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Application of MIKE 21 in a multi-purpose floodway zoning along the lower Hungarian Drava section

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ABSTRACT

Floodway delineation, zoning and hydrodynamic modelling for a section of the Drava River was carried out with MIKE 21 software at a one-time input flood pulse of $3000 \text{ m}^3\text{s}^{-1}$ discharge. The objective of the current study was the delineation and mapping of floodway zones in the form of a set of georeferenced GIS data for the section between Órtilos (river kilometer 236 km) and Drávaszabolcs (70.2 km). Zonation was based on water velocities. Four zones were delineated upstream Barcs, and three between Barcs and Drávaszabolcs, where, due to the confined floodplain downstream Barcs, no stagnant water area was identified. Specific velocities ranged between 0.089 and $3.476 \text{ m}^2\text{s}^{-1}$ and 0.075 and $2.01 \text{ m}^2\text{s}^{-1}$ upstream and downstream Barcs, respectively, markedly lower than stated in the Government Decree (0.2 to $6.0 \text{ m}^2\text{s}^{-1}$). The primary and secondary conveyance zones covered a combined area of about 40% of the entire floodplain, while the remaining 60% included both the transitional and stagnant water zones upstream Barcs and solely the transitional zone downstream Barcs. Our analyses help to mitigate the effects of flood peaks and provide information for decision makers and local stakeholders on flood management tasks.

KEYWORDS

2D hydrological modelling; Design Flood Level; floodway; LiDAR; DEM; Drava River

1. Introduction

Climate change and antropogenic effects on land use have profoundly altered runoff regimes and floodplain flow characteristics along the rivers of Hungary (Lovász *et al.*, 2007; Novák *et al.*, 2013; Rózsa and Novák, 2011). The need for flood control

in Hungary is justified by relatively constant peak flow values and flood waves but increasing peak water levels that reached record heights in the years 2002, 2006 and 2013. Water management experts, however, widely agree that in the future efficient

flood prevention and defense has to be founded on more detailed topographic and bathymetric surveys complemented with computer models (Czigány *et al.*, 2007).

An ongoing project (Water management mapping: Mapping flood risk and preparing strategic risk management plans) aims at exploring the physical background knowledge of floods to be utilized in floodway management planning (Government of Hungary, 2014). The floodway is that portion of the floodplain which is effective in carrying flow (FEMA, 2013). In Europe the term active floodplain is used for this zone (Marriott and Alexander, 1999). Floodway management plans include zoning of the floodway and proposals for imposing restrictions (of construction, land use, etc.) in the various zones (FEMA, 2013). While in the United States it is officially sufficient to distinguish between the floodway and the floodway fringe (inundated during 1%-probability floods), Hungarian regulation (Government of Hungary, 2014) requires a finer distinction between floodplain zones.

For the analysis of water flow in river channel and floodplains various types of numerical models have been used: one-dimensional finite difference hydraulic models (Mishra *et al.*, 2001), two-dimensional finite difference and finite element hydraulic models (Gee *et al.*, 1990; Bates *et al.*, 1992), and two-dimensional finite element hydraulic models coupled with hydrologic models (Bates *et al.* 1996, 2006; Stewart *et al.*, 1999; Jung *et al.*, 2012) and physical downscale models, such as flumes and sand tables (Bertalan *et al.*, 2016). Remote sensing and GIS applications are commonly associated with hydrodynamic modelling and may provide additional data to increase reliability (Liu and De Smedt, 2005).

One of the most challenging problems with numerical modeling of flow through river reaches stems from the complexity of channel and floodplain geometry (Babaeyan-Koopaei, 2003), floodplain roughness (Bedient and Huber, 2002) and shear velocity. Besides geometric limitations, numeric models are further burdened with numerical simplification (i.e. omission of terms or fluid properties), or the use of empirical correlations (Toombes and Chanson, 2011). The resolution of

models usually differs for the channel and the floodplain (the floodway and the floodway fringe, which is inundated with 1% probability). For management reasons, however, a uniform approach is desirable (Szabó *et al.*, 2012; Grêt-Regamey *et al.*, 2015). Therefore, modelling should focus on the flow interface (the velocity profile in the environs of river banks) between the main channel and the floodplain. For similar reasons, it is desirable to have fine grid spacing at the walls to capture the velocity profile near the boundary (Bates *et al.*, 2006).

The staff of the Department of Physical and Environmental Geography, Institute of Geography, University of Pécs, is engaged in hydromorphological and geoecological investigations of floodplains with special attention paid to the Hungarian section of the Drava River. Broad experience has been gathered in hydrological modelling and GIS visualization of various water management issues, first of all, the physico-geographical factors contributing to the generation of flash floods in mountain and hill environments. A recent Government Decree (Government of Hungary, 2014) prescribes the preparation of management plans for the floodways for all major rivers in Hungary. Under contract with the South-Transdanubian Water Management Directorate (DDVÍZIG), experts of the Department undertook the task of modelling the floodway of the Drava River, the border river between Hungary and Croatia for the section between the river kilometers 154.1 and 70.2 (Fig. 1). Supplementing the existing one-dimensional model (Torma *et al.*, 2014), a 2D hydrodynamic model had to be constructed. The 2D simulation results serve practical design goals: the management of the active floodplain to ensure the safe conveyance of flood waves and the maintenance of optimal conditions from the aspect of water management.

The purpose of modelling was the identification of four zones on the map of the floodway based on specific velocity as well as in the form of a set of georeferenced GIS data: (i) the primary floodway zone; (ii) the secondary floodway zone; (iii) a transitional zone and (iv) the stagnant water area (including counter-current flow), and to compare 2D results with a 1D model generated in HEC-RAS 4.1 by Józsa *et al.* (2013) with 300 input cross-sectional geometry data.

Zoning was executed for the current situation and future conditions after development. Through the interpretation, the topographic data the channel and the boundaries of zones had to be referred to the channel edge at bankfull stage. In hydrodynamic modelling, the trends and causes of temporal changes in the hydromorphology of the floodway and its fringe had to be revealed focusing on the combined impact of natural and human-induced processes.

The model of dynamic floodplain zones provides valuable assistance to the planning of channel and floodplain management, including legal restrictions for construction activities, guidelines for insurance of property and optimization of floodway vegetation from the aspect of safe flood conveyance.

2. Methods

The 2D hydrodynamic modelling of the selected Drava floodplain segment was performed by the MIKE 21 flexible Mesh Model developed in

Hørsholm, Denmark (DHI, 2014). MIKE 21 is the leading software package for 2D modelling of hydrodynamics, waves, sediment dynamics, water quality and ecology. MIKE 21 is a modular product and includes simulation engines that are aimed at a very wide range of applications. These include modelling of tidal flows, storm surge, advection-dispersion, oil spills, water quality, mud transport, sand transport, harbour disturbance and wave propagation. MIKE 21 has a menu-driven user interface. The installation also includes manuals, including step-by-step manuals and examples. This model is composed of shallow-water equations, vertically averaging the set of the three-dimensional Navier-Stokes equations, which describes fluid flow but cannot be solved analytically. Since there are several orders of magnitude differences between the investigated water depth and the horizontal extension of the model area, this approach is an acceptable simplification for the implementation of the given task (Weber and DeGiano, 1996). The horizontal velocity vectors are assumed to truly depict the studied flow processes.



Figure 1 Location of the studied reach of the Drava River

The base equations are solved using an unstructured discretization mesh, which equally includes elements of a triangular irregular network (TIN) and a quadrangular network (Mavriplis, 2008). Thus, the sizes and shapes of the individual elements are variable. The model relies on the Finite Volume Method (Chen, 2010) for the solution of partial differential equation system, which calculates water depth and specific flow values in x and y directions. Further derived values include water level, current velocity and shear stress on the channel floor. The model is static and does not need timesteps definition since the highest stable time step for a given element is selected based on the CFL condition from a predefined province and treated automatically.

2.1 Data input

The following input data were used for model setup: (i) calculation grid; (a) filled from ground elevation data; (b) filled with smoothness coefficients; (ii) boundary conditions; (iii) initial conditions; (iv) model parameters.

The basis of the model running were flood wave curves and discharge values used for determination of the levels constituting the input of the Design Flood Level (DFL) model (Budapest Technical University – Józsa *et al.*, 2013).

First we filtered an 8 points per square meter resolution classified ('model key' and 'ground') point cloud to generate a general elevation raster that did not include the river surface. Secondly the river bed geometry was created from the cross-sectional data and subsequently a combined DEM was compiled (Fig. 4). Bank lines were generated using cross sections and orthoimagery, produced by stereophotogrammetry (DDKÖVIZIG, 2000). The final combined raster had a resolution of 1 by 1 meter per pixel.

2.2 Digital Elevation Model and channel delineation

With a spatial resolution of 1 by 1 meter calculations take an excessively long time. To overcome this challenge, a mesh was generated using the flexible

mesh model of MIKE 21 with a spatial resolution of 1-meter for the river and 25-meter for the floodplain. This way we optimized output data quality and this mesh size meant adequately short processing time.

River channel morphological parameters were imported from the cross-sections of the Hydrographical Atlas of the Drava River (DDKÖVIZIG, 2000). The interval between cross-sections was 350 m along the reaches entirely on Croatian territory and 50 m for those entirely on the Hungarian territory.

The floodway model also covers the side-channels, which were surveyed in 2010-2013 within the framework of a joint Hungarian – Croatian IPA landscape rehabilitation project (Purger, 2013). As part of the project, four side-channels (two at Drávatamási, one at Tótújfalu and one at Drávapalkonya) were rehabilitated. Altogether eight of the side-channels are incorporated into our model.

For including the parameters of the areas between cross-sections, a linear interpolation method has been elaborated (Fig. 2), based on similitude estimation. Straight alignment was substituted by 50 alignment line segments, and this allowed a high-resolution depiction of channel morphology.

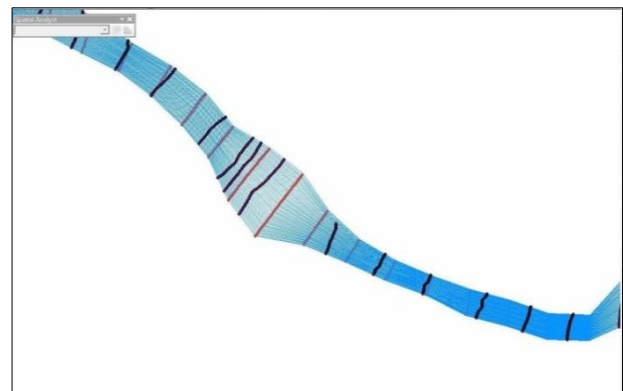


Figure 2 Linear interpolation to depict channel morphology between cross-sections

A source of error is that the channel morphology in the Hydrographical Atlas is rather outdated. It reflects conditions existent during the

cross-section surveys, which took place 12 years ago and the thalweg and bathymetry of the river bed have changed locally to a considerable extent. Riverbed morphology was subsequently masked by the interpolation of LIDAR data. For correction, the channel bank edge was rectified with the help of high-resolution LiDAR images (Fig. 3) and orthophotos. From the ground points of LiDAR images, the first on either on the left or right bank of the water surface were selected and rectified from the interpretation of orthophotos. The set of ground points were further processed by edge filters, and thus an edge detection for the riverbank was achieved.

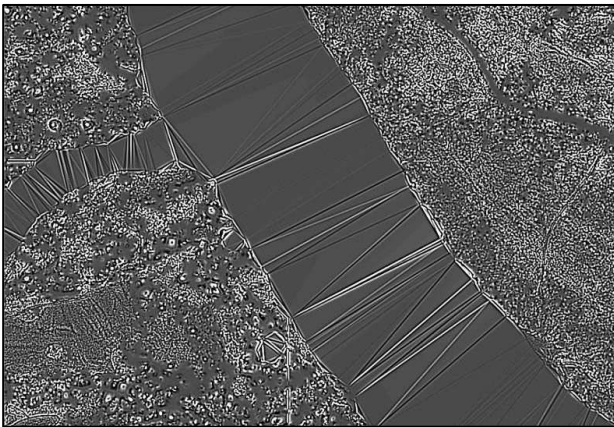


Figure 3 Channel delimitation based on topography from high-resolution LiDAR images using edge filtering

For the digital representation of the riverbank edge at bankfull stage, the DEM was merged with the bathymetry channel model (Fig. 4). The uniform model, where the channel limits are defined by the line where medium water level intersects with the DEM, is suitable for further high-resolution analyses.

In the next step, to define the k factor of the hydrodynamic model with high precision, the LiDAR images were interpreted for the identification of land cover through the selection of the dominant reflectance values.

Five major land cover classes were distinguished: zones of low, medium high and high vegetation, ground surface (seasonally appearing as low or medium high vegetation) and artificial structures (buildings) on the surface.

2.3 Hydrodynamic modeling

The calculation mesh was produced using the Mesh Generator of MIKE Zero application. Since the software is not able to import GIS data directly and to process them, the first step had to be the preprocessing of data.

The calculation mesh is generated employing line chains, both polygons, and free line chains (Fig. 5). An advantage of the unstructured mesh is that the individual elements can vary in area, and the internal angles of the triangular elements can also be different.

Taking advantage of this, finer resolution (smaller element size) can be defined for the river channel, where higher current velocities and diverse flow patterns are typical, than in the active floodplain, where overbank flow spreads out, and currents form at small water depth and, therefore, the size of elements is usually larger (Babaeyan-Koopaei, 2003). Thus, the number of elements can be optimized. This influences the time needed for model running, the size and easy handling of model files. It is not sufficient to identify the study area as a polygon, but further internal polygons are to be defined which signify areas of various size. It was an important goal to minimize the scope of boundary conditions through treating the study area as a single unit.

Imprecise identification of boundary conditions is a major source of error. Therefore, boundary conditions have to be limited to one upper and one lower boundary condition. Also, the spatial resolution of the model (25 and 1 meter, for the floodplain and the riverbed, respectively) has to be in accordance with the technical requirements of floodway management planning. Thus, the number and size of necessary elements are easy to determine.

Consequently, two additional features were introduced to improve the spatial resolution of the mesh: one for the river centerline, and one for the crown level of flood-control levees. The inclusion of the levees is motivated by two reasons. Their size could remain below that of a calculated element, and this means that they are left out from the elevation model used for the hydrodynamic simulation and undoubtedly lead to error. The line chain along the levee crown serves for fitting the calculation mesh.

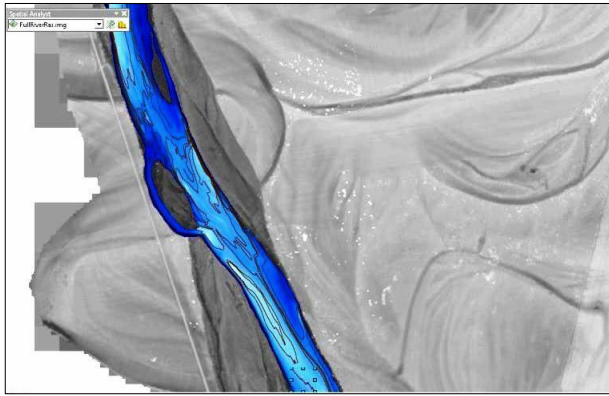


Figure 4 Detail of the unified elevation model

The other reason is that flood-control levees are assumed to be never overtopped and, therefore their representation in the calculations can be superfluous. Given their small size, the elements generated for the levees are much smaller than others in the active floodplain and, thus, the instability, run-time and the number of elements are unnecessarily increased. Therefore, if the water level in the next cell reaches the level of the crown, the levee is overtopped in the model.

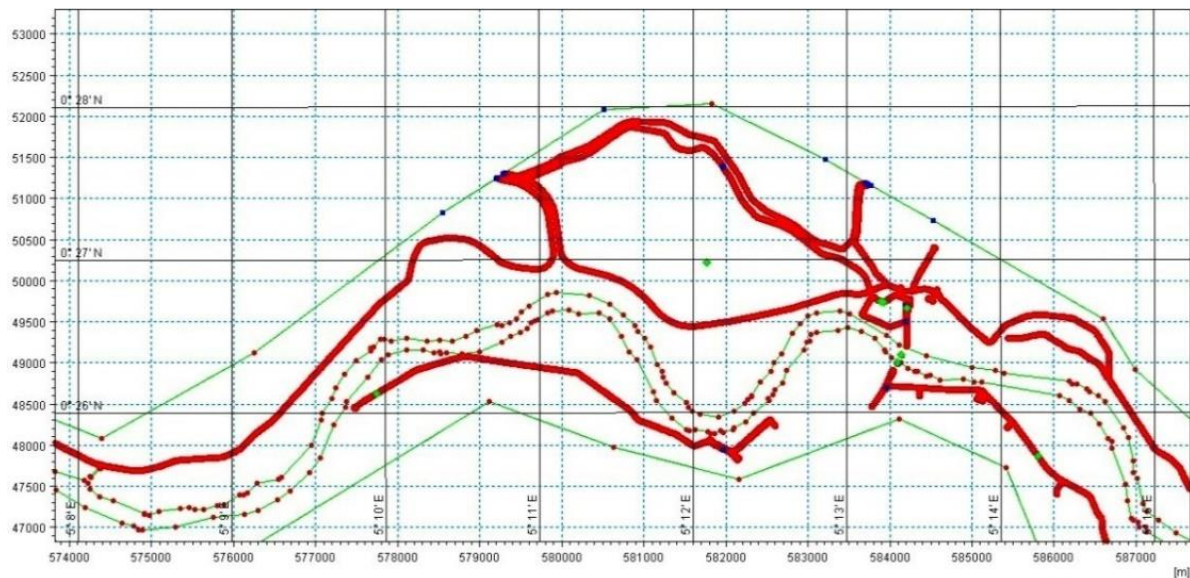


Figure 5 Detail of line chains representing the river channel and flood-control levees created by Mesh Generator

Our objective being the modelling of water flow, only those elements of topography that influence water flow are included in the model. For mesh generation, a corrected set of breakpoints was applied. The distance between two breakpoints determines the opposite internal angle and area of the triangular elements. The shorter the distance, the smaller are the angle and the area and local model sensitivity is proportionally enhanced. Excluded from the calculation mesh, the piers of the two road bridges along the study reach were incorporated into the model with a simplified geometry (Fig. 6).

The maximum allowable size for channel elements (represented by triangles) was 2,000 m² and for floodplain elements 20,000 m². This is the limit to which the software can increase the area of elements where no other condition applies.

Three kinds of boundary conditions are identified. The line chain attributes are explained as 0 means a simple line chain; 1 is model boundary (without a perpendicular component of velocity); 2 is the upper boundary condition (incoming flow); 3 is the lower boundary condition (fixed water level).

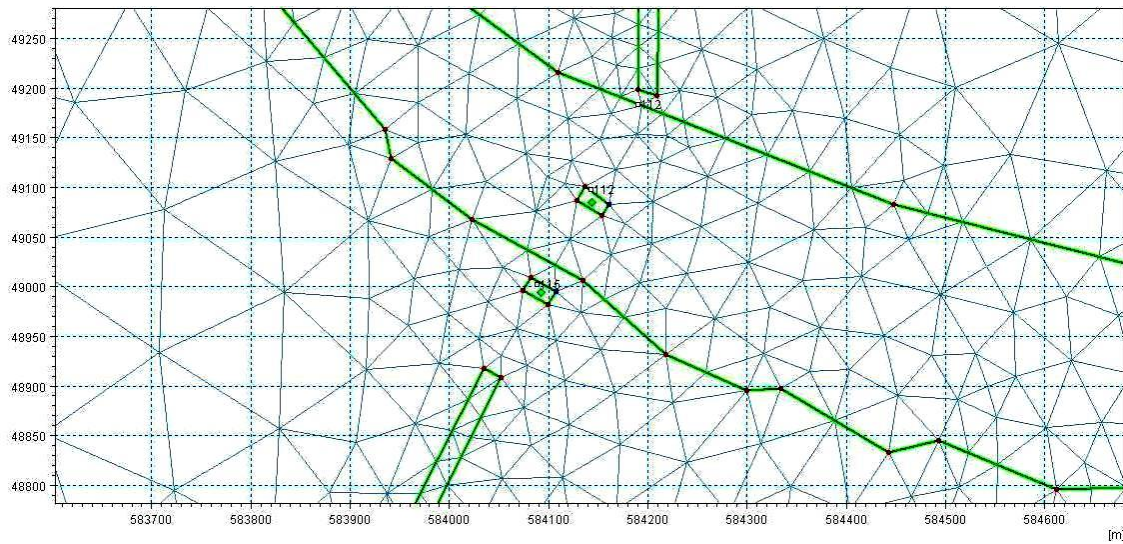


Figure 6 Representation of the piers of the Drávaszabolcs road bridge in the model

Following the above preparatory steps, the mesh was generated with the parameters: maximum permitted element area, the number of elements and minimal internal angle of elements. The last parameter is an important factor of stability, limited by the angles of line chains (to 28° in the presented

model). The resulting mesh is smoothed in several steps until the final mesh is reached (Fig. 7).

Then the final mesh is parametrized with topographic and smoothness data (represented by z coordinate values).

