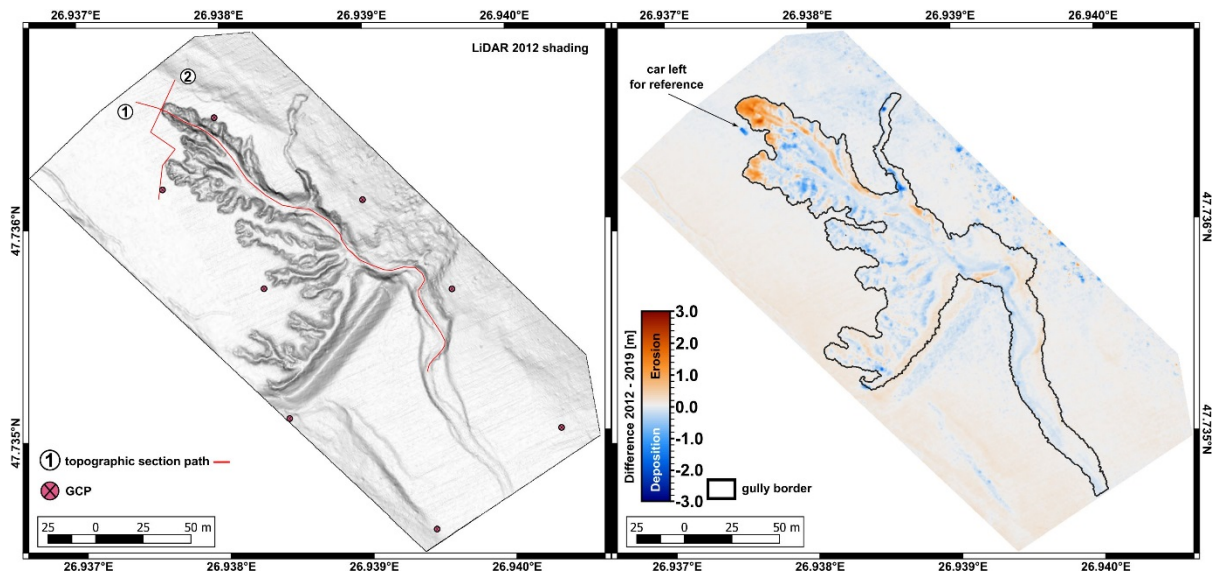


Fig. 13

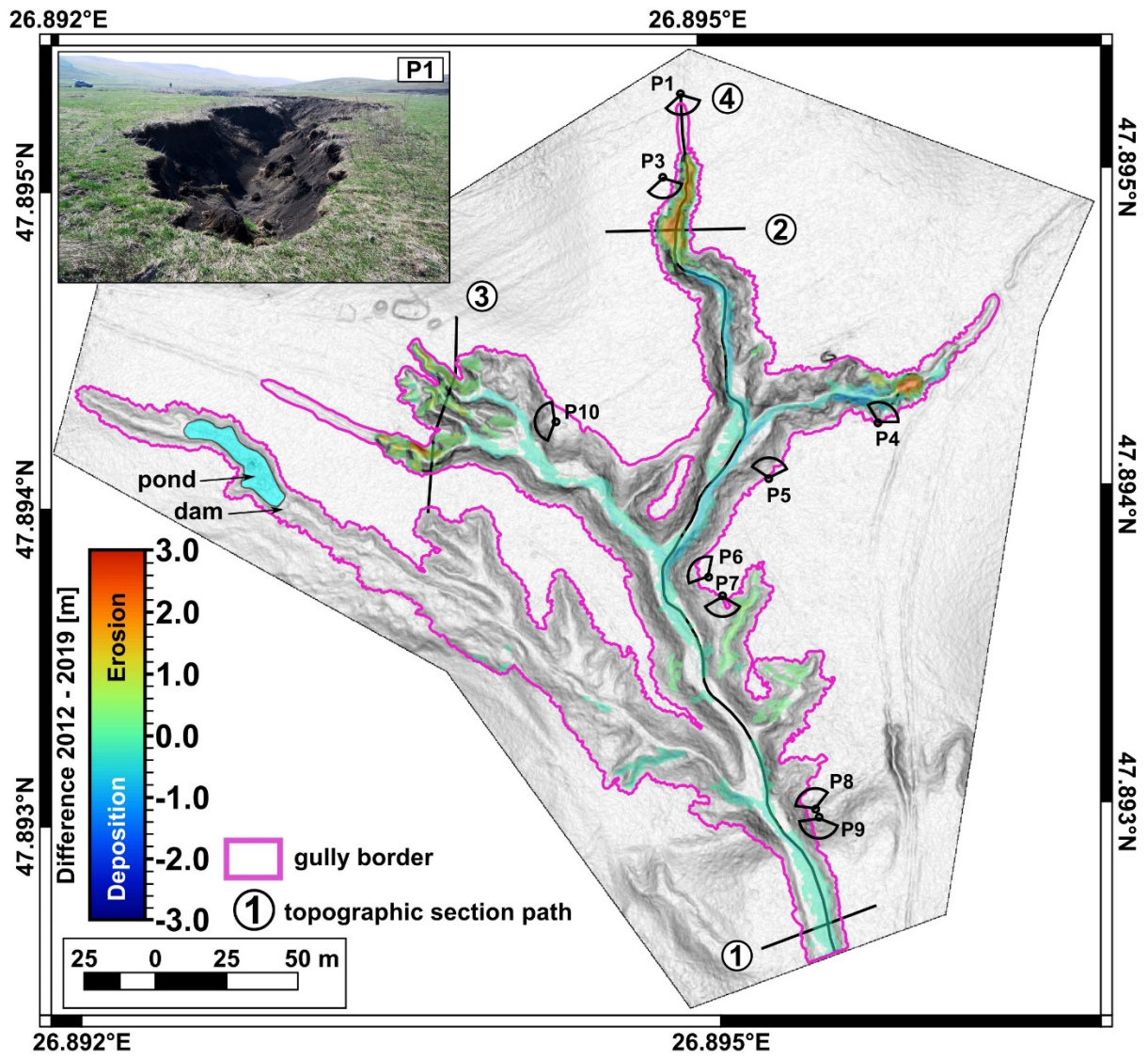


Fig. 14

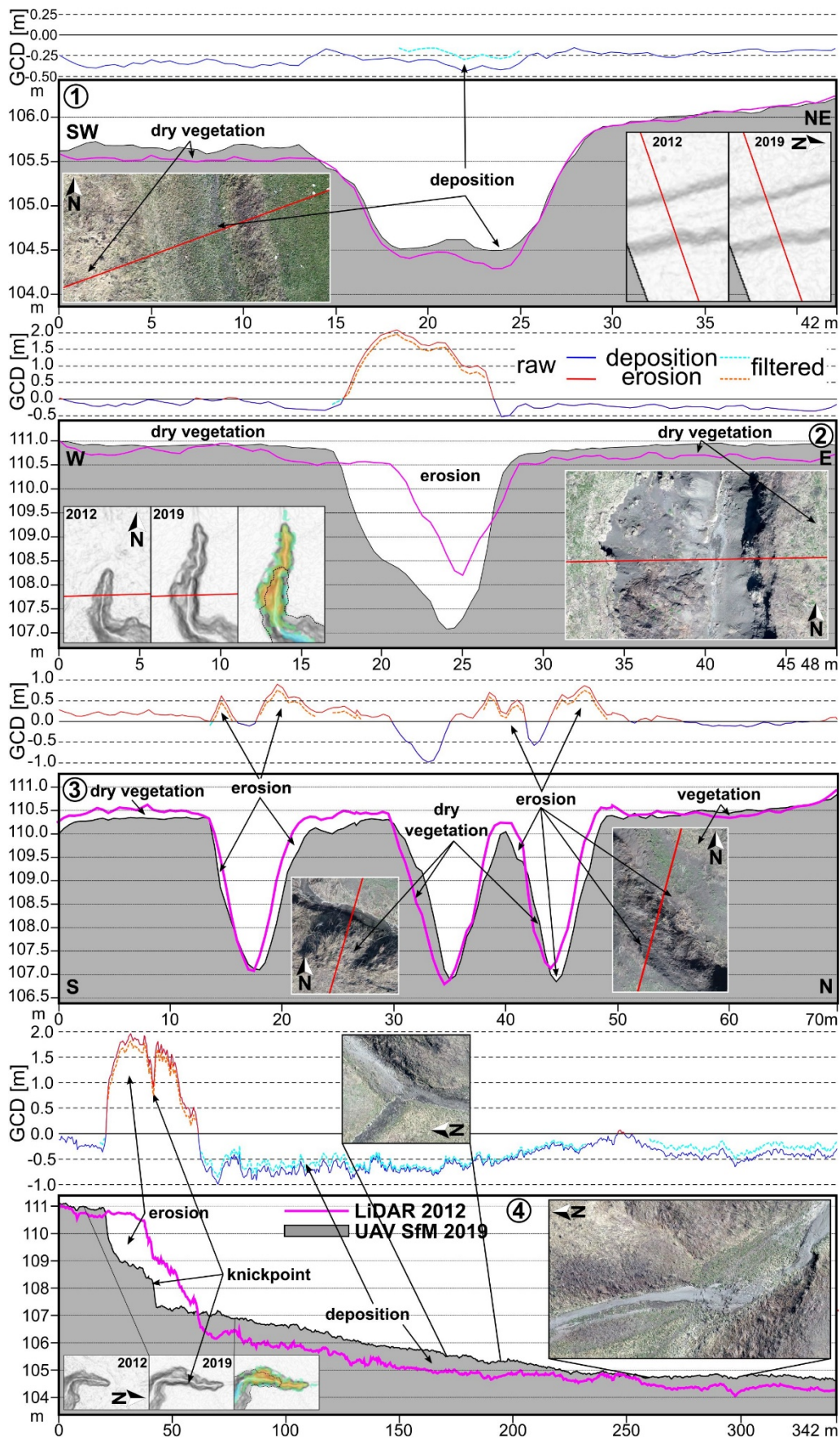


Fig. 15