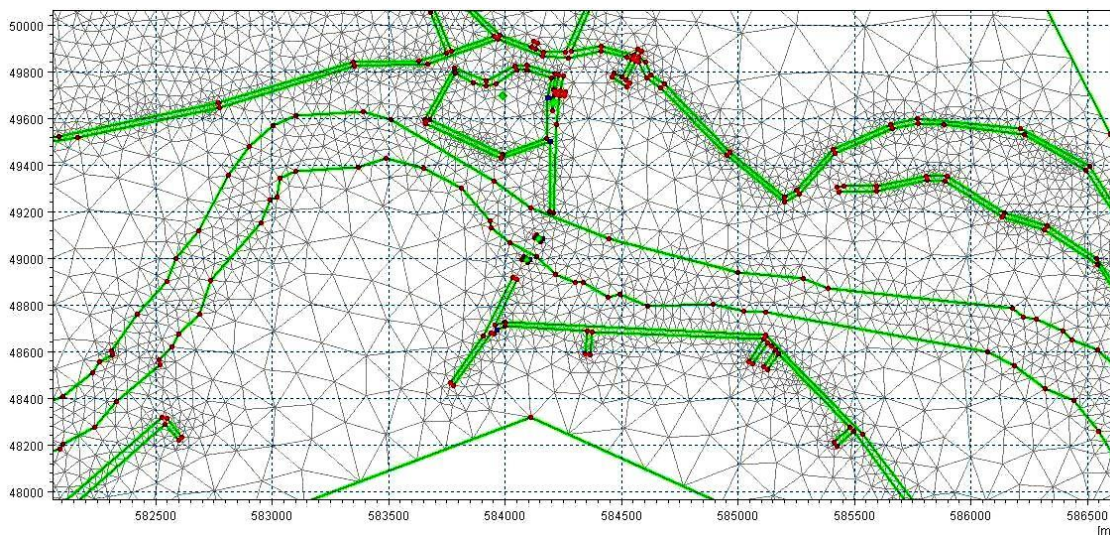


Figure 7 Detail of the final calculation mesh

After interpolation, an elevation model was achieved (Fig. 8). Manning's smoothness (inverse roughness) was defined in four categories: (i) forest

($9 \text{ m}^{1/3} \text{ s}^{-1}$); (ii) channel ($30 \text{ m}^{1/3} \text{ s}^{-1}$); (iii) agricultural area ($30 \text{ m}^{1/3} \text{ s}^{-1}$); (iv) built-up area (sealed surfaces) ($50 \text{ m}^{1/3} \text{ s}^{-1}$) (Fig. 9).

2.4 Boundary conditions

The upper boundary condition, permanent inflow, was equal to the value used in the modelling of DFL. As the lower boundary condition water level or the Q-h loop, curve may have been acceptable. Since they were not known, current velocity, offered by the software, was employed. This, however, involved some degree of imprecision in the description of boundary conditions. Previous model runs supplied characteristic figures of current velocity as a function of water regime of the studied river. Thus, the lower boundary condition was defined as an outward-directed velocity vector of 0.8 m s^{-1} .

Since the design flood passes through the entire width of the floodway, both boundary conditions do not only refer to the channel at bankfull stage, but to the whole delineated floodway.

2.5 Initial conditions

The precise identification of initial conditions is inevitable for the success of any numerical modelling. In most of the cases, this means the specification of initial water flow in percentage of bankfull discharge, specific discharges or velocity vectors. In our project, the goal was to specify as an initial condition a water level as close to DFL as possible. This way the time necessary for the simulation can be minimized.

The specification of an initial condition is based on the relatively high stability of the MIKE 21 FM model. With the critical elements removed from the mesh, time steps between 1 and 30 seconds allow rapid running of the model with acceptable imprecision. Problems arise with small-scale elements, for instance, the environs of bridges, where water levels do not converge with the expected values. For the final calculation, however, the time step is highly reduced, and errors disappear after a few time steps.

Consequently, initial conditions of water depth and velocity components with x and y directions were identified if inflow equals the discharge corresponding to DFL.

2.6 Parametrization

For the MIKE 21, FM hydrodynamic model parametrization was very simple. The dimensions of the modelled phenomenon allowed us to disregard Coriolis force, tensions deriving from wind pressure and ice cover and focus on two parameters.

The software permits distinctions between the inundation and emergence of elements (flooding and drying). Modelling utilizes three parameters which determine limits to the individual elements. Drying depth shows the water depth at which a previously inundated element emerges above the water surface and is qualified dry, while above the flooding depth a previously dry element is inundated but do not take part fully in the calculation. The third parameter is wetting depth: below which an inundated element only takes part in the continuity equation, i.e. the model takes into account the amount of water stored in the element. If this water depth becomes equal to wetting depth, the model applies dynamic equations for the given element, which takes part fully in the current capable of covering further elements with water.

A basic requirement is that these parameters have to unequivocally control the advance rate and final extension of flooding. Therefore, the selection of parameter values must be made with profound knowledge on the study area (vegetation cover, sealed surfaces, microtopography). Using the figures proposed by model developers, drying depth was fixed at 0.05 m, flooding depth at 0.1 m and wetting depth at 0.2 m.

Another aspect which deserves special attention is eddy viscosity. Since in reality, significant processes take place at scales below mesh resolution (impossible to depict in the model), the losses of energy at subgrid scales cannot be neglected. In our case, the Smagorinsky formula, proposed by the developers, was applied with a constant coefficient of 0.28 (Spalart, 2009). The official definitions of floodplain zone according to the new government decree (Government of Hungary, 2014) A 83/2014. (III.14.) and the limitations on construction activities in the individual zones are shown in Table 1.

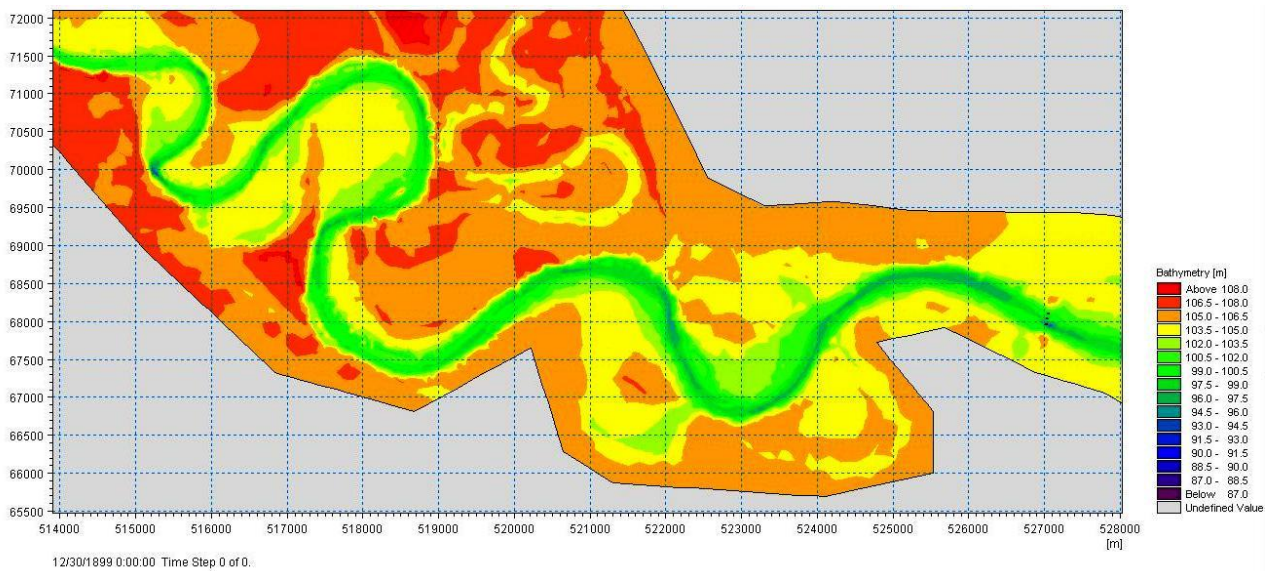


Figure 8 Detail of the DEM for the active floodplain (floodway) of the Drava River

3. Discussion and results

3.1 Zoning the floodway and floodway fringe

For the identification of channel zones, as proposed by the DDVÍZIG, specific stream velocity, i.e. current velocity multiplied with water depth (m^2s^{-1}), derived from previous modelling, was taken into consideration (Fig. 10).

Specific velocity is more than $6.0 \text{ m}^2\text{s}^{-1}$ for the primary floodway zone, 6.0 to $2.0 \text{ m}^2\text{s}^{-1}$ for the secondary floodplain zone, and 2.0 – $0.2 \text{ m}^2\text{s}^{-1}$ for the transitional zone. Probably because of the low current velocity of the Drava River, however, the resulting figures proved to be extremely low. Therefore, when establishing the classes of specific velocity from 2D model runs, the distribution of specific velocity was taken into consideration. For more precise zoning, however, the course of the river was divided into two sections. On the section upstream the town Barcs all the four floodplain zones were identified, while in the section downstream no stagnant water area was delimited and, consequently, only three zones could be identified. Downstream Barcs the area of the primary floodway zone was almost exactly equal to that of the secondary zone (19.13 and 19.39% of total area – Table 2). The velocity classes were also low here (between 0.68 and 2.01 ms^{-1} for the

primary zone and 0.299 to 0.68 ms^{-1} for the secondary zone in the case of the $3000 \text{ m}^3\text{s}^{-1}$ input discharge) (Table 3). The share of the transitional zone was found to be 28%, while the largest area was occupied by stagnant water (61.48%), where specific current velocity ranged between 0.074 and $0.299 \text{ m}^2\text{s}^{-1}$.

With lower variation in velocity in the downstream section, the values of specific flow do not show so remarkable differences as on the upstream section. Entrainment force values are not considerably different for the three zones, the average values are between 0.018 and 0.04 kPa , while maximum values were similar for all the three zones (0.18 – 0.2 kPa).

3.2 Comparison of results of 1D and 2D modelling and DFL

The differences between the 1D model of the Józsa *et al.* (2013) and our 2D model (Mike 21) and the differences between the DFL and the MIKE 21 model were calculated for the upper and lower sections of the Drava River. Differences were observed between 1D and 2D model outputs with the largest difference of 1.16 m at river kilometre 236. The difference between the DFL and the MIKE 21 model amounted to 3.77 m on the upper river section (at river km 183).

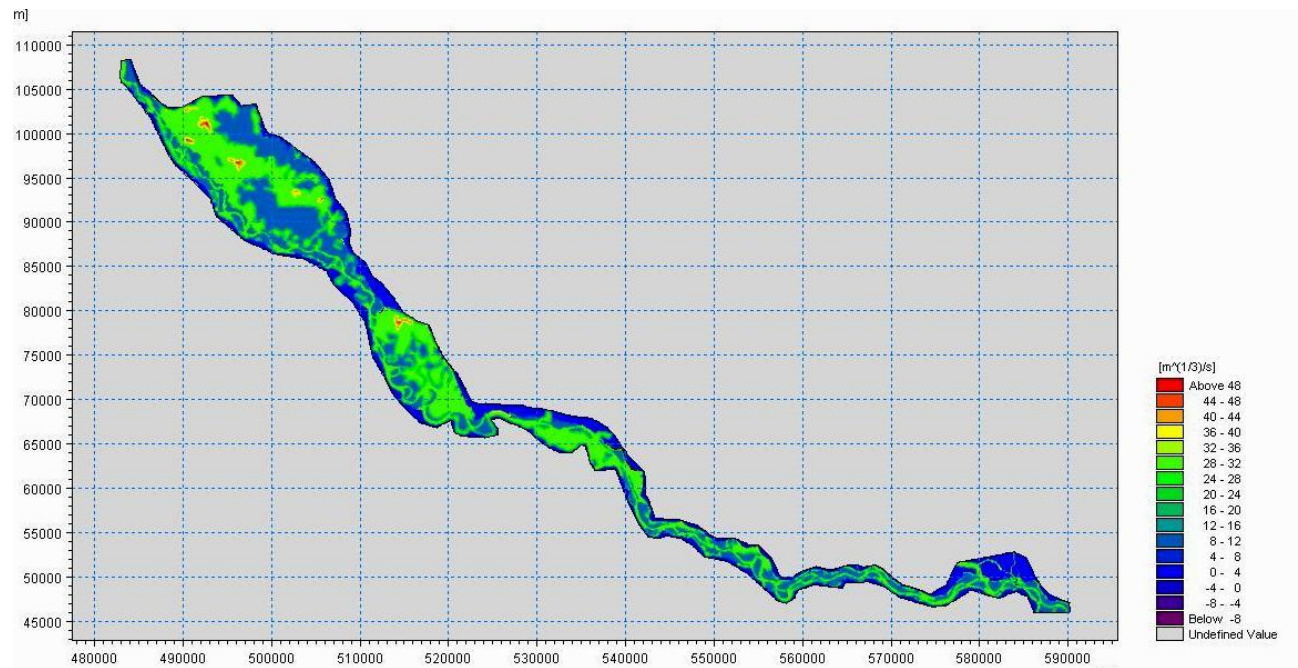


Figure 9 Manning's smoothness map of the floodway of the Drava River

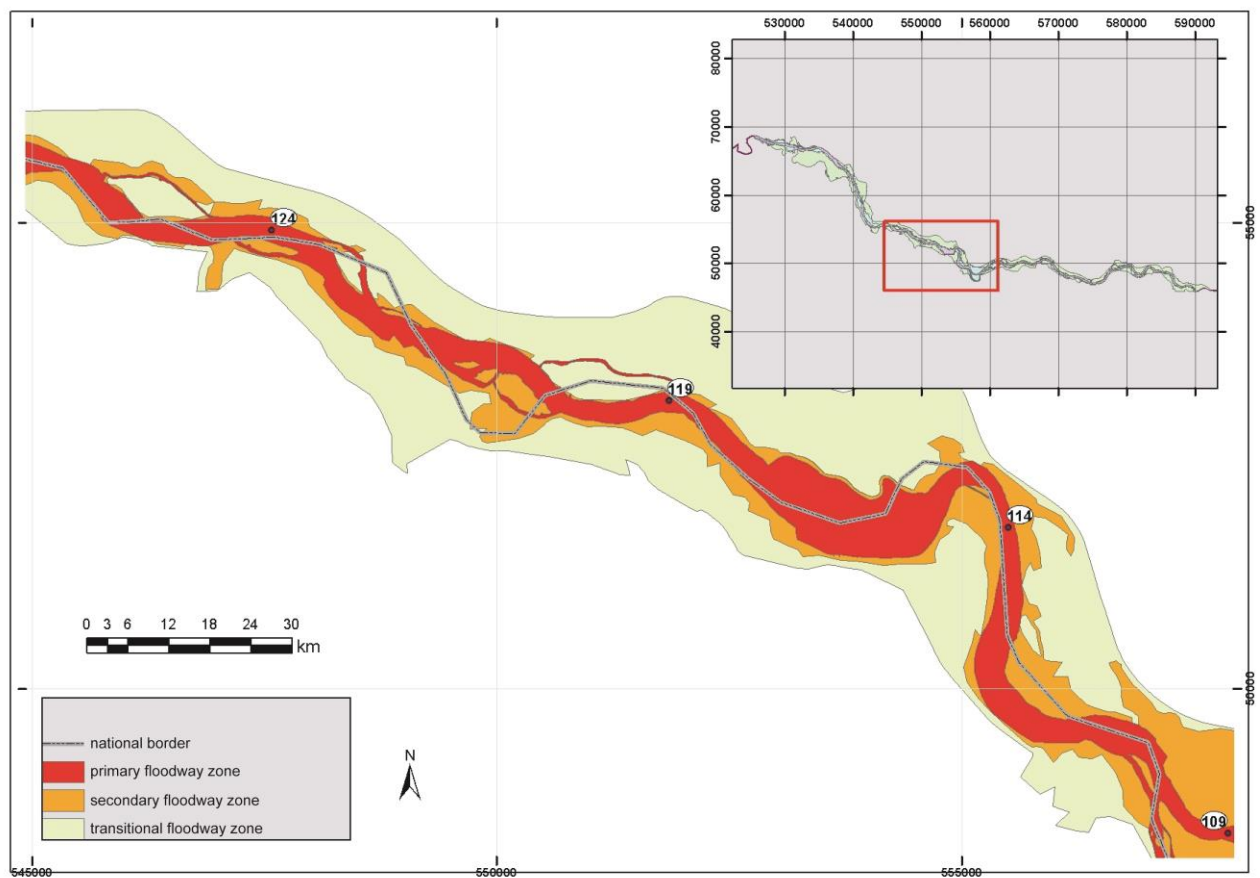


Figure 10 Hydrodynamic zonation of the studied reach of the Drava River and its active floodplain

Table 1 Definition of zones and construction limitations

<i>Building or structure rising above ground level</i>				
Floodway Zone	Technical requirements of structure	New structure emplacement	Restoration, transformation and enlargement of existing structure	Measures
Primary	All-time unhindered passage of water; no obstacle above ground level; if possible, adjusted to the riparian zone	Not permitted	Not permitted	Demolishing structures built without permit; removing obstacles to flow deriving from improper use
Secondary	Maintenance of conditions ensuring throughput capacity as defined in the floodplain management plan	Stations of observation, recording (e.g. water gauge), structures necessary for the use of the river, port, ferry, water police water facility; the linear structure of public use which does not directly influence the passage of flood waves; flood defense lines within the internal zones of settlements. Occasional temporary structures are permitted to be emplaced for max. 15 days	Only allowed in case of a valid permit, without enlarging the ground area. The inhabited parts of the building have to be raised above the safety level prescribed in floodplain management plan	Removal of private resorts and obstacles deriving from improper use
Transitional	Persons responsible for water management tasks (occasional or regular measurement, investigations, checks, maintenance works) are permitted to enter a zone 10 m wide for major rivers, 6 m wide for other watercourses, lakes, reservoirs and dead arms, 3 m wide for other water bodies; access for the operation of flood-control, excess-water draining and other public structures is regulated by the water management authority; if not regulated in floodplain	Same as for existing structures. Occasional temporary structures are permitted to be emplaced for max. 90 days; recreational, commercial or servicing facilities in resort areas are permitted to be built without enlarging the built-up area. The inhabited parts of the building has to be raised above the safety level prescribed in floodplain management plan	Same as for existing structures, but the ground floor is permitted to be inhabited. The use and enlargement of buildings conforming to construction prescriptions and not older than 10 years are permitted	In undeveloped areas removal of obstacles to flow. In development areas structures established without construction permit are to be demolished

	management plans, agricultural use presenting no obstacle to and not endangering the functioning of the riparian zone and the channel is permitted; stations of observation, recording (e.g. water gauge), structures necessary for the use of the river, port, ferry, water police facility are permitted to be emplaced. Seasonally inundated area ensuring sufficient throughput (of culverts, bridges etc.			
Stagnant water area	Outside the passage way of floods. Before approval an analysis has to be performed: focusing on whether the total volume from the stagnant water area does not reduce floodwater storage capacity to an undesirable degree	Same as above. The new building can be erected on undeveloped plots in existing resort area, conforming to prescriptions for zones. The protection of structures located here against floods has to be ensured.	Same as above. Enlargement is permitted for buildings with construction permit, maximum 25 m ² groundfloor area, built more than ten years earlier	If necessary, structures built without permit are demolished

4. Conclusions

In general, our 2D model outperformed the 1D model as the latter model provides a more realistic description of actual physical processes. From the results of the 1D modelling of DFL (Torma *et al.*, 2014), long-term trends in the behaviour of the Drava River could only be established if changes in flow conditions induced by neotectonic movements and climate change as well as sedimentation and channel incision trends are incorporated into the model.

Table 2 Areal proportions of zones identified by modelling

	Area (km ²)	Proportion (%)
Primary floodway zone	21.125	19.13
Secondary floodway zone	21.413	19.39
Transitional zone	67.896	61.48
Total	110.435	100.00

The variation between DFL and the MIKE 21 model were more moderate on the lower section, but on the upper, less regulated, section higher differences were found. River behaviour is more unpredictable along this section, which is manifested in comparisons of our findings with both the 1D model and the DFL. The major shortcoming of the employed 2D model was the need for reduced spatial resolution (25-meter for the floodplain) that significantly worsened output data quality. Although the 2D MIKE 21 model performed better than the 1D model, 3D models would provide more accurate outputs than any 2D models. Therefore for future floodplain simulations and hydrologic-hydraulic analyses, if increased computational capacity is available, the use of 3D models will be indispensable.

According to the results of our 2D model, we delineated four major flow zones upstream Barcs, and three between Barcs and Drávaszabolcs. Due to

the confined floodplain downstream Barcs, no stagnant water area was delimited there. Specific velocities were markedly lower than stated in the Government Decree (0.2 to 6.0 m²s⁻¹), and ranged between 0.089 and 3.476 m²s⁻¹, and 0.075 and 2.01 m²s⁻¹, upstream and downstream Barcs, respectively. The primary and secondary conveyance zones covered a combined area of about 40% of the entire floodplain, while the remaining 60% included both the transitional and stagnant water zones upstream Barcs and solely the transitional zone downstream Barcs. If stream power increases due to the intensification of the hydrologic cycle, on the section downstream of Barcs, where the channel is

more strictly regulated, lateral erosion will be reduced, and channel incision will become predominant.

Flood waves significantly contribute to lateral channel shift with rapid bank erosion. At the same time, within meanders, intense deposition is observed in times of lower flow. The bars rising above mean water level are occupied by pioneer vegetation and this hinders fluvial erosion.

The findings of the model runs are unsuitable to draw conclusions on the trend of undoubtedly observed vertical channel change (incision). The model was run for the impacts of a single flood wave of 3,000 m³s⁻¹.