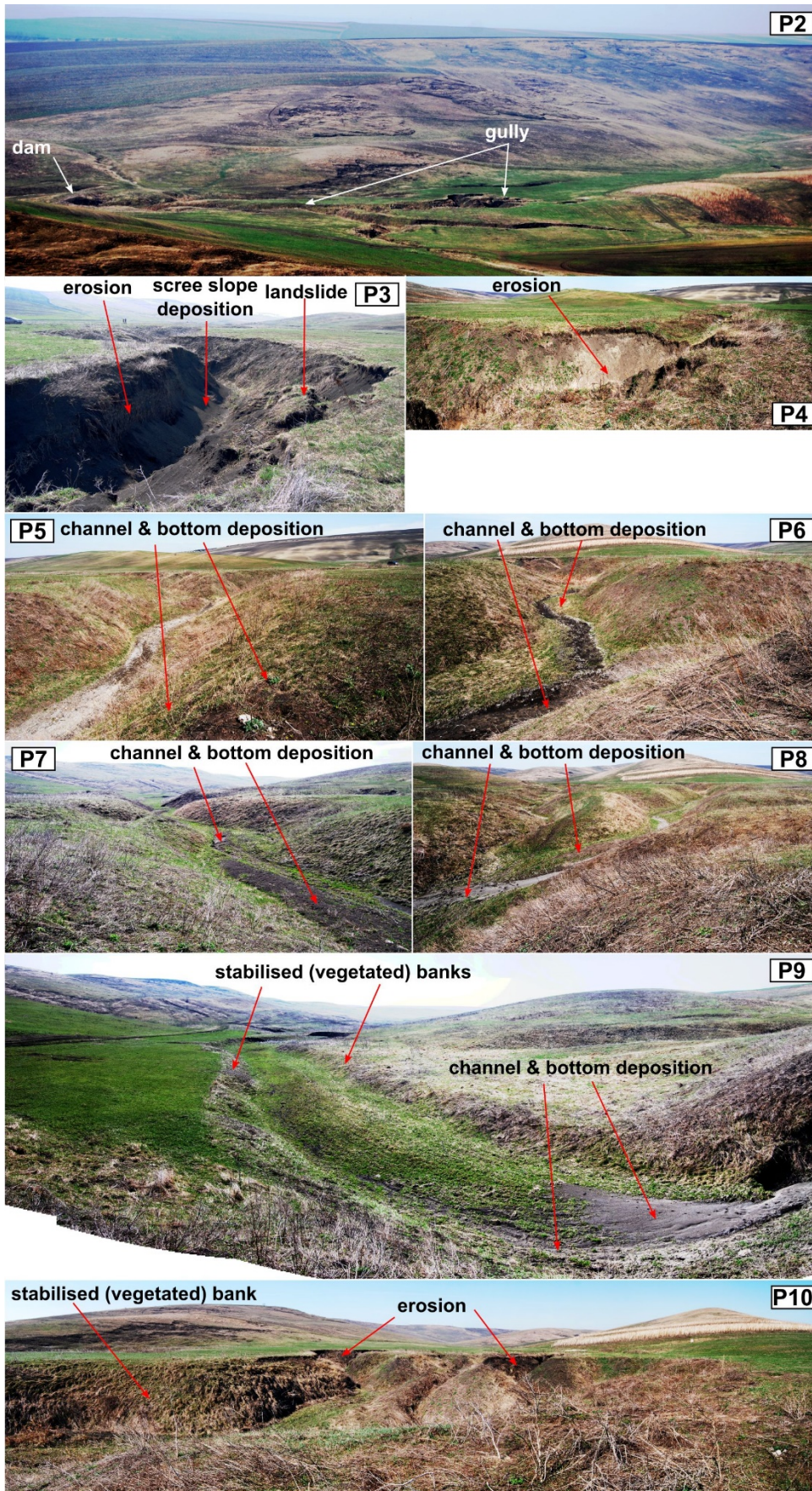


Fig. 16

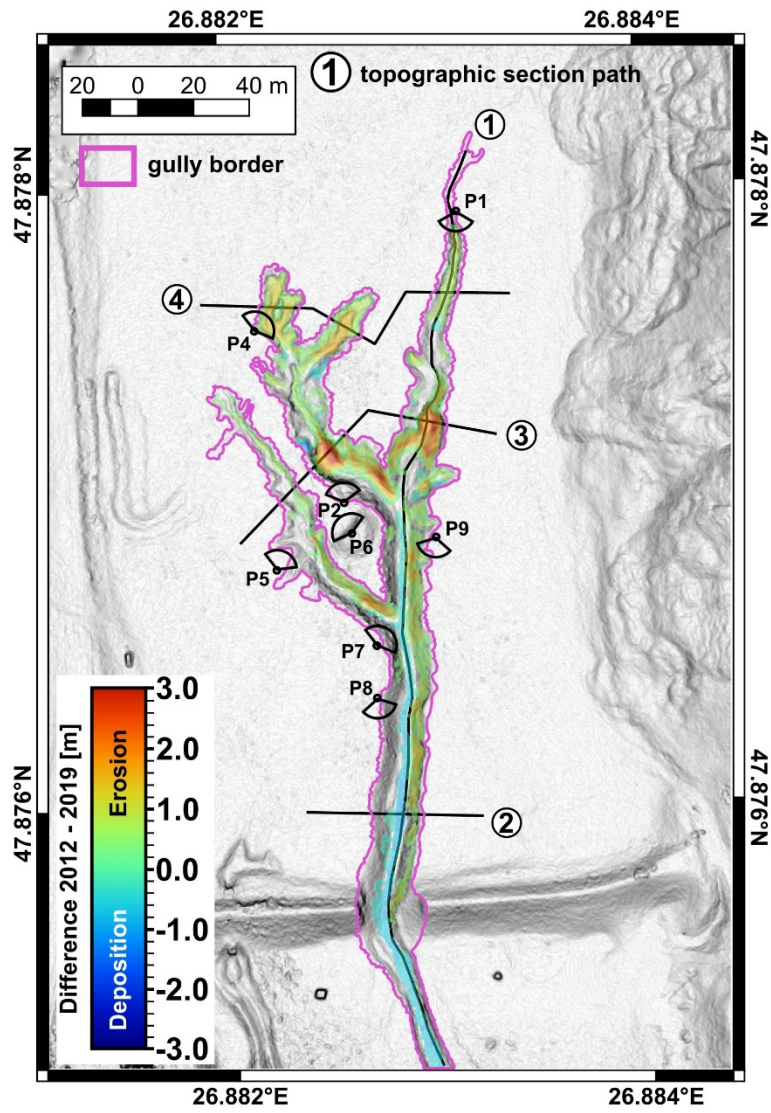


Fig. 17

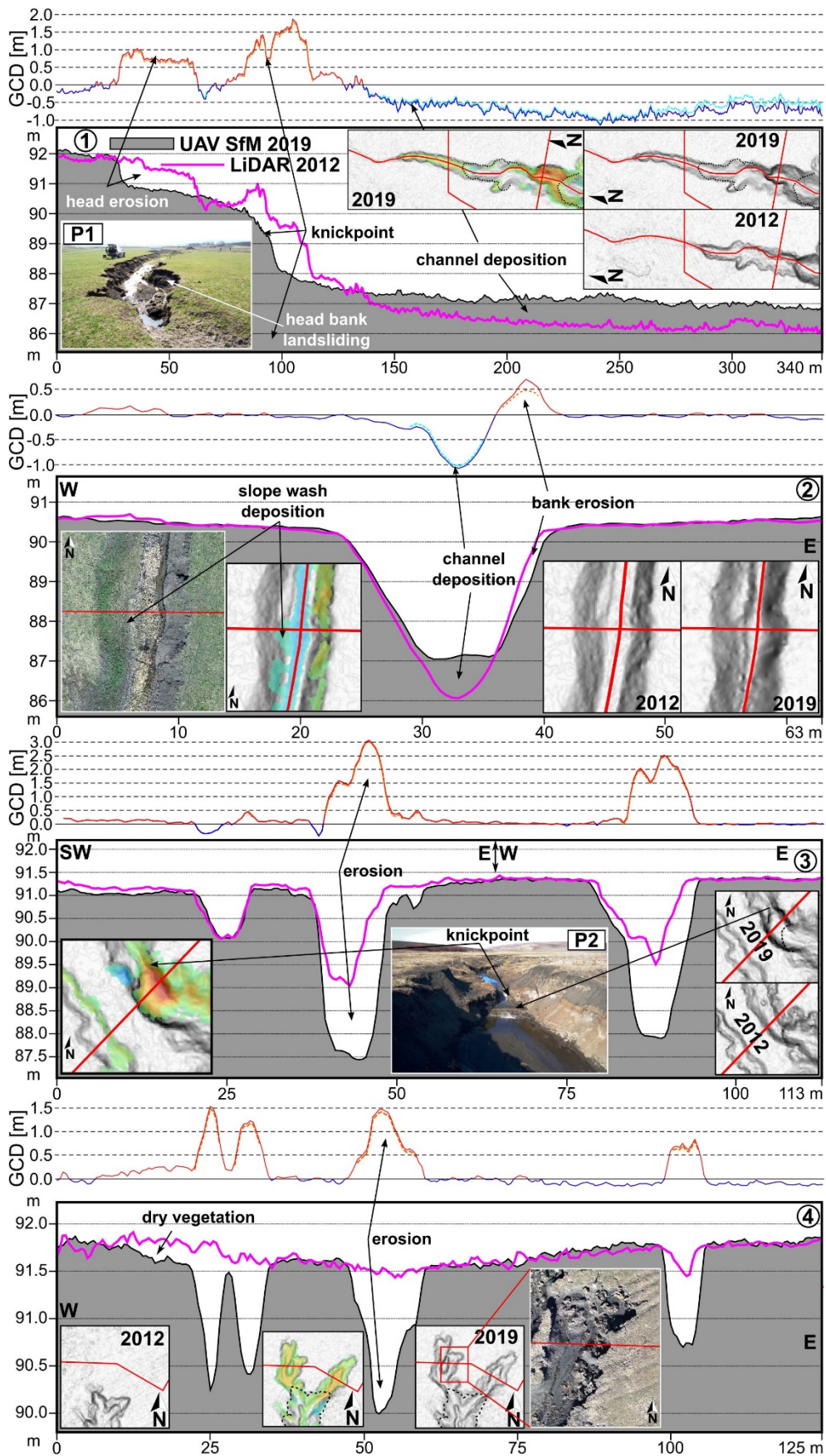


Fig. 18

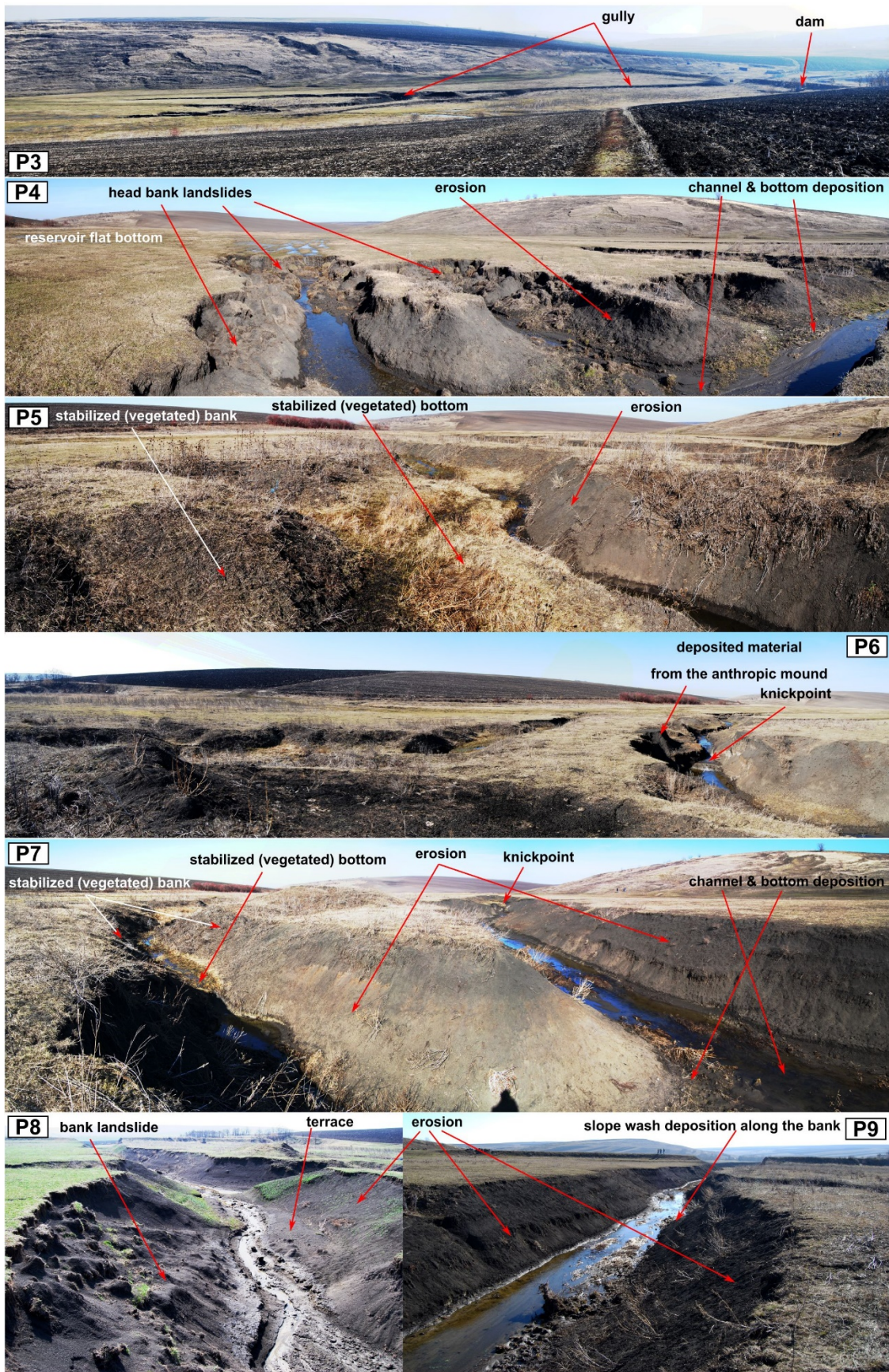