Table 3 Basic hydrodynamic properties of the identified zones

	Average model current velocity (m s ⁻¹)*	Maximum model current velocity (m s ⁻¹)*	Average entrainment force (kPa)	Maximum entrainment force (kPa)	Average specific flow (m ² s ⁻¹)	Maximum specific flow (m ² s ⁻¹)
Primary floodway zone	0.68	2.01	0.018	0.18	3.3	11.26
Secondary floodway zone	0.41	2.99	0.04	0.20	0.9	8.09
Transitional zone	0.075	0.299	0.020	0.200	0.085	4.350

*Zoning was based on model current velocity and local hydrographic conditions

Long-term vertical changes equally reflect the impacts of alterations in stream power, tectonic movements, climate changes and human interventions manifested in changes in water discharge and current velocity (Lovász, 2014; Kiss and András, 2014).

With the intensifying hydrological cycle and the extreme temporal precipitation distribution (Nováky and Bálint, 2013) higher-than-usual flood waves are expected to occur more frequently. In September 2014, for instance, the preventive release of discharge stored in the reservoirs of the Croatian hydroelectric plants successfully reduced the flood peak which had been envisioned to surpass the previous record flow in 1972. Similarly, with more sophisticated, model-based flow estimates, operation of the Croatian Hydropower plants may also be optimized in the future.

When most future climatic scenarios are considered, flow values, exceeding 3,000 m³s⁻¹ are expected with a shorter return period. Despite the incision of the river, higher flood levels are expected for the river due to its more extreme behaviour and water regime. Consequently, development in the transitional zone should be limited, or their insurance costs should be charged accordingly. Nonetheless, environmental consciousness and ecological concerns should also enjoy priorities in both floodway zones and also in the transitional zones, while wetland restoration actions and sustainable water management are strongly advised in the broader floodplain.

Recent technological and methodological developments in the field of environmental modelling, provides valuable indicators for decision support actions and the stakeholders' challenges (Klug and Kmoč, 2015). Exact delineation of the

floodways, transitional zones and floodplains, based on the digital terrain models and hydrological modeling, enhances the future development of appropriate water management approaches and policies, and may provide adequate approach for multi-purpose decision making and adequately supports operational actions. We believe that strategies of these types are especially crucial when multi-national water management authorities, with different motivation and economic interests, are forced to collaborate in order to elaborate best management practices. In correspondence with flow modeling, sediment transport models are further optimized and may provide more accurate results for channel development and estimation of sedimentation rates behind dams. When flow models are combined with sedimentation models, information may also be gathered on sand bar locations and development rates, as well as more detailed information will be available on navigation routes and pathways on the Drava.

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The correlative behavior of sandbars and shoreline along Sulina – Sf. Gheorghe beaches (Danube Delta Coast)

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ABSTRACT

Longshore sandbars along wave-dominated sandy beaches are important for beach-dune system protection during storms. Our analysis is based on 6 years of seasonal and annual bathymetric surveys along 16 km of erosive, stable and accumulative low-lying non-tidal beaches northward of Sf. Gheorghe arm mouth (Danube Delta – Romanian Black Sea coast). Our results show significant correlations established between longshore sandbar crest positions and morphology with more intense coupling between the inner and outer sandbar sub-systems during high-energy conditions and more frequent along the northern erosive sector in comparison with the southern/central accumulative/stable ones. There is a good connection between the long-term shoreline mobility and sandbars offshore migration rates along different sectors of the study area, with faster sandbars movement and shorter cycle return periods along the northern erosive sector in comparison with the central (stable) and southern (accretionary) sectors. The longshore variations of the nearshore slope are the main driver of the relationship between long-term sandbars dynamics and shoreline variability along the study site.

KEYWORDS

longshore sandbars; offshore migration; bar migration cycle; shoreline dynamics; sediment transport

1. Introduction

Sandbars are underwater sandy ridges parallel to the shoreline that characterize many wave-dominated beaches, affecting surfzone circulation and beach morphology and behaviour. Surfzone

sandbars are some of the most intriguing, dynamical and complex morphological features of the coastal area. They develop two-dimensional (2D), alongshore- uniform or three-dimensional

(3D), cross-shore varying geometries, each of them with specific patterns and behaviour. The international literature contains multiple references regarding the coupling between sandbars along different coastal environments and sandbar systems. The apparent coupled (Sonu, 1973; Van Enckevort and Wijnberg, 1999; Castelle *et al.*, 2007; Ruessink *et al.*, 2007; Quartel, 2009; Almar *et al.*, 2010; Price *et al.*, 2011) and non-coupled ((Homma and Sonu, 1962; Bowman and Goldsmith, 1983) behaviour in 3D patterns of double sandbar systems was considered as reminiscent of the relationship between inner bar patterns and shoreline dynamics (Short, 1999; Coco *et al.*, 2005; Thornton *et al.*, 2007). Castelle *et al.* (2010) successfully simulated the coupling patterns observed in the field inside a crescentic double-sandbar system, showing that there is a morphological coupling between the outer bar geometry and the inner-bar rip channel development through the positive feedback between flow, sediment transport and the evolving morphology. This morphological coupling in multiple sandbar systems was reviewed by Price and Ruessink (2013) and Price *et al.* (2014). The shoreline – sandbars coupling was found to be related to the reduced separation between the inner sandbar and the shoreline (van de Lageweg *et al.*, 2013), while the alongshore differences in outer bar behaviour influences the inner bar state and sensitivity of bar and beach profile (Gervais *et al.*, 2013).

Rozynski (2003) found that, along a non-tidal four-barred Polish coastal site, there is a strong correlation between sandbars movement, the outer bars behaviour controlling the long-term evolution of the inner bars (with more than 60%). On the Danube Delta coast, first information regarding the sedimentary exchanges and linkages between inner sandbar and shoreline were presented by Vespremeanu-Stroe (2001, 2007). Despite the relative high amount of information in the international literature, the factors and processes involved in the correlated behaviour of multi-barred systems (in connection or not to the shoreline) are not entirely and properly understood and further investigations should be done on different coastal environments in order to fully solve this gap. The

aim of the current study is to analyse whether exists a coupling of sandbars and shoreline (taken individually and together) during their long-term cross-shore behaviour along a deltaic double/triple-barred non-tidal coast.

2. Study area

The study site is represented by the inter-distributary Sulina – Sf. Gheorghe beach, Danube Delta, Romanian Black Sea coast (Fig. 1A, B). It is a virtually non-tidal environment, characterised by medium-wave conditions ($H_{s,0} = 1.43$ m; $T_0 = 5.5$ s). Predominant and most energetic winds and waves are coming from N to NE directions (Fig. 1C). The nearshore is composed of predominantly quartz sand with an average median grain size of the shoreface of $d_{50} \sim 200 \mu\text{m}$ (Fig. 1D).

The upper shoreface slope is gradually decreasing from 0.45–0.5deg along the northern study site (P8 – P18 profiles in Fig. 1B) to 0.35–0.4 deg along the central (P3 – P7) and southern sectors (P1 – P2) of the study site (Tătui and Vespremeanu-Stroe, 2016). Following beach characteristics (width, slope, particle size), the northern part of the study site presents intermediate conditions (narrower beaches, higher slopes, coarser sediments) and erosive character, whereas the central and southern parts have a dissipative behaviour and show stable to advancing shoreline dynamics (Tătui *et al.*, 2016). The upper shoreface of these erosive, stable and accretionary sectors presents two-three longshore sandbars, parallel with the shoreline, quasi-linear in shape, with no apparent 3D morphology. They experience significant intra-site variability expressed by narrow and steep bars (with low volumes) that migrate fast (migration rates of 43 m/yr and corresponding cycle return periods of 3 years) over the narrow bar zone along the erosive northern sector and wide, flat bars (with high volumes) with slow migration (migration rates of 25 m/yr and cycle return periods of 5.5 years) over the very large bar zone along the accumulative southern sector (Tătui *et al.*, 2016).

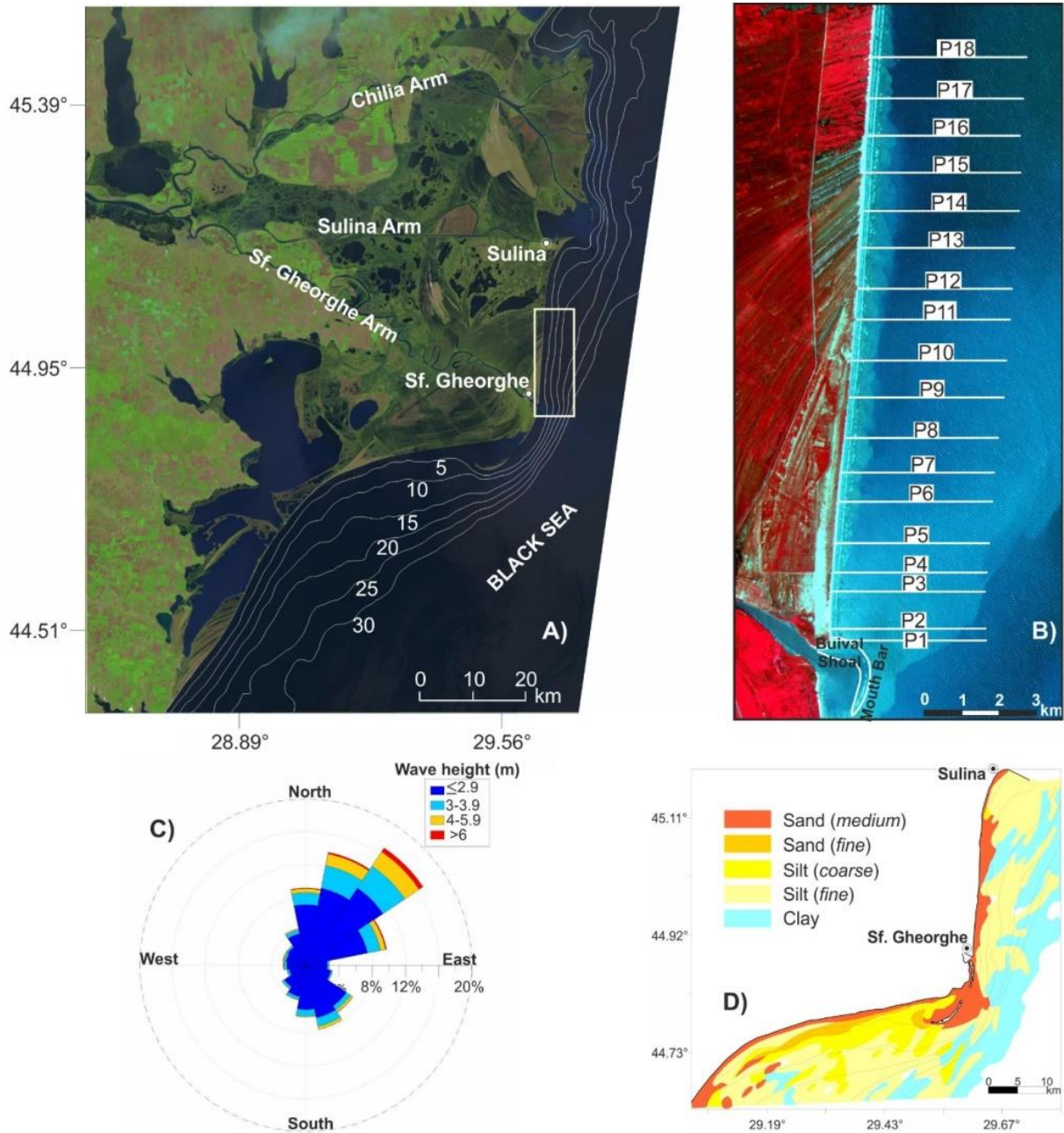


Figure 1 (A) The Danube Delta, Romanian Black Sea coast; (B) Location of the study site, as indicated by the white rectangle (P1 – P18 represent the cross-shore bathymetric profile used in the study); (C) Storm wave rose diagram (above 1.6 m); (D) Sedimentological map of the study area (modified after GEOECOMAR, 1995)

3. Data and methods

Our dataset covers 6 years (September 2003 – October 2009) of seasonal (especially spring and autumn) to annual bathymetric surveys (from shoreline to water depths of about 20 m) along 18 cross-shore profiles, relatively equally spaced on 16

km northward from Sf. Gheorghe arm mouth (Fig. 1B), profiled with a Garmin echo-sounder. The resulting database comprises 5 to 15 temporal observations for each cross-shore profile. Based on the methodology described in Ruessink and Kroon (1994) and Grunnet and Hoekstra (2004), we extracted a number of simple morphometric

parameters (bar crest position and depth; sandbar height, width and volume – Fig. 2) for each profile, as detailed in Tătu *et al.* (2011, 2016). The database was first reduced to a perturbation data set (containing residual profiles) by subtracting from each measured profile the smoothed mean profile for each longshore position. The mean profile was

obtained by averaging all temporal measurements for each cross-shore position along the profile and was further smoothed (fitted profile in Fig. 2) using a low-step 5th-order Butterworth filter with a 200 m cut-off wave length (Ruessink *et al.*, 2003; Grunnet and Hoekstra, 2004).

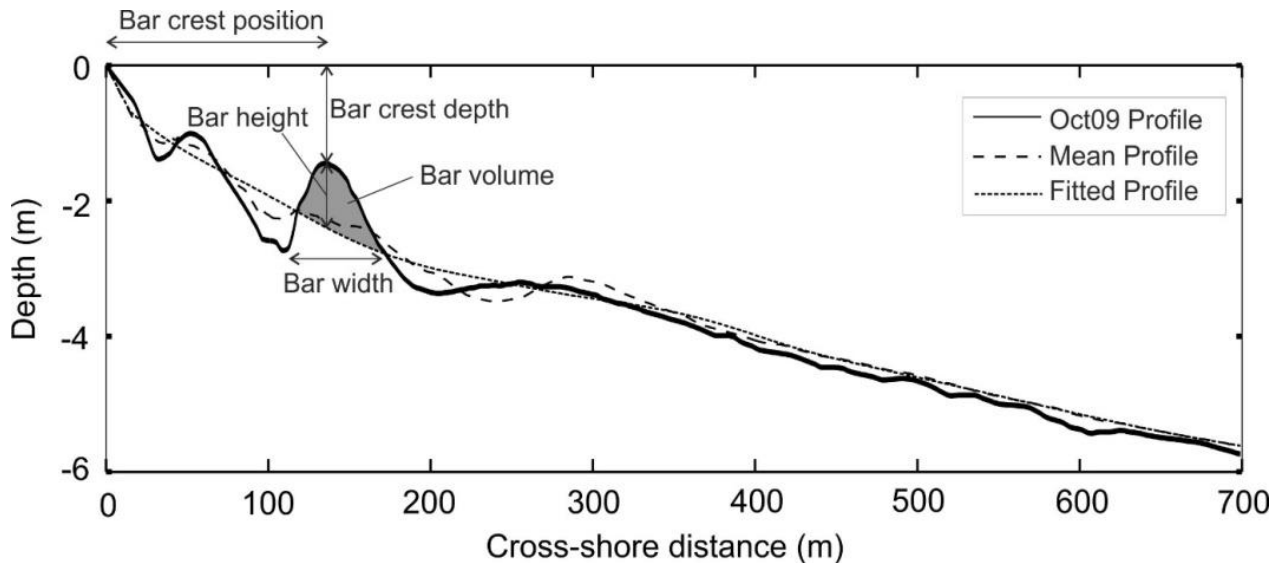


Figure 2 Illustration of sandbar morphometric parameters using P7 profile measured in October 2009

A positive (negative) perturbation corresponds to a sandbar (trough). Shoreline position was extracted for each profile from the seasonal and annual GPS surveys performed in the frame of Sf. Gheorghe Marine and Fluvial Research Station, University of Bucharest. The morphometric parameters were correlated by simple statistical means (Pearson correlation coefficient, significance levels).

4. Results and Discussions

4.1 Correlative dynamics of the sandbar system

Our analysis focuses on the correlations established between longshore sandbar crest positions and morphology registered at each survey along different sectors of the study site. There is a spatial

variability of bar crest positions on Sulina – Sfântu Gheorghe coast between September 2003 and October 2009 under the influence of energetic conditions expressed by mean daily wind speed measured at Sulina meteorological station and mean daily offshore significant wave height obtained from NCEP hindcast data (Fig. 3). We can observe a relative concordance of sandbar movement for both P1 – P7 and P8 – P18 sectors: most of the time they move simultaneously in the same direction – offshore during energetic conditions (e.g. stormy intervals in Fig. 3a,b) and onshore during calm intervals. Sandbars experience a pronounced offshore movement during winter, due to intense storm activity (Vespremeanu-Stroe *et al.*, 2007), as a result of increasing offshore sediment transport during storms caused by wave breaking and powerful undertow currents (Tătu, 2015).

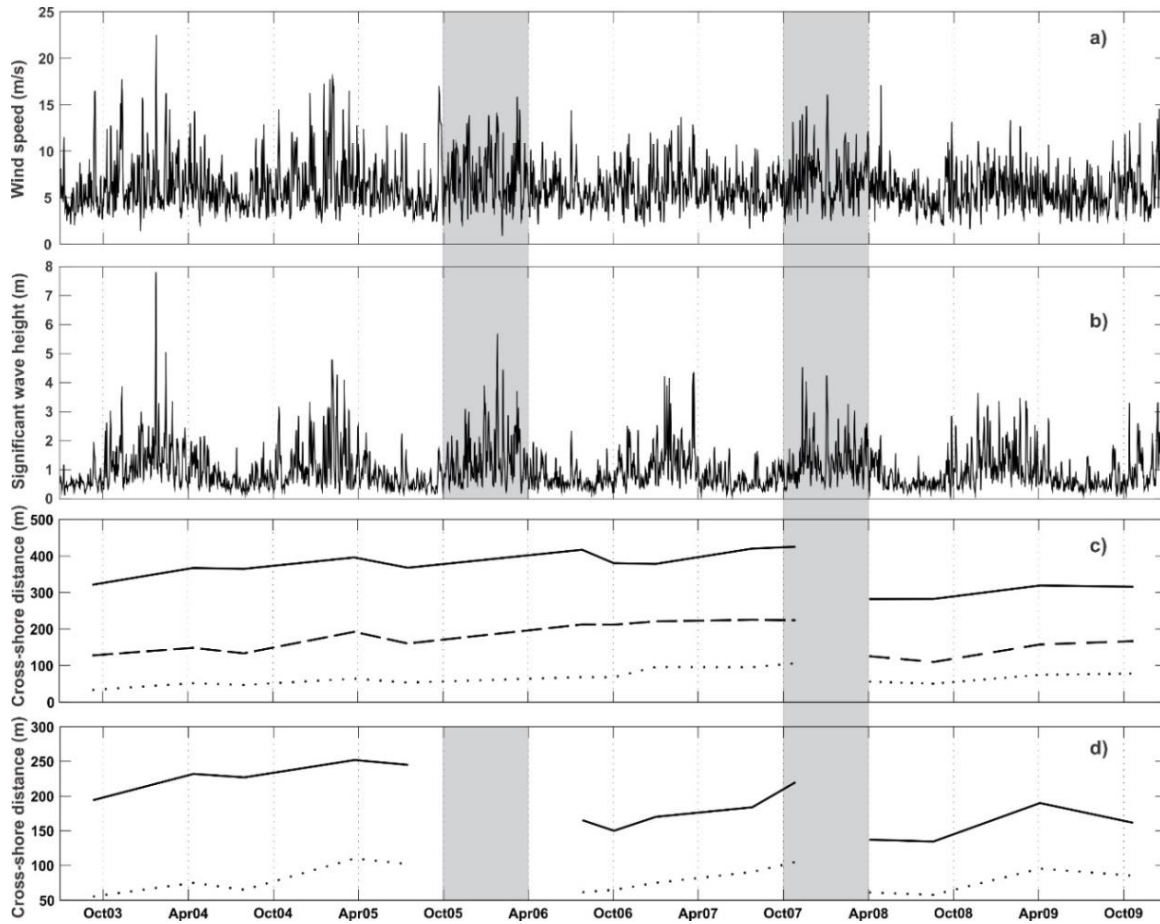


Figure 3 Average bar crest position (outer bar – solid line, middle bar – dashed line, inner bar – dotted line) along (c) P1-P7 and (d) P8-P18 sectors versus (a) average daily wind speed measured at Sulina meteorological station and (b) mean daily offshore significant wave height obtained from NCEP hindcast data for an offshore reference point (40 m depth, 18 km offshore, in front of the Sf. Gheorghe distributary mouth). The grey areas represent the end of a bar migration cycle and the beginning of a new one (time interval when the outer bar disappeared at the offshore limit of the bar zone and a new inner bar formed in shoreline proximity)

During fair weather conditions (summer), sandbars exhibit a moderate/slight onshore movement (Vespremeanu-Stroe *et al.*, 2007) caused by predominant onshore sediment transport due to wave asymmetry during low-energy storms (Tătui, 2015). Overall, the offshore migration rates are higher than onshore ones and, at a multi-annual scale, the sandbars move net offshore in a cyclic manner (Tătui *et al.*, 2016), in a similar way with other sites worldwide: Dutch coast (Ruessink and Kroon, 1994; Wijnberg and Terwindt, 1995); Duck, NC, USA (Plant *et al.*, 1999); New Zealand (Shand and Bailey, 1999); Japan (Kuriyama, 2002); France

(Certain and Barusseau, 2005); consistent with the model proposed by Ruessink and Kroon (1994). From time to time (average cycle return periods ranging from 2.8-3.5 years for the P12 – P18 sector and 4.5-5.0 years for the P3 – P7 area to 5.0–5.5 years for the P1 – P2 sector – Tătui *et al.*, 2016), after continuous movement through the bar zone area (with widths of 250-350 m on the P8 – P18 sector, 350-450 m on the P3 – P7 sector and 500-550 m on the P1–P2 sector – Tătui *et al.*, 2016), the outer sandbar reaches the offshore limit of the bar zone during a stormy interval, causing it to decay and, eventually, disappear (as it was the case in 2005 –

2006 winter for the P8 – P18 sector and during 2007 – 2008 winter along both P1 – P7 and P8 – P18 sectors – Fig. 3c,d). Its place is immediately taken by the next shoreward located bar and a new bar

appears near the shoreline (Fig. 3c,d), marking the end of an offshore bar migration cycle and the beginning of a new one.

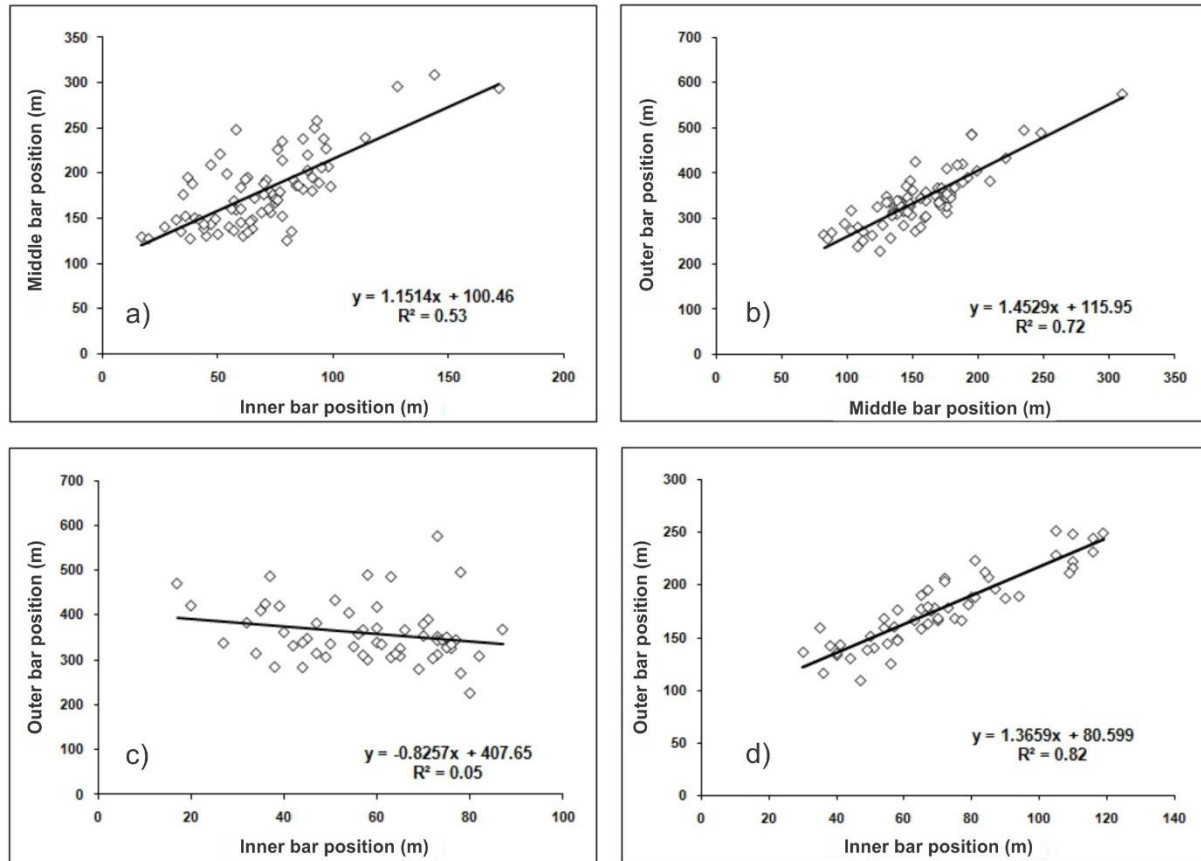


Figure 4 Correlations established between (a) inner and middle sandbars positions; (b) middle and outer sandbars positions and (c) inner and outer sandbars positions along P1 – P7 sector and (d) inner and outer sandbars positions along P8 – P18 sector. Discussion in the text

In order to analyse the longshore and cross-shore variability of sandbars correlative behaviour along P1 – P7 sector, we split the three-bar system in two sub-systems: inner one, composed of the inner and middle sandbars (Fig. 4a), and outer one, comprising middle and outer sandbars (Fig. 4b). There is a good positive statistical dependency between inner and middle bar crest positions as 53% of the inner bar position variability is explained by the middle bar position variability, with a Pearson correlation coefficient of 0.73 ($p < 0.001$) between the two datasets (Fig. 4a). The positive dependency is more powerful for middle and outer bar crest positions as 72% of the middle bar position

variability is explained by the outer bar position variability, with a Pearson correlation coefficient of 0.85 ($p < 0.001$), Fig. 4b. The different variance and correlation coefficients values show that the middle bar is more sensitive to the outer bar behaviour and vice-versa in comparison with its relation with the inner bar. The inner bar is very heterogeneous, unstable, mobile and sensitive to the shoreline and lower beach behaviour, so it is trickier to put it in direct relation with middle bar movements. The middle sandbar represents "the bridge" between the two subsystems, moving offshore and onshore and transferring sediment from the inner to the outer bar and the way back.

At longer time-scales (seasons to years), there is no correlation between the inner and outer bar crest positions (Fig. 4c), showing that, most of the time, the two systems act independently one in relation to the other. For instance, under low to medium-energy conditions, when the currents are onshore directed as a result of wave asymmetry, the onshore sediment transport is susceptible to be more effective in the inner sub-system to the beach, rather than in the outer sub-system, as the outer bar feels very small to no influence of waves during these energetic conditions due to the high water depth over its crest. With the increasing energy (medium to high conditions), waves could break on the inner and middle sandbar crests and could be asymmetric on the outer bar crest, determining a sediment transport convergence and exchange between the two sub-systems. Under high energy conditions, the two subsystems are both experiencing intense offshore sediment transport as waves break over all sandbars, creating powerful undertow currents. The sediment fluxes are directed from the inner sub-system to the outer sub-system

and, sometimes, there is a loss of sediment offshore from the bar zone area (outer sub-system) to the lower shoreface, through bar decay and disappearance, or alongshore, to adjacent areas. During these conditions, the middle and outer sandbars experience the highest correlations between their positions.

Along the double-barred northern erosive P8 – P18 sector, there is a strong interdependence between the inner and outer sandbar crests positions (Fig. 4d), expressed by a very strong positive statistical dependency – approximately 82% of the outer bar position variability is explained by the inner bar position variability, with a Pearson correlation coefficient of 0.9 ($p < 0.001$). This fact shows a higher coherence of sandbar behaviour along the northern sector in comparison with the southern one, which could be related to the higher nearshore slope and narrower bar zone area (with smaller distance between the two sandbars) which determine synchronous movement (onshore or offshore) of the entire bar system function of the energetic conditions.

Table 1 Correlation coefficients established for the same morphometric parameters between different sandbars along P1 – P7 and P8 – P18 sectors: B_i – inner bar, B_m – middle bar and B_o – outer bar; the values in italics are 95% statistically significant. Please see explanation in text.

Morphometric parameter	P1 – P7 Sector		P8 – P18 Sector	
	B_i/B_m	B_m/B_o	B_i/B_o	B_i/B_o
P_c	0.73	0.85	-0.22	0.90
d_c	0.39	0.92	<i>0.11</i>	0.63
W_b	0.56	0.64	0.46	0.49
h_b	0.68	0.50	0.26	<i>-0.10</i>
V_b	0.68	0.57	0.35	0.24

Furthermore, we computed the correlation coefficients between the main sandbar morphometric parameters (bar crest position – P_c and depth – d_c , bar width – W_b , height – h_b and volume – V_b) for different sandbar couplings along the two sectors of the study area (Table 1). The highest correlations are registered for sandbar crest position (as we have seen before) – coefficients ranging from 0.73 to 0.9, with the exception of inner/outer sandbar coupling along P1 – P7 sector (no correlation). Good correlations are also encountered for middle/outer (P1 – P7) and

inner/outer (P8 – P18) sandbar depth and for middle/outer (P1 – P7) bar width. Regarding sandbar height and volume, the strongest correlations are registered between inner and middle bars along P1 – P7 sector and are decreasing offshore. The poorest correlations are registered by the inner/outer sandbar coupling along P1 – P7 sector for all morphometric parameters (Table 1).

These correlations imply that, statistically speaking, the two sub-systems are not permanently coupled in their long-term cyclic offshore behaviour. The two sub-systems can behave independently or

coupled during their seasonal onshore/offshore movement function of the energetic conditions in the surf zone, as we have previously discussed. High energy conditions (storms) are more conducive for the coupling of the two sub-systems, while this coupling is more frequent along P8 – P18 sector for a wider range of energetic conditions in comparison with the P1 – P7 sector.

4.2 Sandbar system – shoreline correlations

Researchers tried to establish empirical relations, based on theoretical formulations, laboratory experiments or field measurements, between shoreline mobility and sandbar behaviour. Sunamura and Takeda (1993) investigated the relationships established between the direction of net sandbar migration and shoreline dynamics. Using experimental methods, they established an empirical dimensionless coefficient A , defined by the following equation:

$$\frac{H_0 \tan \beta}{w_s T} = A \frac{w_s}{\sqrt{gH_0}} \quad (1)$$

where,

H_0 = offshore wave height

$\tan \beta$ = nearshore slope

T = wave period

g = gravitational constant

w_s = sediment fall velocity, defined by:

$$w_s = \frac{(s-1)gd_{50}^2}{18\nu} \quad (2)$$

in which,

s = relative density, expressed by $\rho_s/\rho = 2650 \text{ kg/m}^3 / 1000 \text{ kg/m}^3 = 2.65$

d_{50} = median particle size

ν = kinematic viscosity = 10^{-6}

Using $L_0 = gT^2/2\pi$, equation 1 transforms in:

$$A = \left(\frac{1}{\sqrt{2\pi}} \right) \left(\frac{w_s}{\sqrt{gH_0}} \right)^{-2} \left(\frac{H_0}{L_0} \right)^{\xi_0} \quad (3)$$

where,

L_0 = offshore wave length

ξ_0 = surf similarity parameter, defined by:

$$\xi_0 = \tan \beta / \sqrt{H_0 / L_0}$$

(4)

Equation 3 indicates that parameter A has three components:

i) Wave-sediment parameter = $w_s / \sqrt{gH_0}$;

ii) Wave steepness = H_0/L_0

iii) Wave-topography parameter = ξ_0

Based on experiments conducted in large wave flumes, Sunamura and Takeda (1993) found the following relations:

a) if $A \geq 14$, sandbars migrate offshore and shoreline retreats;

b) if $A \leq 3.5$, sandbars migrate onshore and shoreline advances;

c) if $3.5 < A < 14$, sandbars migrate offshore and shoreline is stable or advances.

After applying these formulations to field measurements, they adjusted the value of A from 14 to 17.

Based on the above described methodology, we computed the values of A (taking into consideration a threshold value of 14, which we consider more suitable for dissipative and intermediate beaches, as it is our case) for the southern (P1 – P7) and northern (P8 – P18) sectors of our study site, in different energetic conditions, using the following inputs:

- H_0, T_0 = lacking in-situ measurements of wave height and period along the study site and adjacent coasts, we have included in the computations the mean values of H_0 and T_0 obtained by Vespremeanu-Stroe (2007) using theoretical formulations. Despite small differences regarding offshore wave height and period between the two sectors, we have considered in our analysis similar values of the two parameters;
- $\tan \beta$ = the upper shoreface slope has a longshore variability along the study area (Tătu and Vespremeanu-Stroe, 2016). In our computations, we have used the mean values of $\tan \beta$ for the barred area: 0.0065 (for the southern sector) and 0.0085 (for the northern sector);

- w_s = depends on d_{50} . As there are very small alongshore differences in d_{50} values (Preoteasa and Vespremeanu-Stroe, 2010) along the study site, we have considered a constant value of 0.2 mm for the two sectors.

Analysing the above presented methodology and parameters and assuming that, at larger time-scales (years, decades), the wave climate and sediment characteristics do not register major differences between the two sectors, we can conclude that two (*wave-sediment parameter* and *wave steepness*) of the three components of coefficient A are constant along Sulina – Sfântu Gheorghe coast. The only component that registers significant longshore variability is the *wave-topography parameter*, which is mainly influenced by the nearshore slope: even if the offshore waves

do not show significant differences between the two sectors, the higher slope along the northern sector imposes larger wave breaking on sandbars crests and, hence, more powerful undertow currents which determine faster sandbars offshore movement (Tătui *et al.*, 2016) and, eventually, shoreline erosion. The analysis of coefficient A values function of the energetic (wave) conditions of the study area resulted in the identification of five cases with different sandbars and shoreline behaviour along the two sectors (Table 2). In all cases parameter A values are higher along the northern sector (P8 – P18) in comparison with the southern one (P1 – P7) because of the higher nearshore slopes which determine larger waves and more powerful currents (especially undertow) along the first sector during the same energetic conditions.

Table 2 The values obtained for parameter A for different energetic conditions along the study site.

	Frequency (%)	Energetic conditions		Parameter A	
		$H_{s,0}$ (m)	T_0 (s)	Sect. P1 – P7	Sect. P8 – P18
Case 1	0.7	> 3.85	≥ 8.4	> 14	> 14
Case 2	0.3	3.2 – 3.85	8.4	3.5 – 14	> 14
Case 3	13	1.3 – 3.2	6.5 – 8.4	3.5 – 14	3.5 – 14
Case 4	8.5	1.1 – 1.3	6.5	< 3.5	3.5 – 14
Case 5	77.5	< 1.1	< 6.5	< 3.5	< 3.5

Low-energy waves (case 5), which have the highest frequency during the year (but lowest morphological impact), create conducive conditions for shoreline progradation and onshore sandbars movement. During these conditions, the inner sandbar is placed very close to the shoreline and the sediment transport is oriented onshore. Under long-lasting low-energy conditions, the inner bar splits its crest in a ridge, which maintains its relative position, and in a moving body of sand which fills the innermost through (the area between the shoreline and the inner bar), transforming it in a sort of platform and, eventually, attaching to the sub-aerial berm. This is the main mechanism of shoreline progradation along the study site and these type of processes and behaviour were first documented by Vespremeanu-Stroe (2001, 2007) through field measurements of the shoreline – inner bar area.

During medium-energy conditions (case 4 and, especially, case 3), which account for almost 25% of

the year, an important part of sediment is transported offshore by undertow currents which determine offshore movement of the inner and middle sandbars. This mechanism takes place under lower energy conditions along the northern sector due to the higher nearshore slopes. A small part of the sediment transport is still onshore oriented, feeding the inner bar and the berms and maintaining the shoreline stable or slightly advancing. This is mainly the case of the southern sector which benefits from higher sediment budgets in the proximity of the Sf. Gheorghe river mouth. One of the main causes of this different behaviour of the sandbars – shoreline system during medium-energy condition could be related to the fact that the same waves could be characterised by asymmetry (which favours onshore sediment transport) along the southern sector and by breaking (which determine the formation of undertow currents responsible for offshore

sediment transport) along the northern sector, as a results of the differences in nearshore slope. Further investigation is needed in order to document these differences in wave characteristics under medium-energy conditions along the two areas of the study site.

High waves (case 2 and, especially, case 1) during intense storms determine wave breaking on sandbars crests and the formation of undertow currents which are responsible for offshore sediment transport and, hence, for shoreline retreat, beach erosion and offshore sandbars movement. Lower waves (case 2) determine the shoreline to erode and the sandbars to move offshore along the northern sector in comparison to the southern one, where higher waves (case 1) make this possible. This is related to the larger nearshore slope and narrower bar zone area (265 m on average) along the northern sector, which allows intense wave breaking on inner and outer sandbars; still, the wave energy is not entirely dissipated and part of this energy reaches the shoreline determining beach erosion and shoreline retreat. Along the southern sector, the wide bar zone area (505 m on average) assures sufficient space for wave dissipation

(breaking on inner, middle and, eventually, outer sandbars and reformation in the troughs) during case 2 energetic conditions, protecting the beach against wave attack and erosion (the shoreline is stable).

The predicted short-term (days to seasons) behaviour of shoreline and sandbars (obtained using the methodology developed by Sunamura and Takeda, 1993) for different energetic conditions show good correspondence with the nearshore dynamics and processes observed along the study area. This methodology is able to offer valuable information regarding the immediate response of sandbars and shoreline to changing energetic conditions. Still, the established thresholds should be treated cautiously because these empirical mathematical relations are based mainly on flume experiments, without being properly validated with field measurements.

At longer time scales (years), the analysis of the cross-shore profiles (from waterline to depth of closure) show very good agreement between the multi-annual shoreline behaviour and sandbar movement along Sulina – Sf. Gheorghe inter-distributary coast (Fig. 5).

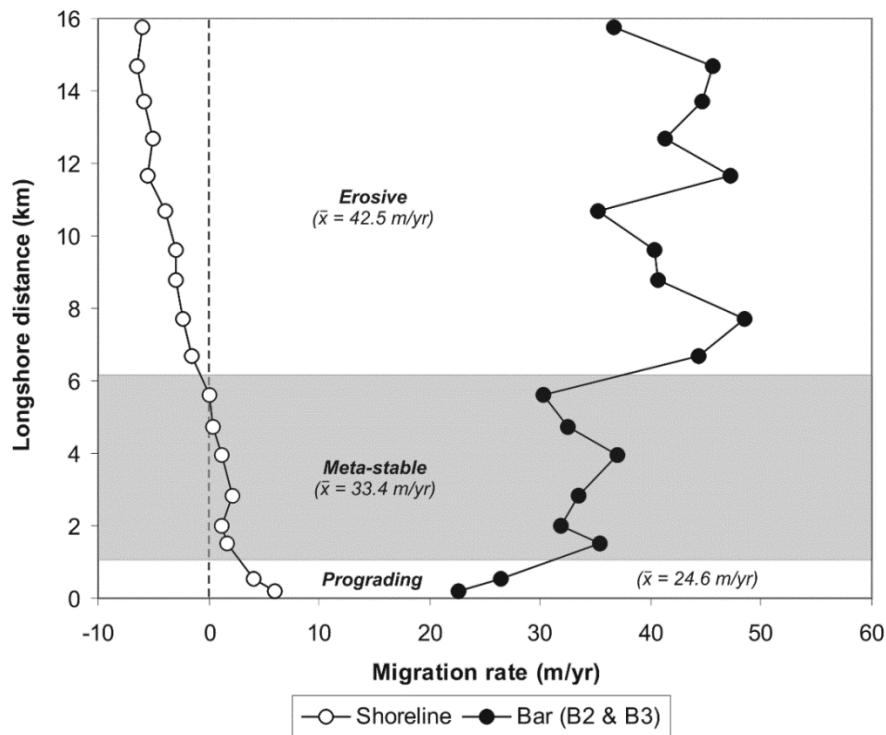


Figure 5 Shoreline dynamics versus sandbars offshore migration rates along Sulina – Sf. Gheorghe beaches (2003-2009)

The multi-decadal shoreline dynamics is characterised by gradually decreasing downdrift (from North to South) erosional processes along the northern sector: average retreat rates ranging from 7.5 m/yr at km 16 (P18) to 1.8 m/yr at km 6 (P8) between 1979 and 2009. The stable central sector (P3 – P7 / km 1 to 6 northward of Sf. Gheorghe river mouth) shows a meta-stable shoreline equilibrium since the beginning of the 20th century, while the southern sector (P1 – P2 / km 0 to 1) registered average shoreline advance rates of 1 – 2 m/yr between 2003 and 2009 (Vespremeanu-Stroe *et al.*, 2007; Tătui *et al.*, 2013). The latter sector is highly influenced by the presence and dynamics of the river mouth bar which controls the sedimentary fluxes and wave characteristics (Tătui *et al.*, 2016).

The multi-annual cyclic offshore sandbar behaviour is closely related to the long-term shoreline evolution, the sandbar migration rates increasing progressively from accumulative to erosive conditions along the study area (Fig. 5). The accumulative sector is characterised by the lowest sandbar migration rates (20 – 30 m/yr); along the stable sector, the sandbars migrate offshore with mean rates between 30 and 37 m/yr; the erosive sector registers the highest offshore sandbar migration rates of 40 – 50 m/yr. These connections between shoreline and sandbar behaviour are related to the controlling factors (nearshore slope and sediment availability) which determine different hydrodynamic conditions, sediment dynamics and morphology along different sectors of the study site.

5. Conclusions

The upper shoreface profile of the interdistributary Sulina–Sf. Gheorghe deltaic coast shows significant correlations established between longshore sandbar crest positions and morphology. These connections involve sedimentary exchange between neighbouring sandbars and, under certain conditions, simultaneous movement in the same direction (onshore, during low-energy conditions or offshore, during high-energy events). Along the three-bar system of the central and southern

sectors, the two sub-systems (inner one, composed of inner and middle sandbars and outer one, composed of middle and outer sandbars) act more or less individually, the middle bar movement and associated sediment transfer being the linkage between them. High-energy conditions are conducive for the most intense interactions between the two sub-systems. The coupling between the inner and outer sandbar sub-systems is more frequent during a wider range of energetic conditions (from low/medium- to high-energy) along the northern erosive sector in comparison with the southern/central accumulative/stable ones (where only the medium/high-energy events drive this coupling).