Fig. 19

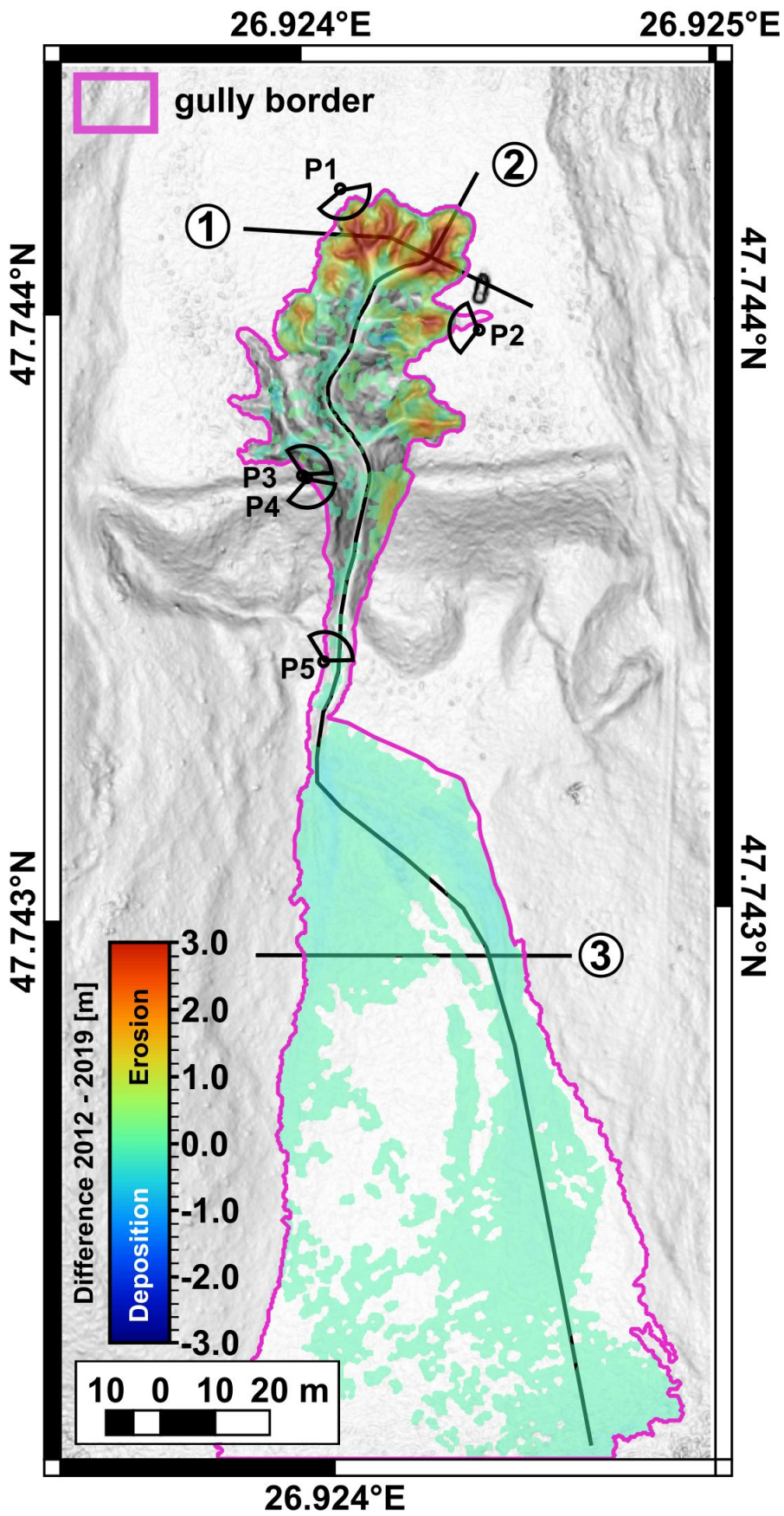


Fig. 20