The methodology developed by Sunamura and Takeda (1993) predicted reasonably well the shoreline behaviour and the direction of sandbars movement observed for different energetic conditions along the study site, even if the established thresholds should be used cautiously. Nevertheless, there is an obvious connection between the long-term shoreline mobility and sandbars offshore migration rates along different sectors of the study area. The lowest sandbar migration rates (with associated longer cycle return periods) occur on the prograding sector, while the fastest sandbar movement (with associated shorter cycle return periods) registers on the retreating sector. Parameter *A* analysis helped us to validate our previous findings (Tătui *et al.*, 2016) stating that, along the study site, the main driver of the relationship between long-term sandbars dynamics and shoreline variability is represented by the longshore variations of the nearshore slope.

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Hydrological and suspended sediment regime in the Kolubara River during the extreme year of 2014

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ABSTRACT

The previous methodology of sampling and determining the suspended sediment concentration (*SSC*) in the rivers of Serbia is characterized by a number of disadvantages, so that any research of this kind has a large water management impact. In the largest number of hydrological stations in Serbia, daily *SSC* were obtained based on only one sampling, which raises the question of the representativeness of such sample. Previous *SSC* – water discharge relationship and detailed analyses of errors in calculating the suspended sediment transport on the profile of Draževac were done for the year of 2004, when the annual difference was very high, which required a very detailed analysis and methodological improvements. In order to define the sediment regime in the Kolubara River, precise monitoring of *SSC* has been implemented since 2013. The Kolubara River has an unfavourable water regime which is reflected in the excessiveness of water runoff, with floods that are sudden, expressive and short-term, and long-term low waters, so, that are why it is characterized by a large discharge and *SSC* variability. Incidentally, monitoring also covered the year of 2014, when the area of western Serbia (in particular the Kolubara River Basin) was under the influence of extreme climate events that strongly reflected on the hydrological condition with the absolute highest daily discharge. A total of 220 water samples were collected on Draževac gauging station in 2014, in order to determine *SSC* and sediment discharge. The total number of days covered was 206, which means that there were even more samplings per day, when the discharge was changing fast. The minimal daily measured *SSC* was only 0.0016 g/l and the maximal recorded value of *SSC* was 2.6122 g/l and was measured in May at the water discharge of 1 260 m³/s. The total amount of suspended sediment discharge at the profile of Draževac in 2014 was 1 104 435 t (the specific suspended sediment yield – 308 t/sqkm/yr). The main objective of this study is to improve *SSC* – water discharge relationship in the Kolubara River based on the extreme hydrological conditions in 2014.

KEYWORDS

flood events, water discharge, *SSC*, sediment discharge, Kolubara River, Serbia

1. Introduction

River sediment fluxes are sensitive to many influences, including soil erosion intensity caused by human activities and land use changes, erosion and sediment control works, extreme weather events caused by climate change, etc (Walling, 1995; Chen *et al.*, 2001; Dragičević, 2002; Lu *et al.*, 2003; Zhang *et al.*, 2008; Petković *et al.*, 2009). Some of these influences cause sediment loads to increase, whilst others, namely, erosion control works and reservoir construction cause decreased sediment fluxes (Walling and Fang, 2003; Rădoane and Rădoane, 2001, 2005; Walling, 2006; Milevski, 2011; Tošić *et al.*, 2012, 2013; Kostadinov *et al.*, 2014; Živković *et al.*, 2015). Studies intended to highlight the pattern of sediment concentration and sediment discharge during single hydrologic events, such as a flood, have been reported (Wolman and Miller, 1960; Walling and Webb, 1981; Lenzi and Marchi, 2000; Romanescu and Nistor 2011; Obreja, 2012; Mustafić *et al.*, 2013; Dragičević *et al.*, 2013). These studies have shown that the bulk of sediment in most rivers is transported during single floods and that the relationship between suspended sediment concentration (SSC) and water discharge (Q) during floods is highly variable. Suspended sediment concentrations during flood events depend primarily on sediment supply, which is greatly affected by factors such as climate, topography, drainage basin area or land use (Salant *et al.*, 2008). Comparison of the results for the discharge and SSC records emphasized the complexity of the relationships between the two variables, but provided some insight into the causes of the changes in sediment load (Dragičević, 2002; Walling, 2005; Walling and Fang, 2003; Gautier *et al.*, 2007; Mustafić *et al.*, 2013a). Based on the previous analyses (Dragičević, 2001, 2002, 2007), it has been clearly recognized that under the influence of extreme hydrological conditions for two months, 70% of the annual suspended sediment discharge can be evacuated from the Kolubara River Basin. It happens that most of the sediment discharge is done over several days in a year, or floods that are present almost every year (Petrović *et al.*, 2015). So, during the previous studies were analyzed a lot of extremely water and extremely dry years, and sediment transport during the large number of

flood waves. Therefore, the intent of this study was not a comparison of sediment transport during different flood waves because we published many similar results. The primary idea was to analyze the historical maximum in 2014, in which we could not applied previous relationship between Q and SSC .

The methodology of studying the concentration of suspended sediment in Serbian rivers is different, depending on the observed aspects. There were about 200 gauging stations for stationary monitoring of suspended sediment concentrations on watercourses in Serbia in the seventies of the twentieth century (actually in 1975). In addition to the network of stations that were under the jurisdiction of the Republic Hydrometeorological Service of Serbia (RHMSS), there was also a number of stations that were managed by individual universities and research institutes, as well as sites with periodically exercised stationary and itinerary observations in order to develop a number of projects related to resolving specific water management problems. Methodology of sampling at gauging stations in the Kolubara River Basin was completely different, so that the water sampling frequency ranged from a seven-day rhythm (Dragičević, 2002), over a two-day, to everyday (RHMSS, Dragičević, 2007). Unfortunately, the number of gauging stations for suspended sediment is continuously decreasing, so that none of the stations within the RHMSS no longer worked in 2004. Since 2013, the Laboratory of Physical Geography on the Faculty of Geography of the University of Belgrade has again established the suspended sediment monitoring in the Kolubara River, on Draževac gauging station. We even could not have an idea that already the year of 2014 would be the year that, in research terms, was waited once in many centuries.

The Kolubara River has an unfavourable water regime, and it is reflected in the excessiveness of water runoff, with floods that are sudden, expressive and short-term, and long-term low waters that approach to minimum discharges to ensure the maintenance of biological functions. As an index of unfavourable runoff characteristics, a ratio of the extreme discharge is usually taken which places the Kolubara River in the highest place among the rivers in Serbia (of similar river basin size). The ratio is 101, taking into account the average maximal discharge

in Draževac for the last 46 years, which amounts to $255 \text{ m}^3/\text{s}$ and the average minimal discharge of $2.53 \text{ m}^3/\text{s}$. At absolute extremes, it is about 2 100 ($1\,260 \text{ m}^3/\text{s}$ on May 15th, 2014 – towards $0.6 \text{ m}^3/\text{s}$). Previous measurements in the Kolubara River Basin (Dragićević, 2002, 2007) have shown that reliable conclusions regarding the suspended sediment concentration in the water should not be made if we only have available data of lower water discharge, but the authoritative conclusions can be made only if we have data of a higher range of discharge as well.

In 2014, water samples were collected in order to determine suspended sediment transport on Draževac gauging station in the Kolubara River. The total number of covered days was 206, which means that there were more samplings per day, when the water discharge was changing fast. Since the intention was to make a connection between the amount of water discharged in the river and the suspended sediment concentration, these multiple data were very useful in defining their relationship, because it is known that at the time of the flood, the sediment concentration in the river is rising sharply. Considering that during 2014 the area of western Serbia (in particular the Kolubara River Basin) was under the influence of extreme climate events that strongly reflected on the hydrological condition, the analysis presented in this paper offered the possibility of determining the relationship between suspended sediment concentration and discharge during extreme hydrological conditions. The highest

discharge in a hundred years would be $740 \text{ m}^3/\text{s}$, and the highest discharge in a thousand years would be $960 \text{ m}^3/\text{s}$. In 2014 year, the absolute highest daily discharge on Draževac gauging station was $1\,260 \text{ m}^3/\text{s}$ (15.05.2014.). The main objective of this study was to improve SSC–discharge relationship interpretation in the Kolubara River based on extreme hydrological conditions in 2014.

2. Study area and methods

The Kolubara River Basin is located in the western part of Serbia and covers 4.12 % of Serbia's surface area (Fig. 1). The watershed drainage area is open towards the north, the highest point is at 1346 m and the lowest has an altitude of 73 m. The Kolubara River is the last large tributary of the Sava River, and according to the flow length (86.4 km) and the watershed drainage area ($3\,641 \text{ km}^2$), is classified as a middle-sized river within the territory of Serbia. The Kolubara River flows through the different parts of terrain. This diversity is reflected in geologic structure and age of some parts of the basin, as well as in the geotectonic complexity of the terrain through which the river flows. The drainage basin is built of Mesozoic and Cenozoic age igneous and sedimentary rocks and of Paleozoic metamorphic rocks (Dragićević *et al.*, 2012).

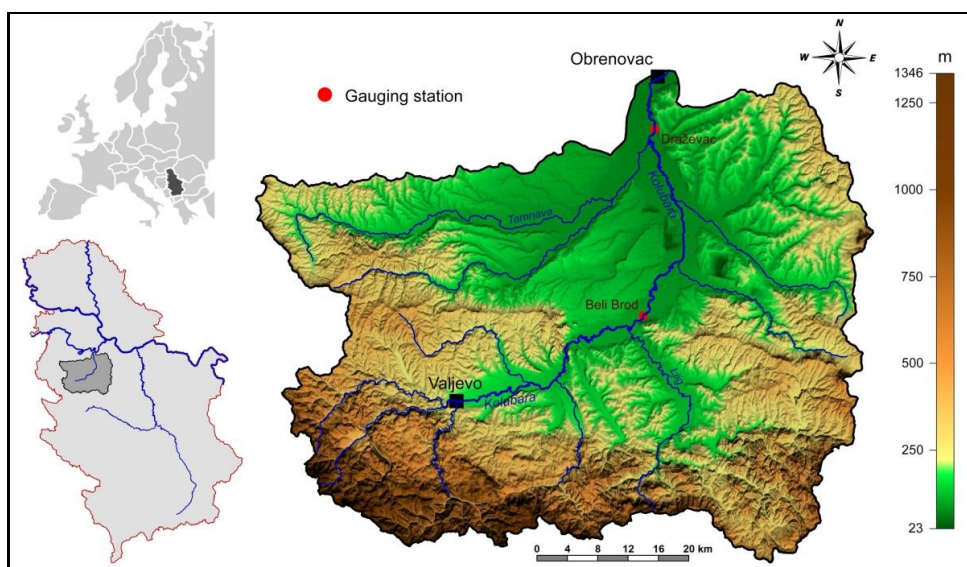


Figure 1 Hypsometric map of Kolubara River Basin in Serbia.

Analysing the amount of annual rainfall in the Kolubara River Basin in the period 1959-2010, it can be concluded that the Kolubara River Basin has a continental-pluviometric regime which is characterised by a maximum rainfall at the beginning of summer and a minimum rainfall in the winter. Based on rainfall data from 27 rain-gauge stations in the Kolubara River Basin, the most quantity of precipitation falls in warmer part of the year – June (13.4% of annual sum), July (10%), May (9.9%), and the lowest quantity in February (5.5%) (Petrović *et al.*, 2015). Average annual rainfall in the Kolubara River Basin is 809 mm for the period 1959-2010. The Kolubara River has the highest coefficient of monthly flow variation in comparison to other larger river basins in Serbia, and very disbalanced ratio between high and low waters. The highest discharge of the Kolubara River in the period 1959-2013 was 646 m³/s and it was registered on Draževac gauging station. According to probability curve of high discharges, the discharge of 646 m³/s may occur once in 46 years. The lowest value of annual maximum discharge would be about 25 m³/s, the highest discharge in a hundred years would be 740 m³/s, and the highest discharge in a thousand years would be 960 m³/s (Dragičević *et al.*, 2007; 2013). And that happened 2014 year with the absolute highest daily discharge on Draževac gauging station of 1 260 m³/s (15.05.2014.).

Table 1 Main characteristics of the Kolubara river basin

Variables	Symbol and measuring unit	Values
Drainage basin area	A (km ²)	3641
Perimeter	O (km)	317.5
Average elevation	H_{av} (m)	272.0
Highest point	H_p (m)	1346.0
Confluence point	C_p (m)	73.0
River length	L (km)	86.4
Drainage density	D (km/km ²)	1.1
Mean annual water discharge 1959-2014	Q_{av} (m ³ /s)	21.1
Mean specific sediment discharge 1985-1992	Q_s (t/km ² /yr)	16.5

Sediment monitoring methodology is standard and consists of daily sampling of water and sediment, with laboratory determination of the sediment concentration. All measurements on which performed RHMOS, as our measurements were performed at the same location, on Draževac gauging station! In order to avoid methodological errors and to provide a representative sample at the hydrological profile were carried out very precise measurements of suspended sediment during the 2013/14 year. Specifically, using the sampler with extended filling water sampling was carried out on the left and the right river bank, and then in the middle of the river flow (from the bridge) at a depth of 0.2 and 0.6 h. Such methodology is determined by the profile concentration of suspended load. To obtain a profile of the concentration for the days when there was only the measurement data along the bank, was introduced corrective coefficient K . The proposal for the introduction of corrective coefficients in order to determine the concentration profile is known from earlier (Michalec, 2003).



Figure 2 Sampling location

As is known, on the basis of many experiences showed that it is "possible on the basis of previous results more complete measurements to choose a permanent place in the profile (period or vertical) in which the concentration of suspended sediment (K_a) is in unambiguous depending on the average concentration throughout Profile (K_{sr})" (Dragicevic, 2004).

Daily measurements of suspended sediment concentration and daily recording of water level permit determination of the suspended sediment discharge for a given time period (using the water discharge rating curve).

Suspended sediment concentrations (*SSC*) of each sample taken in 2014 were determined by filtering, drying and weighing the samples. Water sampling for the use of determining the suspended sediment concentration was carried out on the hydrological profile Draževac. All analytical procedures were done in the Laboratory of Physical Geography on the Faculty of Geography, University of Belgrade.

The calculation of one-day sediment discharge on the monitored hydrological profile includes the values of mean daily flow ($Q - \text{m}^3/\text{s}$) and the relevant concentration of the suspended sediment ($SSC - \text{g/l}$). Consequently, sediment discharge (Qs) is obtained from the following equation (1):

$$Qs(t) = Q(\text{m}^3/\text{s}) \times SSC(\text{g/l}) \times 86.4 \quad (1)$$

where, 86400 is the number of seconds in one day. Shortening is made, for the conversion of the t/day.

Very important steps were done in order to improve establishment of the mean daily concentration. Considering the fact that instruments for continual deposit monitoring are quite expensive, good results were obtained during the flood waves by sampling on several samples in 24 hours, which provided realistic value of the mean daily concentration, which was more significant than doing one sampling per day.

3. Results and discussions

Dataset of 121 recorded torrential flood events in the Kolubara River Basin for the period 1929-2013 is derived from the Inventory of torrential floods in Serbia. The first maximum of flood events occurs in May (33 or 27.3%) and June (22 or 18.2%) in warmer part of the year and the second maximum is related to March (18 or 14.9 %) in colder part of the year (Ristić R. *et al.*, 2009, 2012; Petrović *et al.*, 2014; 2015). Catastrophic floods of the Kolubara River and

its tributaries spread over the area of lower part of the Kolubara River Basin during the spring of 1937, and they lasted two months approximately (from March to May). In this area big floods also happened in 1965, 1975, 1981, 1996, 1998, 1999, 2001, 2004, 2006, 2008 and 2010.

The flood in the Kolubara River Basin which occurred in May 2014 and caused catastrophic material damages and casualties was the latest and historical flood. The highest amount of rain was recorded in the period between May 14th and 16th, 2014. Western and central parts of Serbia were the most affected, with three-day rainfalls exceeding the average values for the month of May. Parts of the Kolubara River Basin were affected by rainfall which exceeded 1,000-year three-day rains. As the cyclone was stationary between May 14th and 18th it caused intensive rainfalls of over 200 l/m^2 and in some parts in the watershed of over 300 l/m^2 (RHMOŠ, 2014). Rainfalls over a 48-hour period exceeded the amount that in some places would normally occur over three months. At a measurement station Valjevo, 180 mm of rain was recorded in 48 hours, equal to the normal average rainfall for three months. In Serbia, Belgrade's rainfall was even higher, with 225 mm in the same period, equivalent to the maximum rainfall normally recorded over three months. The city of Obrenovac (where 90 percent of the city was flooded, with flood waters in some areas more than 4 meters deep) in the lowest part of the Kolubara watershed was significantly affected. This combination of circumstances caused disastrous floods, excessive erosion and sediment discharge, landslides, etc.

3.1 Temporal variability of water discharge and *SSC* during the year of 2014

As we know, sediment supply is usually greatest in the first freshet or early period of a flood event, as readily available sediment sources - typically from outside the channel - are mobilized and rapidly transported. Under these conditions, small increases in discharge contribute to rapid increases in *SSC*. As these sources are depleted, however, *SSC* will rapidly decline, often long before a decrease in discharge.

Taking into account that we had only mean daily discharge at our disposal, it was concluded that the error in the daily suspended sediment transport from the basin can be significant. If the sampling was done at a stable discharge in the morning, and after that the high wave of water came, it was calculated that the error in assessment of the daily sediment discharge can be from several hundred to several thousand tons. The same is true if there is a delay in sampling, and the shock wave passes. Thus, on May 5th, 2014, the sampling was done at 8, 12 and 18 o'clock, and the suspended sediment concentrations amounted to 1.38, 0.82 and 0.74 g/l. At the mean daily discharge of 49.3 m³/s, the suspended sediment transport of the individual concentrations would amount to 5 860, 3 494 and 3 145 t/day. Since we have no intraday changes in water discharge, the only thing left is to reduce the measured sediment concentrations to the mean value. Thus, the daily transport of 4 166 t of suspended sediment is received for 0.978 g/l. In the event that we only possessed the value of the lower *SSC* (0.74 g/l), and assuming that it was constant throughout the day, as well as the water discharge, more than about 1 000 t of suspended sediment would be evacuated from the basin. Error at the estimate of sediment discharge for the concentration of 1.38 g/l would be about 1 700 t, but now below the real value. Such detailed analyses of errors in calculating the suspended sediment transport on the profile of Draževac were done for the year of 2004, when the annual difference was about 100 000 t, which was a serious error that required a very detailed analysis and methodological improvements (Dragicević *et al.*, 2007a).

As the water discharge and the suspended sediment concentrations are highly variable over time, it is obvious that the methods of sampling once a day, as well as reducing water discharge to mean daily values, has serious difficulties to explain the relationship water discharge-*SSC*, and also the sediment discharge from the Kolubara River Basin. However, since these were the only valid data in the historic water year of 2014 (there have been no measurements of the *SSC* concentration by RHMSS since 2002), we tried to achieve the best assessment

of the *SSC* for those days when there was no sampling and hence derived conclusions about annual sediment discharge in extreme hydrological conditions.

By establishing the dependence $SSC = f(Q)$, we get the following diagram of the relationship of water discharge values and suspended sediment concentrations (Fig. 3). The basic idea of this research is to try and linking *SSC* and *Q* due to the fact that the year 2014 was extremely wet and that these conditions have never appeared so far on the Kolubara River (recurrence period of max. *Q* is over 1000 years). In addition, at the time of the high water coming samples were taken and determined turbidity, which is rare in Serbia over the last 10 years. Since the analyzed year had the minimum and maximum flows of the historical period it was concluded that this is sufficient reason to try to form the models which would result in the link *SSC* and *Q*. Otherwise, the procedure itself is not new, but given the fact that the conditions were gained, the challenge was not allowed to drop. Another objective was to calculate the annual sediment transport and set up what is the share of him in May of maximum flow. Figure 3 should not have any practical use, except that we visualize the position of points and point to two different formations. Therefore the function was unnecessary, be it linear or non-linear. However, if we use logarithm for data or axes we will not get a good look of points at the scatterplot.

It can be seen that the required relationship does not have the best references, but also that there is a grouping of data that should be examined. Taking into account all paired values (*n* = 206), we have found that the best result is achieved through the polynomial connection of the second degree, where the coefficient of explanation of *SSC* through water discharge is 0.64. What has obviously spoiled the assessment is a group of samples which had the increased values of *SSC* at a relatively small water discharge. This group is concentrated by the y-axis on the graph and it has a difference in *SSC* of 1 g/l for small changes in water discharge. It is obvious that their occurrence is associated with the special conditions of runoff, and this can be examined through analysis of the hydrograph and correspondent values of *SSC*.

Suspended sediment discharge from the Kolubara River Basin calculated through the measured values for 206 days during 2014 amounted to 915 514 t, and the one achieved through the formula was 1 047 075 t (Fig. 3). Thus, the difference was 131 561 t, or 14.4%. This difference is important, so that any rational explanation of turbulences of *SSC* and improvement of the relationship with water discharge significantly

contributed to the understanding of the erosion processes in the basin and estimation of the sediment discharge. It is obvious that this relationship should be researched in some other way as well, so as to understand its nature, and that is what statistics is missing. The dispersion diagram shows the points formed of pairs of data (*Q* and *SSC*), but they are completely independent and do not have a time dimension.

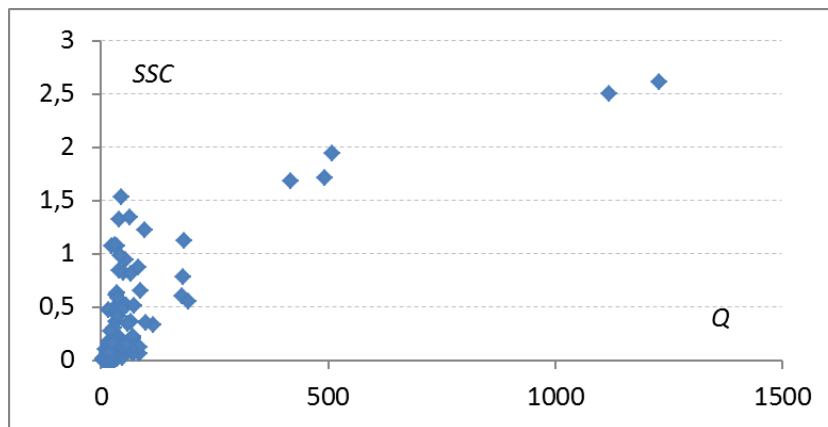


Figure 3 Relationship between water discharge Q (m^3/s) and SSC (g/l)

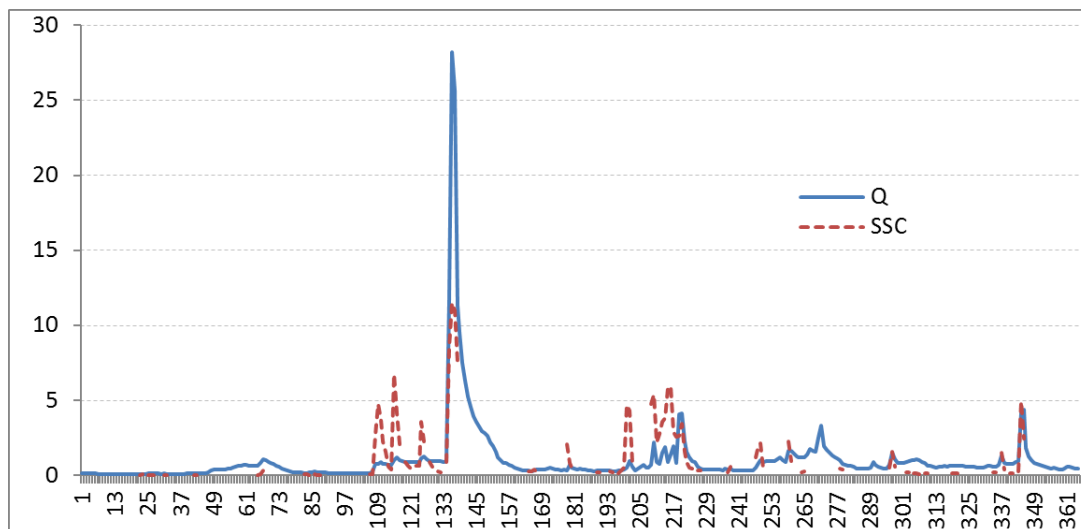


Figure 4 Relationship of modular values of Q and SSC during year 2014

Compatibility of the researched phenomenon is most noticeable on the graph where the water discharge (for a calendar year) and suspended sediment concentrations (for 206 days) are presented via modular values (each daily value is

divided by the arithmetic mean of the entire series). At first glance it has been already noticed that there is a certain relationship between the water discharge and *SSC*, especially in periods when high waters occurred.

Table 2 Daily values of water discharge and *SSC* at the end of April, 2014

Date	Time of sampling	Q (m ³ /s)	C (g/l)	M_Q	M_C
16.04.	19 ⁰⁰	6.18	0.0149	0.1762	0.0311
17.04.	15 ⁰⁰	13.2	0.0156	0.3763	0.0325
18.04.	18 ⁰⁰	33.7	0.6124	0.9607	1.2774
19.04.	10 ⁰⁰	35.0	1.0774	0.9977	2.2474
20.04.	11 ⁰⁰	39.6	0.8437	1.1288	1.7599
21.04.	13 ⁰⁰	35.1	0.5196	1.0006	1.0839
22.04.	15 ⁰⁰	33.4	0.3606	0.9521	0.7522
23.04.	17 ⁰⁰	31.9	0.1314	0.9094	0.2741
24.04.	17 ⁰⁰	32.3	0.0887	0.9208	0.1850
25.04.	18 ⁰⁰	44.7	1.5363	1.2742	3.2046
26.04.	12 ⁰⁰	54.3	0.9456	1.5479	1.9725
27.04.	15 ⁰⁰	45.0	0.4756	1.2828	0.9921
28.04.*		41.6		1.1859	
29.04.	8 ⁰⁰	40.7	0.1993	1.1602	0.4157
30.04.	15 ⁰⁰	39.5	0.1424	1.1260	0.2970
Aug.		35.08	0.4974		

*Water sampling was not done on April 28th. M_Q and M_C – modules of water discharge and *SSC*.

Visual confirmation would be even more convincing if the May flood did not "pulled" the ordinate to unbelievable 28 (so many times the mean daily discharge was higher on May 16th than the average for 2014). It is obvious that the analysis of individual high water waves had to be done in order to obtain the more concrete conclusions, and there were 7 such waves in 2014. For this, it was necessary to have continuity in the sampling for those days when the wave appeared. The longest

such series of holding data on *SSC* was in the second half of April of the analyzed year.

Graphic display of the last two columns gives a much clearer picture of the nature of these relationships. Namely, by April 17th, 2014, water discharge on the Kolubara River at Draževac was constantly low and almost thirty days ranged from 6 to 10 m³/s. At the same time, the *SSC* was also low with a mean of 0.018 g/l. With the significant increase in water discharge to 33.7 m³/s, the *SSC* increased 35 times and reached 0.6124 g/l on April 18th. The next day, the water discharge slightly increases, and the *SSC* rises to 1 g/l. It was only the third day since the beginning of the flood that the *SSC* is showing signs of decrease and this trend holds no matter the fact that the water discharge is maintained at a constant level. After that, since the water discharge increases sharply to 45 m³/s on April 25th, the *SSC* also reaches its maximum of 1.5 g/l. And as in the previous wave, the maximum discharge is followed by the slight decrease in *SSC*. What conclusion could be drawn? What this case demonstrates is that the erosion processes in the basin are the most intensive at the beginning of the flood wave. They cannot be in the increase long, at most one or two days, after that a decrease in *SSC* follows. Such a relationship is also greatly confirmed by the situation from the end of July and beginning of August, when there is continuity in the daily water sampling and the water discharge had significant fluctuations.

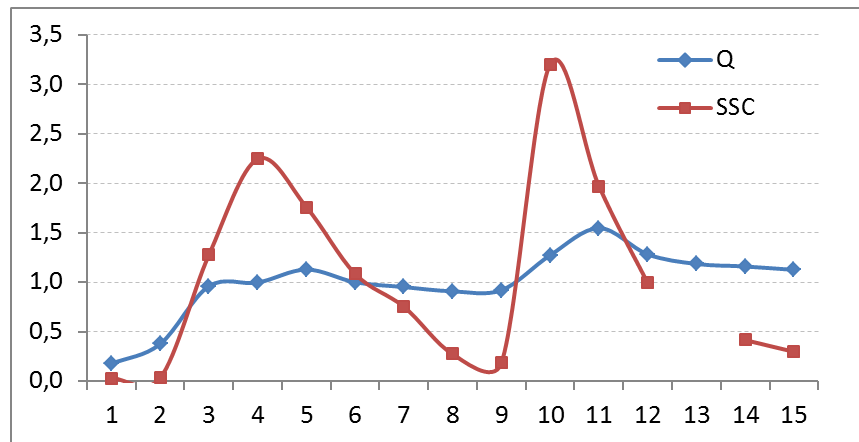


Figure 5 Relationship of modular values of Q and *SSC* during 15 days (16 – 30.4.)

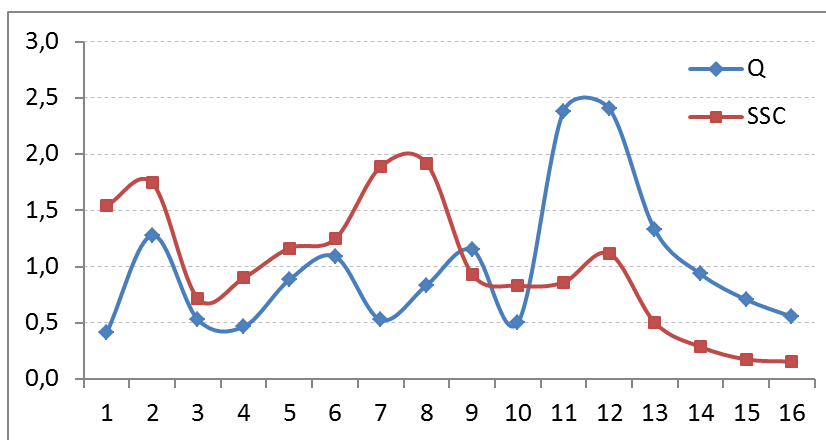


Figure 6 Relationship of modular values of Q and SSC during 16 days (28.7. – 12.8.)

During the period from July 28th to August 12th, 2014, the water discharge was in the range from 35 to 180 m³/s, and the SSC from 0.11 to 1.34 g/l. This period is slightly more complicated than the one in April. First illogicality represents the seventh day in a row (August 3rd), when the water discharge decreased doubly compared to the previous day, the SSC increased 50 % for the same time. The second less clear situation is transition from the 10th to the 11th day (from 37.5 to 178 m³/s) when the SSC remains unchanged. This only shows that the relationship water discharge- SSC should not be taken strictly formal, since the erosive processes in the basin are not only affected by the amount of water (rainfall) but also their intensity, the previous condition of the basin, soil moisture, vegetation, etc. Longer field research is required for such an analysis, and our intention was the attempt to separate the data from the chart that disrupt a good relationship water discharge- SSC , find the real explanation for that, as well as to define a new relationship for them in order to be actively involved in determination of the sediment discharge. What is likely, and for which we have no concrete proof, is that the anomalies in the relationship discharge- SSC arise in situations where bank erosion takes place, and all the material passes through the gauging point, and that it has not been initiated by discharge water. It belongs to the different nature of the problem that is well expressed in the Lower Kolubara Basin (Roksandić *et al.*, 2011, Dragićević *et*

al., 2013a, 2015). That is why in the records of the final results on the annual basis, we will not be able to turn them into specific erosion, at least not in the classical sense which implies the denudation process.

3.2 SSC -discharge relationship at the normal and flood time-scale

Dispersion diagram (Fig. 3) clearly shows that water discharge and SSC have double relationship. It is obvious that it is conditioned by the time of the characteristic water discharge appearances. Making rules meant the separation of these data and the analysis of individual values.

There have been separated 28 pairs of data (Fig. 3) in the first sample (Model 1) obtained by analyzing the dispersion diagram, which did not fit into the scheme of the vast majority of the daily values of water discharge and SSC . By their highlighting on the hydrograph, it was found that these were exactly those days when the water discharge suddenly increased, respectively, reaching the peak of the wave. These 8 days in 2014 have been already described in the period from April 18th to 27th (Table 2), then increase in the discharge on May 5th and 6th, June 27th, July 19th, 20th and 24th, the entire turbulent period from July 28th to August 6th (Fig. 6), September 4th to 6th and October 17th. Therefore, these are the days when the sampling was done, but the concentrations were higher than the expected. The period from May 15th to 19th should be added to

this, when the absolute water discharge maximums and highest *SSC* were recorded. Therefore, the establishment of the *SSC* depending on the water discharge for these 33 pairs of data led to the coefficient of determination of 0.733 obtained through the logarithmic relationship. However,

given that we have already had a large number of original data with the lowest water discharged *SSC* (which belong to the "regular" group), there were no obstacles to include them in this relationship in order to make counterweight to the upper extremes.

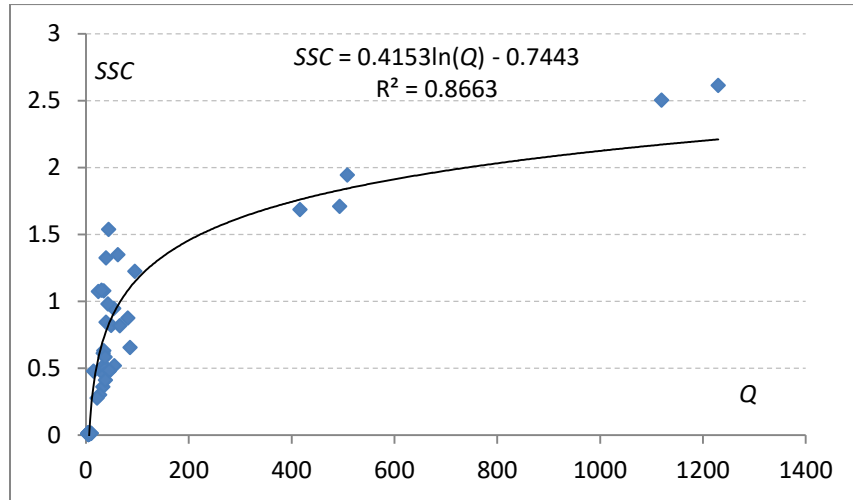


Figure 7 Model 1 (*SSC* dependence of *Q*)

With the Logarithmic function of data, or without, clearly noticeable that when the value of the discharge is about 10 m³/s something is going on with turbidity. That is, when a sudden increase in flow over this value rapidly increases and sediment transport. The reason for this is the hydraulic nature and is subject to other research, but on this occasion it was essential to define a relationship that would be able to assess the sediment transport. That is why the linearization of the model (over power functions) unnecessary. First, this procedure did not want to make comparisons with the world's examples, and secondly, that the annual assessment *SSC* by Logarithmic function (model 1) and Polynomial function (model 2) is much better than Power function (it has been observed and by the residuals).

In this way a very good assessment of the *SSC* in the water was achieved that the Kolubara River water discharge explains by 86.7%. The maximum deviation from the line of the equation have the samples (3 samples) grouped around the value of the *SSC* of 1.5 g/l, as well as the two extremes at the highest water discharge. Subsequent analysis will show how far these deviations are really essential in

assessment of the sediment discharge on a daily, and how much on an annual level. The second sample (Model 2) for the assessment of the *SSC* is formed of all daily pairs of data, except those 28, which are the basis of the first group. Thus, this group involves a total of 178 samples. Here the dependence is adjusted to the polynomial relationship of the second degree, which has made the coefficient of determination of 0.953.

An important question that arises is which functions would be implemented for which water discharge? The answer has been already given largely through way of forming the derived dependences. However, one should know that the proposed models have not yet solved the sediment transport for the whole year, because they have yet to be applied on those days when there was no water sampling, and their number was 159. This was followed by a detailed analysis of the hydrograph for 2014.

Selection of daily water discharge that will be used for Model 1 or Model 2 was dependent on the previously observed rules of conduct in the movement of the suspended sediment:

1. All of the water discharge belonging to a multi-day uniform water discharge was adapted to Model 2, regardless of the water discharge value in question. It is mainly small water discharge, typical for summer or winter.
2. All of the Kolubara River water discharge of over 100 m³/s on the profile of Draževac belongs to Model 2. Namely, it has been shown that the upper extremes of water discharge are more adaptable to the function of this model (this can be seen on the graphs as well).
3. Model 1 includes the turbulent days with values of up to 100 m³/s. Depending on the size of the flood it can only be one day of a sudden increase of water followed by a rapid decrease of the recession curve (as on October 17th). In the event that a high water wave lasts several days with daily oscillations as in the period from July 28th to August 6th (Fig. 6), then Model 1 is applied to water discharge of all these days.
4. If successive peaks, between which discharge was stable, more than one day, occur, these values from the "bottom" of the hydrograph belong to Model 2.

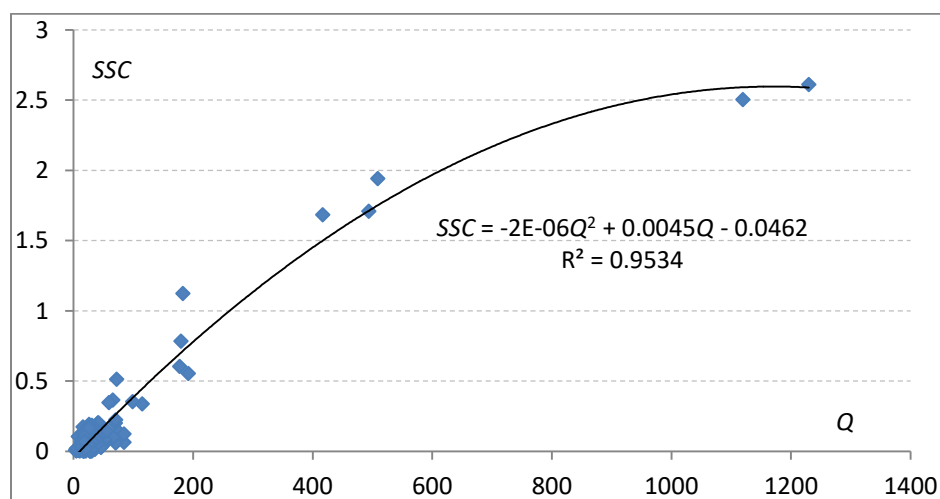


Figure 8 Model 2 (*SSC* dependence of *Q*)

According to the measured data and Models which were applied, we obtained that the average suspended sediment concentration (*SSC*) was 0.187 g/l at the average annual discharge of 43.64 m³/s on Draževac gauging station in 2014. The minimal daily measured *SSC* was only 0.0016 g/l and the maximal recorded value of the *SSC* was 2.6122 g/l and was measured after the extreme precipitation in May at the discharge of 1 260 m³/s. The ratio between the daily extremes was 1:1 633.

3.3 Annual sediment discharge in the year of 2014

Taking into account that our attention is focused on the annual sediment discharge from the basin, we are aware of the fact that many of the daily values

will be assessed. However, the proposed models for the assessment of the *SSC* are there in order to carry out leveling of the overestimated and underestimated values and in the given circumstances provide the most realistic results on the annual level.

3.3.1 Analysis of Model 1

The annual sediment discharge of 824 850 t was obtained by calculating the original values of the mean daily water discharge and *SSC* for those days that belong to Model 1. The sediment discharge of 761 709 t was achieved by applying Model 1 to them. The difference between these two numbers is 63 141 t, or 7.6%, which exactly represents the error in calculation. Analysis of certain values leads to the

conclusion that the biggest mistake occurred when there was also the greatest water discharge. Daily sediment discharge on May 15th was 277 604 t, and 234 704 t was estimated, so the difference amounted to 42 900 t. The next day, the difference was 32 326 t. However, due to the fact that this water discharge is not in the domain of Model 1, such errors cannot even happen. The model itself was designed precisely to solve the problem of water discharge within the range from 20 to 100 m³/s. Their error is much smaller, and the highest recorded was 3 350 t (August 4th). Taking into account only those days with a water discharge of 20 to 100 m³/s, there is a difference of 5 834 t, but now in surplus.

3.3.2 Analysis of Model 2

Suspended sediment discharge of each day when water sampling was done (without 28 days belonging to Model 1) amounted to 829 833 t. The assessment for these same days through Model 2 was 802 398 t, which meant that the error amounted to 27 435 t, or 3.3%. For the sample of 178 members this is an excellent result, which affirms the obtained model. If we accept this model also for the years to come, and we assume that the distribution of suspended sediment will follow water discharge by the line of the same model, we can expect much more accurate results. Namely, if from the obtained residuals of Model 2 we only exclude two highest values (water discharge over 1 000 m³/s), then the sum of all the other errors of the estimated values is of 9 729 t or 1.2%.

To determine the total annual suspended sediment discharge on the profile of Draževac, it was necessary to assess their values for those days when there was no sampling. By following the rules set in this paper, of the remaining 159 daily water discharge, we should only choose the ones between 20 and 100 m³/s, which are in the zone of described turbulent water discharge and add them to Model 1. All the other water discharge will be part of Model 2. The analysis of the hydrograph has reached the following results:

- Only 6 of the daily water discharge belong to the group of those that will realize the assess-

ment of *SSC* through Model 1, and those were on May 7th, July 23rd, 25th, September 13th, 23rd and October 18th. Total amount of the sediment discharge for these days was 17 419 t.

- On the basis of Model 2, 153 data were assessed and a total of 169 439 t obtained.

Finally, after establishing the dependence of water discharge and *SSC* and obtaining daily values of suspended sediment discharge, the calculation of the monthly and annual transport values was done. According to the original water discharge data and their corresponding *SSC* (206), and according to the estimated values (159), the total amount of suspended sediment load that was transported at the profile of Draževac in 2014 was 1 104 435 t. The absolute daily maximum was reached on May 16th, 2014, when the calculated transport was even 277 603.7 t, at the water discharge of 1 260 m³/s. The absolute minimum was measured on January 14th, 2014, when only 1.97 t of the suspended sediment load was transported.

When it comes to intra-annual distribution, the large differences and deviations of one month in respect to the other are observed. On the basis of the perennial values (1985-1992) of the sediment discharge obtained from the daily measures of *SSC* for the profile of Draževac, the highest sediment discharge was done in the spring part of the year, and the lowest in the autumn (Dragičević, 2001; 2002). In 2014, the sediment discharge was highest in May (80.3%), August (5.2%), September (3.7%), which constituted almost 90 % of the annual sediment discharge.