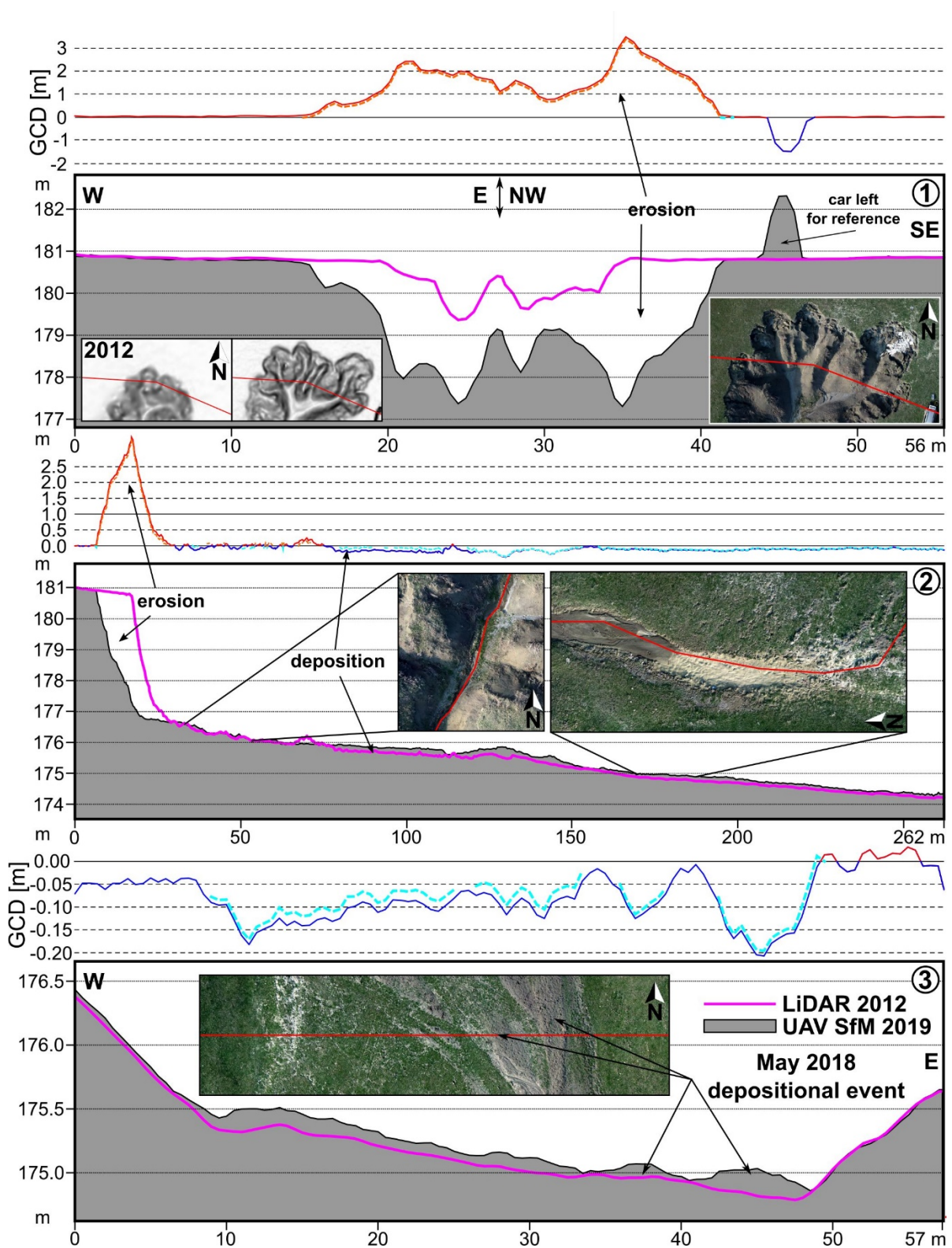


Fig. 21



Fig. 22

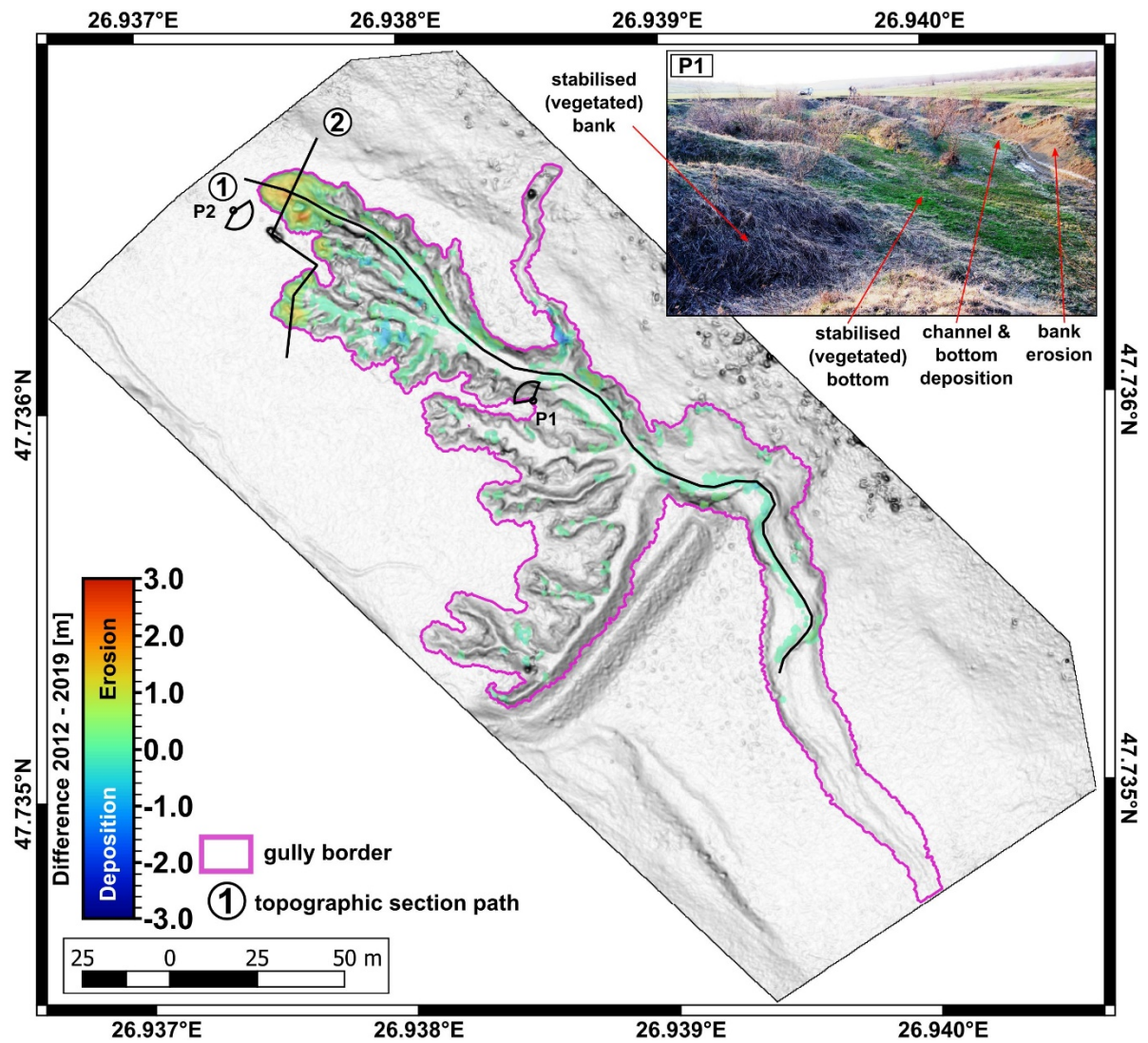