If we compare the year of 2014 with the years of 1999 and 2010, when there were high sediment levels, we observe similarities in the excessiveness of sediment discharge, but the values were significantly below those in 2014. In 1999, 70% of the annual sediment discharge was taken away from the Kolubara River Basin for two months (in July and December), and then the monthly sediment discharge in July amounted to 203 962 t and the yearly was 583 954 t. Only for two days (May 16th and 17th) in 2014, the sediment discharge amounted to 207 604 t and 242 278 t, which was about as much during the whole year of 1999 (583 954 t) and 2010 (452 877 t)!

4. Conclusion

The research results have showed that there is a strong correlation relationship between the suspended sediment concentration and water discharge in the Kolubara riverbed, but when considering the problem of SSC in a function of water discharge, the correct conclusions cannot be made if larger water discharge in the observed watercourse is not represented. Analyses have showed that the largest suspended sediment concentration appear at the very peak of the incoming flood wave, and together with its passing, it comes to an outstanding non-linear decrease in their values. During multi-peak floods such as this, SSC rises rapidly on the first rising limb, peaking a few hours before the discharge peak (positive lag), and drops on much lower levels during subsequent peaks. That is precisely why it was necessary to form two independent relationships that would be used in the assessment of SSC, and depending on time of the water discharge peaks appearance, their size and duration:

- 1) Turbulent days of the water discharge values up to 100 m³/s belong to Model 1 (mostly of the average annual values up to 100 m³/s).
- 2) Model 2 includes all the water discharge of multiday uniform water runoff, no matter which water discharge value is in question. Mostly, it is the case of lower water discharge, typical for summer or winter. Every water discharge above 100 m³/s belongs to this model as well.

Further research should go in the direction of testing the quality of the obtained relationship between the year of 2014 and measured values of the SSC of the average water and low water years. There are indications that these models cannot be replicated in each year, and at all discharge conditions, but it will certainly be a good basis for further analysis leading to the universal solution.

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Dynamics of suspended sediment load in the Morava River (Serbia) in the period 1967-2007

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ABSTRACT

The study is concerned with determination of the trend of water discharge, suspended sediment concentration and sediment load in the most downstream profile of the Velika Morava River in the period 1967-2007. The gradual trend test (Mann–Kendall test – MK test) and abrupt change test (Pettitt test) have been employed on annual, seasonal and monthly water discharge, suspended sediment concentration and suspended sediment load for the given time series. Both the Mann–Kendall and Pettitt tests indicate that water discharge showed no significant annual trend or abrupt shift. However, annual suspended sediment concentration and sediment load showed significant decreasing trends ($\alpha=0.001$). The average decrease of suspended sediment load transport amounted to 3.15 t/km²/yr. The Pettitt test results showed that the change-point year was detected in 1982. The average specific sediment load amounted to 134.6 t/km²/yr before the transition year, and 36.5 t/km²/yr after the transition year, i.e., it was reduced by 73 %. In the intra-annual distribution, the MK test results indicate that the most pronounced decreasing trend ($\alpha=0.001$) of the sediment load is during summer and winter. Strong seasonal and monthly variability in sediment load was found. Sediment was strongly transported during spring months, in the period of frequent flood events. Almost 50% of the annual sediment is transported during March, April and May. Analysis of the discharge and suspended sediment concentration relationship revealed the existence of hysteresis loop in the shape of figure eight. The results of this study confirm the complex and heterogeneous nature of sediment response in the Velika Morava River.

KEYWORDS

trend of water discharge, suspended sediment concentration, suspended load, interannual and intraannual variability, Velika Morava, Serbia

1. Introduction

Erosive sediment production in river basins and sediment load in watercourses are essential components of global natural process. Establishing a quantitative description of riverine fluxes is one of the main goals of contemporary hydrology and geomorphology (Cohen *et al.*, 2014). Factors that control the intensity of suspended sediment load in the riverbeds are different. Precipitation, runoff and lithological composition stand out of natural factors (Chakrapani and Subramanian, 1990; Chakrapani, 2005). On the other hand, studies around the world have shown the evident anthropogenic impact based on different human activities. Walling and Fang (2003) point out the impact of reservoir construction, land clearance and land use change, soil and water conservation and sediment control programmes on changes in suspended sediment in rivers. Some studies have shown that the impact of humans in some cases is greater than the evident climate change, as is the case of impact of the mines (Bobrovitskaya *et al.*, 2003). Hook (2006) attributes changes in the intensity of soil erosion and fluvial systems to the impact of deforestation, different forms of ploughing, as well as demographic changes, urbanization and the impact of construction of large dams. The results obtained by Walling and Fang (2003) and Walling (2006) indicated that almost half (70) of the rivers showed no evidence of a statistically significant trend in the sediment loads, but as a remainder, most (68 rivers) of them showed evidence of a significant decrease. Only 7 rivers were characterized by a significant increase in the sediment loads. They also point out that the observed trend of a decrease in the suspended sediment load is largely attributed to the influence of anthropogenic factors. Researches of other studies have shown similar results.

Due to the consequences on the condition and quality of the environment, the study of the dynamics and suspended sediment load has great environmental and water management impact. The ecological aspect is primarily viewed in the quality of water in river flows and chemical pollution of watercourses, as it is known that suspended sediment is the main transporter of chemical pollutants. The study of the dynamics and sediment load from the water management aspect involves

consideration of its impact on different water management facilities such as regulated riverbeds, irrigation channels, water intakes, etc., but primarily emphasizes consideration of problems regarding the reservoir siltation.

In this context, the study of suspended sediment trends on the Velika Morava River is of great importance, bearing in mind the fact that the sediment transported by this river has a direct impact on the accumulation zone of the Hydroelectric Power Station "Djerdap I" (the Iron Gate I Hydroelectric Power Station). The study of the sediment load trend on the Danube downstream from the reservoir showed that the construction of the dam led to its reduction by 70% (Walling, 2006). It is estimated that in the total amount of sediment entering the reservoir sector downstream of the Velika Morava River, the sediment which entered by the Danube participates by 41%, 26% by the Tisa River, 21% by the Sava River, and 12% by the Velika Morava River (Babić-Mladenović, 2007) and that the reservoir retains about 80% of the total sediment load entered by the Danube, so that the reservoir of the "Djerdap I" is probably the largest reservoir storage of sediments in Europe (Petković *et al.*, 1999). The objective of the research in this study is to statistically detect trends and change-points (transition year) in annual discharge and suspended sediment load and determine changes in sediment transport in the period before and after the observed transitional year. Also, the objective of this paper is to statistically detect trends in seasonal and monthly discharge and suspended sediment load and determine the type of hysteresis loop defined through the relationship of discharge and suspended sediment concentration.

2. Physical-geographical characteristics

The Velika Morava River Basin covers an area of 37,561 km², accounting for 42.5% of the territory of the Republic of Serbia. The basin is of three hydrographic parts: direct basin of the Velika Morava River (6,242 km²), the Južna Morava River Basin (15,469 km²) and the Zapadna Morava River Basin (15,850 km²).

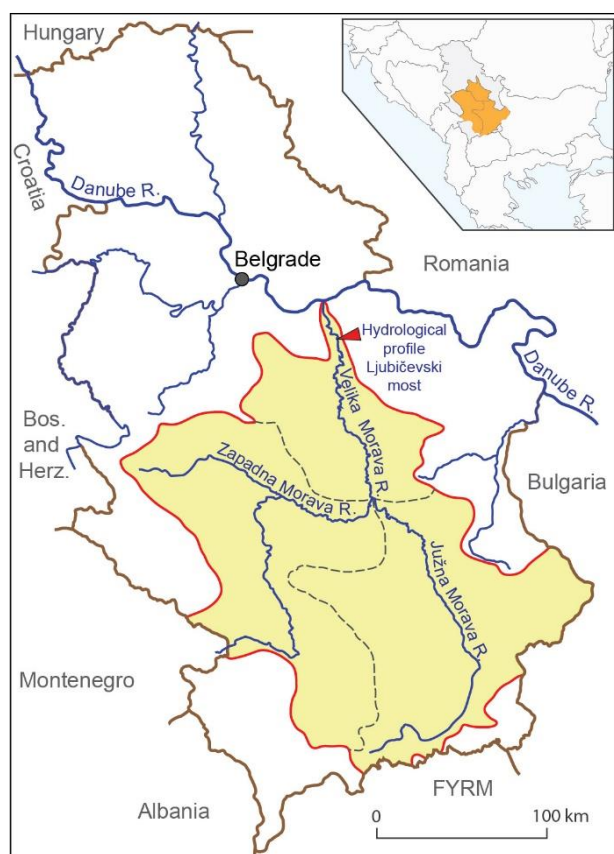


Figure 1 Geographical location of the Morava River in Serbia and on the Balkan Peninsula

Average altitude of the basin is 622 m, the lowest point is 67 m at the confluence of the Velika Morava River and the Danube, and the highest point is on the mountain Hajla at 2,500 m above sea level. In hypsometric terms, the largest part of the basin area (77%) is between 200-1,000 m above sea level (Oćokoljić, 1987).

Dynamics of river discharge and suspended sediment load greatly depend on the basin geological substratum. The Velika Morava River Basin is characterized by a very diverse geological structure. The Zapadna and Južna Morava River Basins, constituting 83.38% of the Velika Morava River Basin, are largely covered by rocks subjected to water erosion and of great quantity of suspended sediment load - flych 23.88%, Holocene alluvium 17.28% (mostly fine particles of silt and clay and larger particles of sand and gravel), quartz sandstones 9.87%, Neogene lake sediments 4.14% (mostly sand and gravel). Direct basin of the Velika

Morava River, covering 16.62% of the Velika Morava River Basin, is mostly covered by Holocene alluvium and Neogene lake sediments.

Integral vulnerability map of the natural hazards in the territory of Serbia shows that the valley of the Velika Morava River near Stalać to the confluence into the Danube, as well as the valleys of its constituents, the Južna Morava River and the Zapadna Morava River, belong to potential flood zones (Dragicević *et al.*, 2011; Ristić *et al.*, 2012). Analysis of floods in the Morava River Basin shows that they usually occur in late spring or early summer during periods of frequent cyclones. They mostly belong to floods caused by rainfall and snow-melt and floods caused by the coincidence of high waters, and torrent floods are common in the Južna Morava River Basin (Gavrilović *et al.*, 2012). In the last hundred years even 479 torrential flood events were registered in the basin (Petrović *et al.*, 2014). Water regime of the Velika Morava River is determined by the regime of its constituents. Thus, the Južna Morava River participates with 43.2% and the Zapadna Morava River with 45.7%, while the direct part of the Velika Morava River Basin with only 10.9% of the total runoff (Gavrilović, 2006). The Velika Morava River is the river with the highest discharge fluctuations, the annual coefficient of variation is of 0.30 and is caused by continental regime of precipitation, high evaporation and pluvial-nival regime of its tributaries (Oćokoljić, 1994). The largest part of the basin area is of 600-800 mm of precipitation on the average, while the highest mountainous parts even up to 1,100 mm (Ducić and Radovanović, 2005).

3. Methodology

In this study we used the measurements from the hydrological station Ljubičevski most (official data of the Republic Hydrometeorological Service of Serbia) in the period 1967-2007. The station is located on the Velika Morava River, at a distance of 21.75 km from its confluence with the Danube. The basin area of the Velika Morava River is 37,320 km² upstream of the station, while the length of river upstream is 471.25 km, together with the Zapadna Morava River

as the source arm. Descriptive statistics for discharge (Q), suspended sediment concentration (SSC) and sediment load (Q_s) are given in Table 1. There are indications that these models cannot be replicated in each year, and at all discharge conditions, but it will certainly be a good basis for further analysis leading to the universal solution.

Two non-parametric tests were used, which meant that their application required no assumption about the distribution of water discharge (Q),

suspended sediment concentration (SSC) and suspended sediment load (Q_s) data from the given time series (1967-2007), on annual, seasonal and monthly basis. In other words, the tests are distribution-free and it is not required to assume a special form of the data distribution, including potentially missing data, which is very common for hydrological data. The Mann-Kendall test is widely used to investigate if the trend exists in a given time series.

Table 1 Descriptive statistics for discharge (Q), suspended sediment concentration (SSC) and sediment load (Q_s)

	Unit	Mean	Minimum	Maximum	Standard deviation	Coefficient of variation
Discharge (Q)	m ³ /s	220.3	101.1	348.9	61.5	0.28
Suspended sediment concentration (SSC)	g/l	0.2173	0.0466	0.6909	0.1827	0.84
Sediment load (Q_s)	t/yr	2568998.6	170197.4	10015588.2	2317405.4	90.2

It is often applied for trend determination of climatic indicators and it is recommended by the World Meteorological Organization (Salarjazi *et al.*, 2012; Mitchell *et al.*, 1996), as well as, for evaluation of hydrological data (Yue *et al.*, 2002; Yue *et al.*, 2003; Yue *et al.*, 2004; Salarjazi *et al.*, 2012; Karmeshu, 2012). The purpose of this test is to statistically estimate whether an upward or downward trend appears in data series in the scope of time. The obtained trend may or may not be linear.

The initial assumption of the Mann-Kendall test is that the trend does not exist (H_0), or otherwise, the observations are not serially correlated during time. In order to reject the initial assumption (accept the alternative hypothesis - H_a), it is necessary that the test result is lower than the significance level - α (common value is 0.001). Lower value of the significance level α decreases the possibility that the (the trend does not exist) is wrongfully rejected. The value of the Sen's slope (b) shows the trend magnitude, either upward or downward.

As the Mann-Kendall test, the Pettitt test (Pettitt, 1979) was carried out to determine whether there was the trend in value changes of water discharge, suspended sediment concentration, and suspended sediment load. The Pettitt test also

shows if there is a transition point – year (change-point) when it comes to a change in trend, and if it exists, which transition point is in question.

The existence of the transition year (change-point) does not mean that the values changed in that particular year, but that there were two periods when the measured values extremely differed. In other words, the change did not happen in one year, but the change-point separated the two different periods. The Pettitt test is widely used to detect changes in the observed hydrological data series, including suspended sediment load (Gao *et al.*, 2011; Gao *et al.*, 2012; Meysam *et al.*, 2012).

Similarly, as for the Mann-Kendall test, the initial assumption of the Pettitt test is that the trend does not exist (H_0), i.e., that the data are homogeneous throughout the whole period of observation, and that there is no transition year when the values change in positive or negative terms. The alternative hypothesis (H_a) is accepted in the case when the test result (p) is lower than the significance level - α . The significance level can be changed with the common values of 0.05 or 0.001. The higher p value, the higher possibility to wrongfully reject the initial assumption, i.e., the lesser probability for the trend and the transition point to exist.

4. Results and discussion

4.1 Interannual variability of suspended sediment load

The average perennial discharge on the hydrological profile Ljubičevski most on the Velika Morava River in the period 1960-2007 is $220.3 \text{ m}^3/\text{s}$, which gives a specific runoff value of 6.2 l/s/km^2 . The minimal average annual discharge value amounted to $101.1 \text{ m}^3/\text{s}$, and the maximal average annual value was of $348.9 \text{ m}^3/\text{s}$, so that the specific runoff amounted to 2.85 l/s/km^2 , or 9.83 l/s/km^2 . The average suspended sediment concentration is of 0.2173 g/l , and ranges from 0.0466 to 0.6909 g/l .

The average perennial suspended sediment transport is of $2.57 \times 10^6 \text{ t}$ ($72.4 \text{ t/km}^2/\text{yr}$), and ranged from $0.17 \times 10^6 \text{ t}$ ($4.8 \text{ t/km}^2/\text{yr}$) to $10.02 \times 10^6 \text{ t}$ ($282.2 \text{ t/km}^2/\text{yr}$). Extremum ratio for Q , SSC and Q_s is 1:3.4, 1:14.8 and 1:58.8 respectively. The results of the Mann-Kendall (MK) test for the gradual trends of discharge (Q), suspended sediment concentration (SSC) and sediment load (Q_s) are given in Table 2. There has been a gradual trend of decrease in Q , SSC and Q_s . However, there are no significant trends detected for water discharge series, but the trends for SSC and Q_s show high significance ($\alpha=0.001$). The Sen's slope curve shows that the average decrease of Q is of $0.82 \text{ m}^3/\text{s/yr}$, respectively $0.021 \text{ l/s/km}^2/\text{yr}$.

Table 2 Results of Mann-Kendall test for annual water discharge (Q), suspended sediment concentration (SSC) and suspended sediment load (Q_s)

Time series	$Q (\text{m}^3/\text{s})$			$SSC (\text{g/l})$			$Q_s (\text{t/yr})$		
	b^*	Z	α^{**}	B	Z	α	b	Z	α
Annual	-0.82	-0.75	0	-0.0096	-4.14	0.001	-111094.5	-4.21	0.001

*Sen's slope estimate (b). **Significance level (α)

Table 3 Results of Pettitt test for discharge (Q), suspended sediment concentration (SSC) and suspended sediment load (Q_s) (significance level $\alpha=0.05$)

Parameter	Pettitt test						
	K	p	Shift	T*	Pre - T	Post - T	average
$Q (\text{m}^3/\text{s})$	128	0.370	No change	-	-	-	220.3
$SSC (\text{g/l})$	346	0.0001	Downward	1982	0.4010	0.1113	0.2173
$Q_s (\text{t/yr})$	350	0.0001	Downward	1982	4778885.9	1294063.6	2568998.6

*Transition year (change-point) (T)

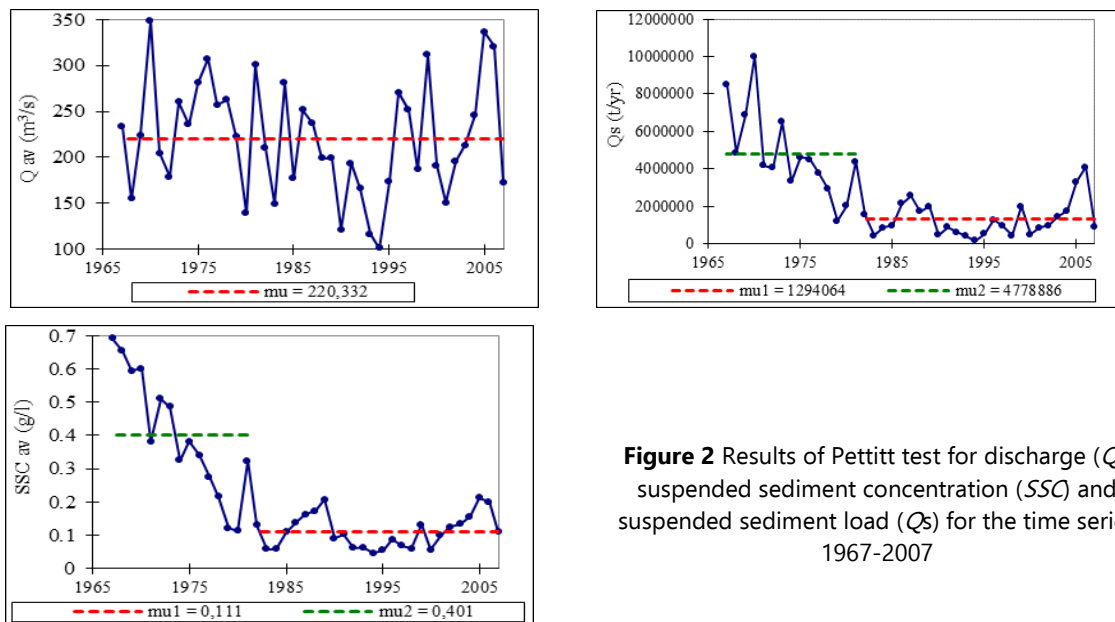


Figure 2 Results of Pettitt test for discharge (Q), suspended sediment concentration (SSC) and suspended sediment load (Q_s) for the time series 1967-2007

The average decrease of *SSC* is of 0.0096 g/l/yr, and the average decrease of *Qs* is of 111,094.5 t/yr, i.e., the average specific rate of decrease is of 3.13 t/km²/yr. The results of the Pettitt test for abrupt changes in *Q*, *SSC* and *Qs* are given in Table 3 and Fig. 2. At the level of significance of 0.05, there are no abrupt changes in discharge for a given period of time. On the other hand, the *SSC* and *Qs* have abrupt significant changes downwards. The change point (transition year) in both cases is the year of 1982. The average specific sediment load before the transition year (change-point) amounted to 134.6 t/km²/yr and after the transition year it was 36.5 t/km²/yr, or it was decreased by 73%. Also, the average values of the *SSC* decreased by 72% after the transition year.

Since the time series of *Qs* are divided into two segments based on their change point, the gradual trends of *Qs* before and after the transition year can be further investigated. The results of the MK for *Q*, *SSC* and *Qs* before and after the transition year are displayed in Table 4. Before and after the transition year, *SSC* and *Qs* show opposite trends. Therefore, although the period before the transitional year, the discharge recorded a slight upward trend, *SSC* and

Qs had a distinctive decreasing trend, significant at the level of 0.0001, i.e., 0.001 respectively. The average decrease of suspended sediment in the period 1967-1982 amounted to 370,176.5 t/yr, i.e., 10.4 t/km²/yr. On the other hand, *Q*, *SSC* and *Qs* after the transition year show a slight upward trend, that is not significant.