Fig. 23

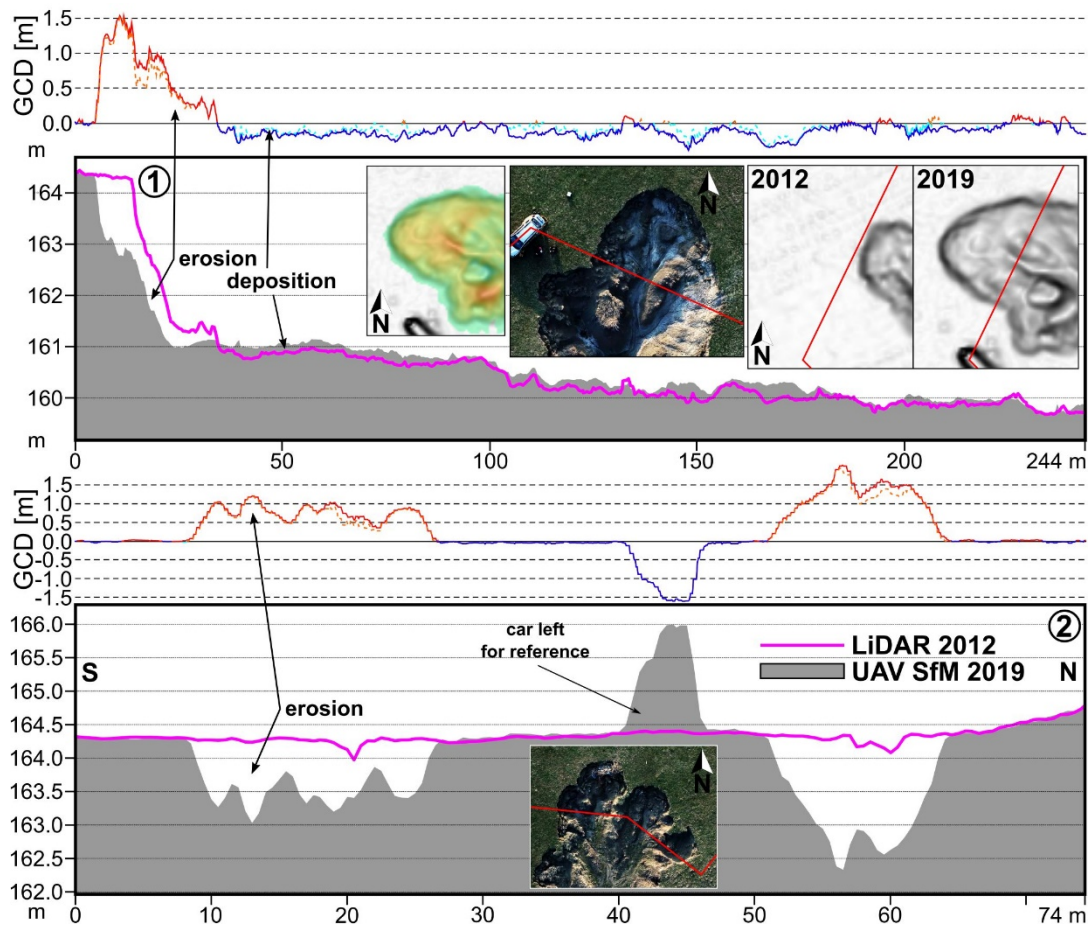


Fig. 24



Fig. 25

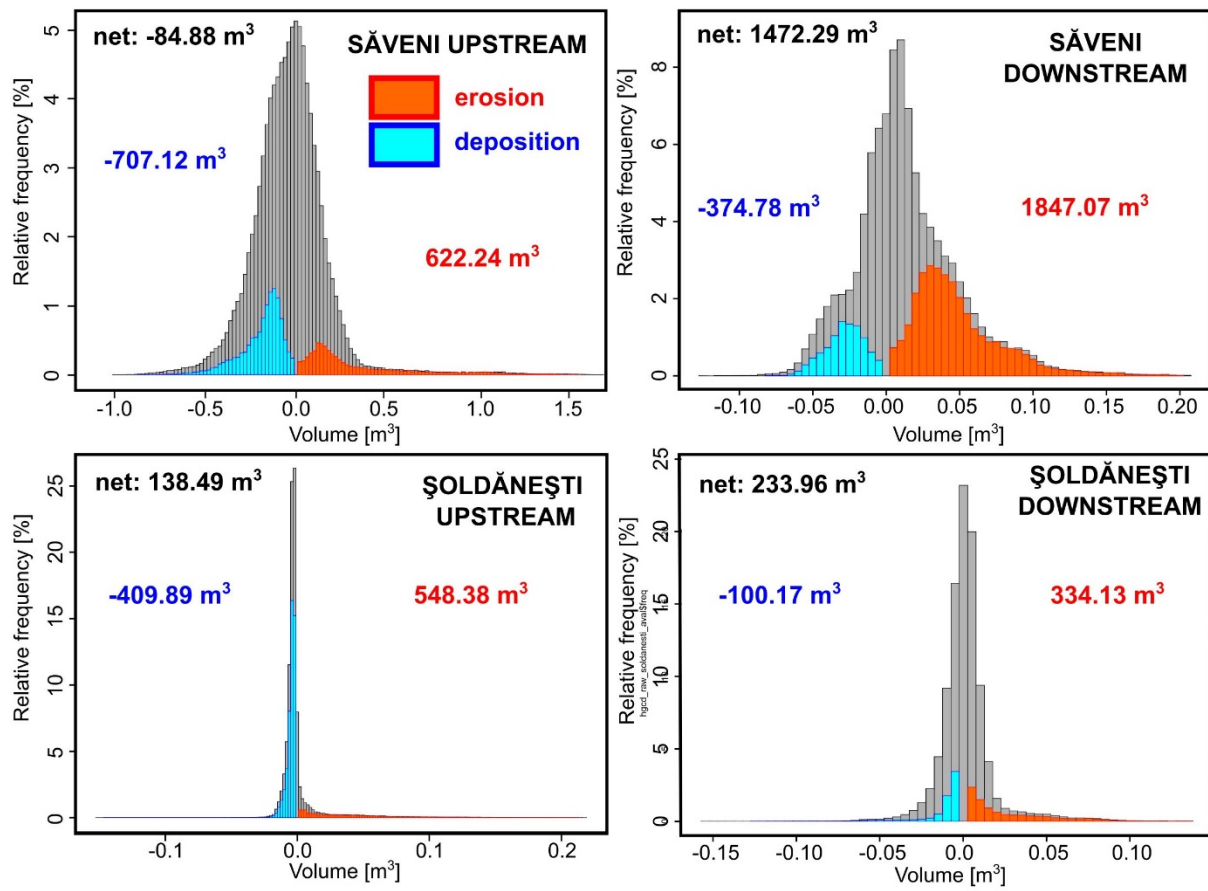


Fig. 26

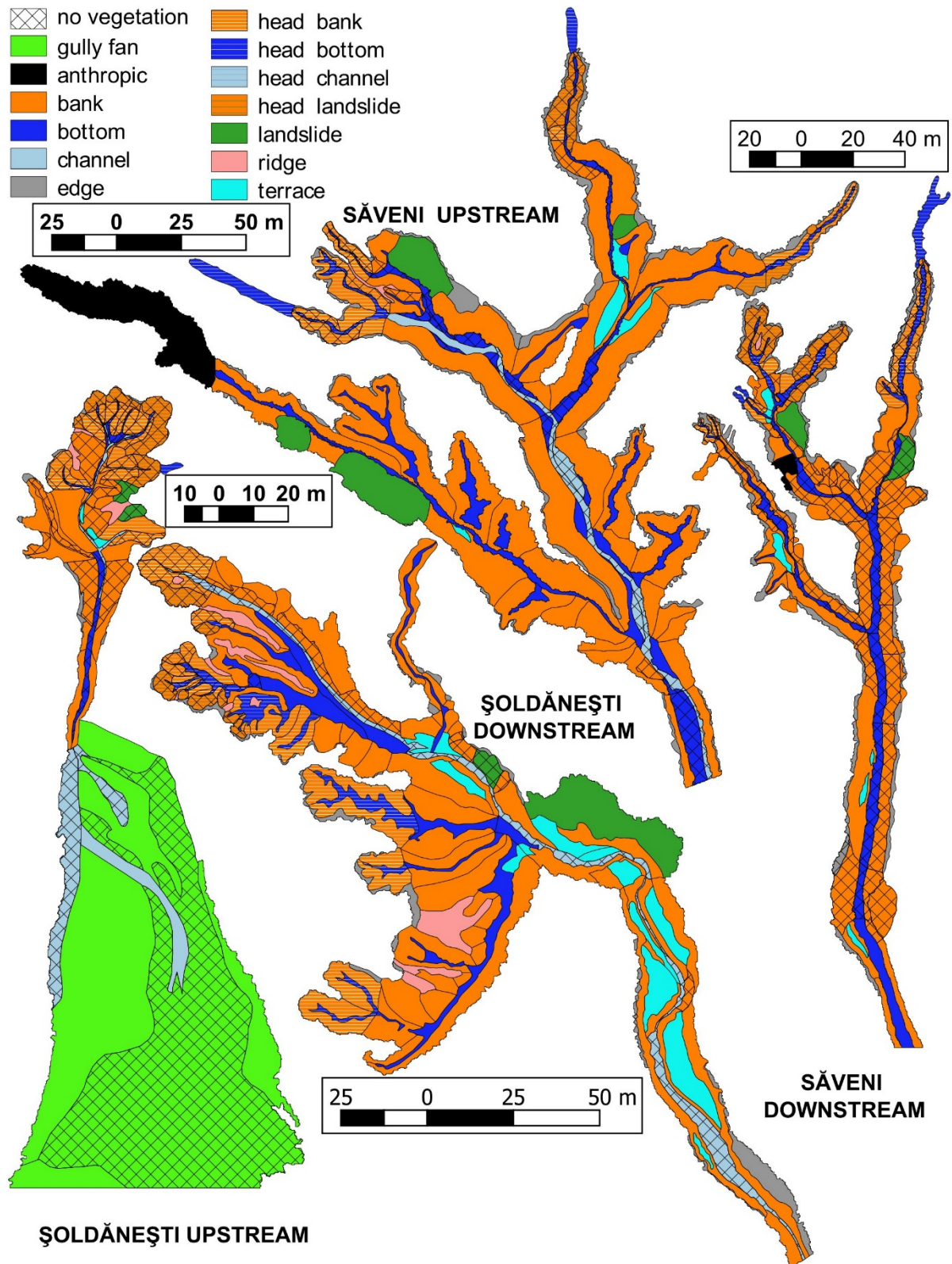


Fig. 27