The opposite trends of *Qs* before and after change points suggest that there were different controlling factors of sediment load in different periods. Gao *et al.*, (2011) suggests that in stable climatic-hydrologic conditions, the trend of decrease in sediment can be explained solely by anthropogenic impacts. Taking into account the fact that the measuring station on the Velika Morava River in the period before the transitional year had a growing trend in the discharge and declining in the concentration and sediment transport, a strong reduction of suspended sediment could be attributed to anthropogenic impacts. On the other hand, the slightly increasing trend observed in all three parameters (*Q*, *SSC*, *Qs*) in the period after the transition year may be due to the influence of precipitation.

Table 4 Results of Mann-Kendall test for annual water discharge (*Q*), suspended sediment concentration (*SSC*) and suspended sediment load (*Qs*) before and after significant points in the year of 1982.

Time series	<i>Q</i> (m ³ /s)			<i>SSC</i> (g/l)			<i>Qs</i> (t/yr)		
	b	Z	α	b	Z	α	b	Z	α
Pre - T	4.09	0.69	0	-0.0421	-4.16	***	-370176.5	-2.79	**
Post - T	1.82	0.79	0	0.0013	1.06	0	12448.8	0.88	0

T- transition year, b - Sen's slope estimate, α - significance level: 0 = no significance; + α = 0.1; * α = 0.05; ** α = 0.01; *** α = 0.001

Specifically, the analysis of precipitation of the measuring stations in the basin shows an increasing trend after 1980 (Gocić M., and Trajković S., 2013). Climate research studies throughout Serbia (Unkašević M., Tošić I., 2014; Kutiel H., Luković J., Burić D., 2015) showed that wet years dominated in climate classification in the first decade of the XXI century.

4.2 Intraannual variability of suspended sediment load

In the intraannual distribution, the highest sediment load is realized in spring: in March (18%), in April

(17.9%), in May (11.7%), accounting for almost half of the annual summary sediment load in total. The smallest sediment load is linked to autumn and the end of the year. So, in September it accounted for 2.1%, 2.4% in August, 2.8% in October, 2.9% in November in the total annual distribution (Mustafić *et al.*, 2014).

The results of the MK test for seasonal and monthly changes in *Q*, *SSC* and *Qs* are given in Table 5 and Table 6. Changes in discharge on seasonal and monthly basis show different trends. Period from February to September (with the exception of April) shows decreasing trend in

discharge, while a mild increasing trend is related to the period from October to January. However, the observed changes are not statistically significant. Seasonal and monthly changes in the suspended sediment concentration are characterized by a strong downward trend. The level of significance is of 0.001 for winter, spring and summer, and 0.01 for autumn. The results of the MK test show the strongest downward trend for May, June, July, August and September and two winter months of January and February.

Changes in the seasonal distribution of suspended sediment load show a downward trend. The most obvious decreasing trend is evident during summer and winter at the level of significance of 0.001, and the lowest in autumn. Changes on the monthly level show negative trends without exception during all 12 months. However, these changes in October and November have no

statistical significance, and in April they are significant at the level of 0.1. The most prominent significant changes of suspended sediment are in July and August at the level of 0.001, which shows a strong downward trend (Z values of the MK test amount to -3.85, -3.45 respectively). Also, two more months, June and September, recorded a pronounced decreasing trend of suspended sediment at the level of significance of 0.01. Monthly suspended sediment load displayed in Figure 3 shows the average decade values. These values clearly reflect the dynamics of suspended sediment load in the seasonal pattern. Intraannual suspended sediment load shows significant changes. It can be clearly seen that the peak of monthly suspended sediment load in recent decades almost always happens in March and April, which is in accordance with intraannual discharge distribution.

Table 5 Results of Mann-Kendall test for seasonal water discharge (Q), suspended sediment concentration (SSC) and suspended sediment load (Q_s)

Seasons	Q (m^3/s)			SSC (g/l)			Q_s (t/yr)		
	b	Z	α	b	Z	α	b	Z	α
Winter	-0.14	-0.01	0	-0.0066	-3.99	***	-18853.1	-3.45	***
Spring	-1.32	-0.53	0	-0.0089	-3.63	***	-35881.8	-3.02	**
Summer	-0.76	-0.86	0	-0.0109	-4.57	***	-16636.4	-4.05	***
Autumn	0.50	0.62	0	-0.0032	-2.86	**	-2330.1	-1.94	+

B - Sen's slope estimate, α - significance level: 0 = no significance; + $\alpha=0.1$; * $\alpha = 0.05$; ** $\alpha = 0.01$; *** $\alpha = 0.001$

Table 6 Results of Mann-Kendall test for monthly water discharge (Q), suspended sediment concentration (SSC) and suspended sediment load (Q_s)

		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Q (m^3/s)	b	0.17	-1.29	-1.06	0.74	-1.45	-0.91	-1.68	-0.27	-0.32	0.39	0.75	0.35
	Z	0.10	-0.91	-0.48	0.19	-1.02	-0.71	-1.70	-0.64	-0.84	0.53	0.84	0.33
	α	0	0	0	0	0	0	+	0	0	0	0	0
SSC (g/l)	b	-	-	-0.0099	-	-	-	-	-	-	-	-	-
		0.006	0.008		0.006	0.008	0.010	0.009	0.005	0.003	0.002	0.002	0.003
		8	0		2	0	9	4	1	7	0	0	5
Q_s (t/yr)	Z	-3.43	-3.47	-3.22	-2.30	-3.31	-4.01	-4.05	-3.56	-3.88	-1.72	-2.12	-2.44
	α	***	***	**	*	***	***	***	***	***	+	*	*
	b	-	-	-	-	-	-	-	-	-872.0	-319.0	-573.9	-
Q_s (t/yr)		5011.	6575.	12236.	5553.	5621.	6393.	4316.	1403.				1775.
		4	1	0	1	3	4	1	4				8
	Z	-2.66	-2.48	-2.44	-1.72	-2.44	-3.27	-3.83	-3.45	-3.27	-1.49	-1.09	-2.03
	α	**	*	*	+	*	**	***	***	**	0	0	*

b- Sen's slope estimate; α - significance level: 0 = no significance; + $\alpha = 0.1$; * $\alpha = 0.05$; ** $\alpha = 0.01$; *** $\alpha = 0.001$

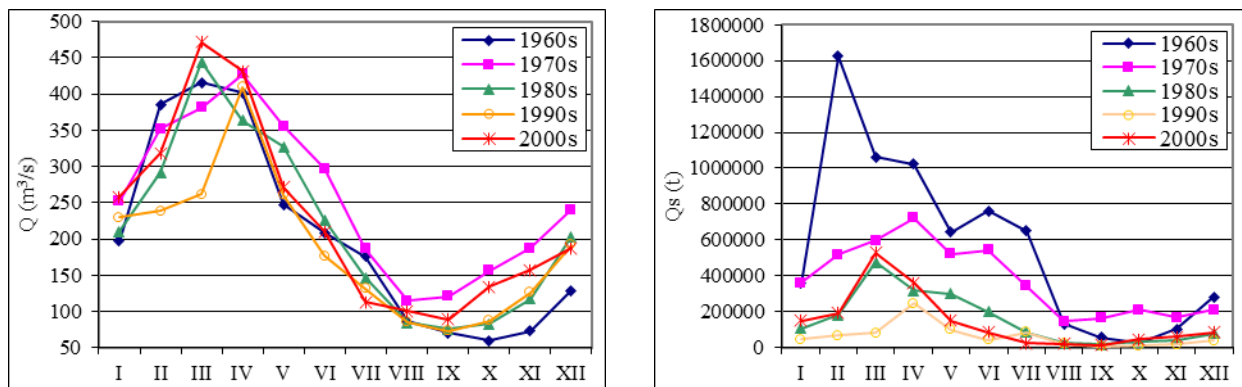


Figure 3 Monthly distribution of water discharge Q (m^3/s) and suspended sediment load Q_s (t/yr) in different decades.

It can be clearly seen that the peak of monthly suspended sediment load in recent decades almost always happens in March and April, which is in accordance with intraannual discharge distribution. The exception is the period of the late 1960s, when it was recorded in February. This distribution of the suspended sediment is generally consistent with the intraannual discharge distribution. Specifically on the rivers in the Velika Morava River Basin, most common periods of maximal discharge phenomena are from the end of spring, in April, May, to the first half of June and the end of winter from February and March (Ristić *et al.*, 2012). However, although the peak of Q_s always occurs in March or April, the differences between certain decades are very significant. The largest suspended sediment load during March and April we have in the period 1960s-1970s, which dramatically decreases during the 1990s, and shows slight upward trend after the 2000s. A change in the dynamics of suspended sediment is best illustrated by the fact that the ratio between the maximal monthly suspended sediment load in March in 1960s and 1990s is 1:13. That is, the suspended sediment load in the 1990s is only 7.6% of the sediment load in the 1960s.

In order to determine changes in the dynamics and suspended sediment load, we widely use the hysteresis curve. Sediment rating curve or hysteresis curve empirically describes the relationship between suspended sediment concentration (SSC) and discharge (Q). In this study, three hysteresis loops are shown (Fig. 4). The first is for the entire observation period 1967-2007, the second for the period before the transition year T (1967-1981) and the third for the period after the transition year T (1982-2007). Given the existence of 5 types of loops

(Williams, 1989), the shape of hysteresis loop is in the form of figure eight in all three cases. Hysteresis loop in the form of figure eight points to complex conditions. It contains the elements of the loop, which is clockwise, but also the elements of the loop of opposite direction. This type of loop can be understood as the sequence of dominant conditions which alterate during the year (Seeger *et al.*, 2004; Soler *et al.*, 2008). In the first phase (January-May), which reflects the loop in a clockwise direction, the conditions of high surface runoff are dominant. Due to soil saturation with water (snowmelt in late winter and early spring and spring rains), its capacity to retain water is getting smaller, which implies more intense runoff. The peak of SSC (February and March) is before the occurrence of the maximal Q (April), which points to the events of short duration. Land particles eroded in the basin can be easily transported during rainfall-runoff events and quickly enter the watercourse (Fang *et al.*, 2011). In the second phase (the period May-October), the loop shows the opposite character. Very high suspended sediment concentration occurs after the occurrence of the maximal discharge. High intensity precipitation (June) is dominant, which shows that the source of sediments can be active in a wider area (Mustafić *et al.*, 2013). After June, SSC has a sudden decreasing tendency and reaches its minimum in October. Since October, the orientation of the hysteresis loop changes again and takes the clockwise direction. Although both hysteresis loops done for the period before and after the transition year T have the character and the shape of the figure eight, certain changes in the relationship between SSC and Q were observed. Thus, for the maximal values of Q (April), the values of SSC after

the transition year were 2.7 times lower than in the period before the transition year. Also, in the period after T, the suspended sediment concentrations significantly decreased, especially during February and June. The MK test results point to this as well: the decrease trend of *SSC* is highly significant ($\alpha=0.001$), and *Z* values for February and June amount to high -3.47, -4.01 respectively. As a result of the current changes, now the largest value of *SSC* can be expected only in March and April, in contrast to the period before the transition year, when the other very pronounced peak of *SSC* was in June. The minimal value of *SSC* moved toward September. In this sense, two periods of the year are clearly demonstrated. The first period records an increase in the value of *SSC* with increasing *Q* and lasts from November to March, which is two months longer than regarding the period before the transition year, when it lasted from October to February. The second period records the decrease in *SSC* and lasts from April to September when it reaches its minimum.

5. Some aspects of human impact on decreasing trend of suspended sediment

The abrupt decrease of suspended sediment load can be largely attributed to anthropogenic impacts. In this context, the factors influencing the established trend can be seen in three aspects: (i) implementation of effective soil conservation practices; (ii) impact of demographic factors and (iii) impact of construction of dams and reservoir siltation.

Implementation of effective soil conservation practices was conducted in a planned manner in certain parts of the basin. Comprehensive scope of anti-erosion works was carried out in the South Morava River Basin in the period 1961-1988, and in the Zapadna Morava River Basin in the period 1947-1977. In addition to the classic forestation, the following has been introduced: application of biotechnical works, anti-erosion techniques in agricultural production and construction of various partition objects on torrential basins (Petković *et al.*, 1995, 1996).

Individual studies in the area of the Velika Morava River Basin have indicated the role of demographic

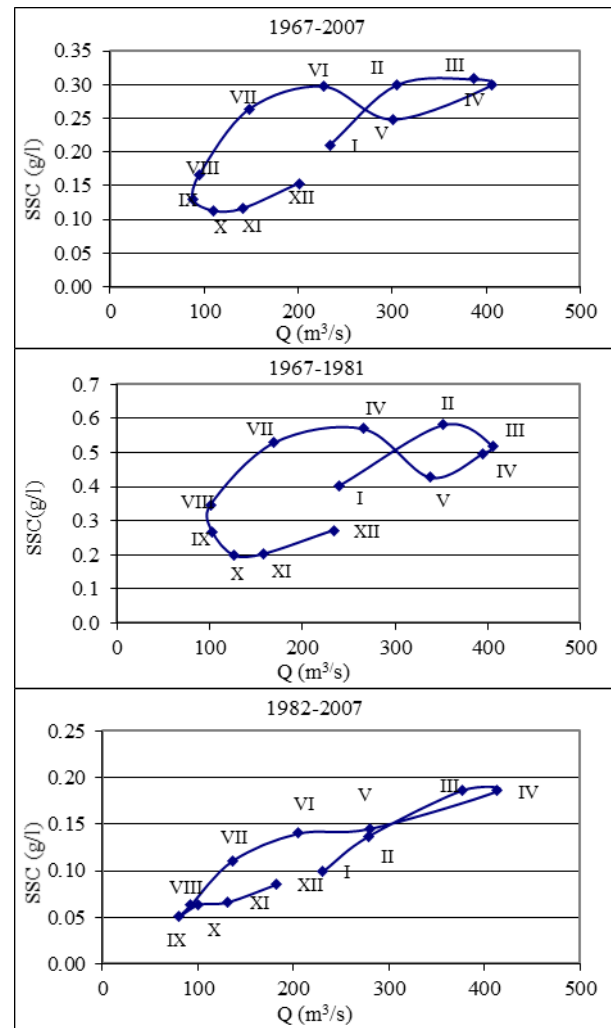


Figure 4 Hysteresis loop in the period 1967-2007, before transition year T (1967-1981) and after transition year T (1982-2007), detected by the Pettit test

component in decreasing the intensity of soil erosion, and therefore the suspended sediment load (Kostadinov *et al.*, 2014; Mustafić, 2007; Mustafić *et al.*, 2008). In this context, the continuing population decline in the second half of the XX and very strong negative average annual rate of the first decade of the XXI century are especially distinguished (Spasovski *et al.*, 2012), as well as, the process of demographic aging of the population, the general deruralization and depopulation in rural areas of Central Serbia (Martinović, 2012). Rural areas experienced the characteristics of rural exodus during the 1960s, culminated in the period 1971-1981, when 1.4 million people left the agricultural production (Martinović and Ratkaj, 2015). Negative

demographic processes have continued until today. Leaving rural areas has resulted in reduction of agricultural pressure on land, which reflected on grassing of arable land and therefore the reduction in intensity of soil erosion.

Certainly one of the most important factors in decreasing the suspended sediment load is the impact of water reservoirs. Reservoir siltation is expressed to the extent that most of them was silted by 30-50% in the first twenty years of construction. The extreme example is the reservoir of the Zapadna Morava River, which lost 50% of the total volume in the first three years of operation and very quickly was completely silted (Milinčić, 2009).

6. Conclusion

The paper deals with interannual and intraannual dynamics of suspended sediment load of the Velika Morava River on its most downstream hydrological profile Ljubičevski most in the period 1967-2007. The following can be concluded from the above mentioned studies:

(i) On the average, the Velika Morava River gives 220.3 m³/s to the Danube, which gives the specific runoff value of 6.2 l/s/km². In addition, 2.57 x 10⁶ t of suspended sediment was transported on the average for a period of 40 years, which made the average specific sediment load of 72.4 t/km²/yr. The results of the Mann-Kendall test showed that the average decrease of suspended sediment load was 111,094.5 t/yr, or 3.15 t/km²/yr. The results of the Pettitt test showed that the change-point year was detected in 1982. Average specific sediment load before the transition year amounted to 134.6 t/km²/yr, 36.5 t/km²/yr after the transition year, i.e., it was reduced by 73%. Interannual trend of decrease of suspended sediment and suspended sediment concentration was very pronounced ($\alpha=0.001$), compared to the runoff trend which recorded no statistical significance.

(ii) Intraannual distributions of suspended sediment exhibit strong seasonal characteristics. The largest sediment load was carried out during March, April and May (nearly 50%). Changes in the seasonal

distribution of suspended sediment load showed a decreasing trend. The most obvious decreasing trend was evident during summer and winter ($\alpha=0.001$), and the lowest in autumn ($\alpha = 0.01$). Changes on the monthly level showed negative trends without exception during all twelve months. The most prominent significant changes of suspended sediment were in July and August, and then in June and September, on the level of significance of 0.001, and 0.01 respectively.

(iv) The ratio of discharge and suspended sediment concentration showed that the hysteresis loop was in the shape of figure eight, indicating complex conditions in the basin. Analysis of the hysteresis loop, done for the period before and after the transition year T, indicated some changes in the relationship between SSC and Q . Thus, for the maximal values of Q (April), the values of SSC in the period after the transition year were 2.7 times lower than in the period before the transition year. Also, in the period after T, the suspended sediment concentrations significantly decreased especially during February and June.

(v) The decreasing trend of suspended sediment is mostly attributable to anthropogenic impacts. The impact of humans manifested through various forms of anti-erosion soil conservation practices, negative demographic trends reflected in the depopulation of rural areas of the basin, as well as the impact of water reservoirs which largely deposited suspended sediment over time.

The obtained results have great application value. First of all, they can be involved in the adequate planning of water resources.

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Speleomorphology of M3-R2 – The highest cave in the SE Carpathians

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ABSTRACT

High-alpine caves are currently in the spotlight of research as they are host to speleothems, key recorders of Quaternary environmental change. Based on modern survey and analytical techniques, we investigated the karst morphology of M3-R2 Cave, the highest alpine cave in the Romanian Carpathians. Spatial modeling in Compass has shown survey details and cave morphology. We recalculated the main cave parameters (development/extension/depth), obtaining 47 m/21 m/-18.15 m, respectively. Slope ranges between 25° and 45°, with short passage segments of 5° to 10°. The cave developed at the intersection of a SW-dipping schistosity plan with two fracture sets, occurred under compression conditions. It is a remnant of a once longer cave system, which was progressively eroded under glacial conditions. Speleothem diversity is uncommonly rich for a marble cave, with dominant moonmilk formations, stalagmites and draperies. Due to its location/elevation, evolution and speleothems, this cave has a great potential in providing important paleoclimatic information compared to other karst landforms in South Carpathians.

KEYWORDS

karst, cave survey, geomorphological mapping, Făgăraș Mountains, South Carpathians

1. Introduction

According to Bögli's simple and concise definition, 'speleomorphology is cave-oriented geomorphology, the description and interpretation of the forms in the underground which are due to corrosion, erosion, and breakdown', excluding the forms which

are the result of sedimentation (Bögli, 1980). Analysis of cave morphology – the size, shape, mineral deposits, and patterns – provides abundant information on the present or past behavior of the groundwater flow system (White & Culver, 2012). High-alpine karst is of particular importance as it develops under certain climate conditions in a cold

environment and is able to better record the changes typical to climate islands (Hedberg, 1964).

In this study we conducted a preliminary work on the morphology of M3-R2, a high-alpine cave developed in the metacarbonate stripes which occur in Făgăraș Mountains, South Carpathians. This cave is located at the highest elevation in Romania (2430 m a.s.l.). It was discovered and preliminarily surveyed in 1989 by a team of speleologists from the 'Emil Racoviță' Speleological Club (CSER) in Bucharest (Giurgiu, 2006). Ancient speleothems of M3-R2 were subject to paleoclimatic investigations and found extremely interesting as recorders of past interglacials (Drăgușin, 2013). We performed a complete survey, cave mapping and preliminary geomorphological analysis with modern cave survey instruments and methods. This study is part of a multidisciplinary research project that our team is currently carrying out in the alpine Mușeteica area in Făgăraș Mountains. Extended research on the entire karst system will result in a proper interpretation of underground morphology and speleogenesis of M3-R2 and the other caves from this area.

2. Geographic and geological setting

The M3-R2 cave (cadastral number 2015/19) is located at 2430 m a.s.l. in the central ridge-crest area of Făgăraș Mountains, 12 meters below Peak Mușeteica (2442 m a.s.l.) – Fig. 1 and Fig. 2. Karst features are developed in the metacarbonate rocks or marbles in the amphibolites facies, retromorphosed to greenschist facies (Giușcă *et al.*, 1977). Metacarbonates are hosted by medium-grade amphibolites facies in the Moldoveanu Nappe (Balintoni, 1986), the uppermost Supraetetic Unit in Făgăraș Mts.

Reported radiometric ages of its thrust plane were 114-102 Ma (Lemne *et al.*, 1983), indicating that the nappe was emplaced during the Middle Cretaceous Austrian tectogenesis.

Six caves were discovered and surveyed in the Buda-Mușeteica marble enclave at the end of the '80s: M1, M2, M3-R2, R1, M4 and M5 (Giurgiu, 1990,

2006). All these caves are presently located at elevations between 2090 m and 2430 m a.s.l. Only some small caves formed by distension in schists in the nearby Lespezi Mt exceed these elevations (2493-2512 m). The role of marble stripes in shaping the geomorphological diversity of alpine landscape in Făgăraș Mountains was outlined by Nedelea (2006a, 2006b). Karren, sinkholes, caves and potholes resemble the alpine karst morphology.

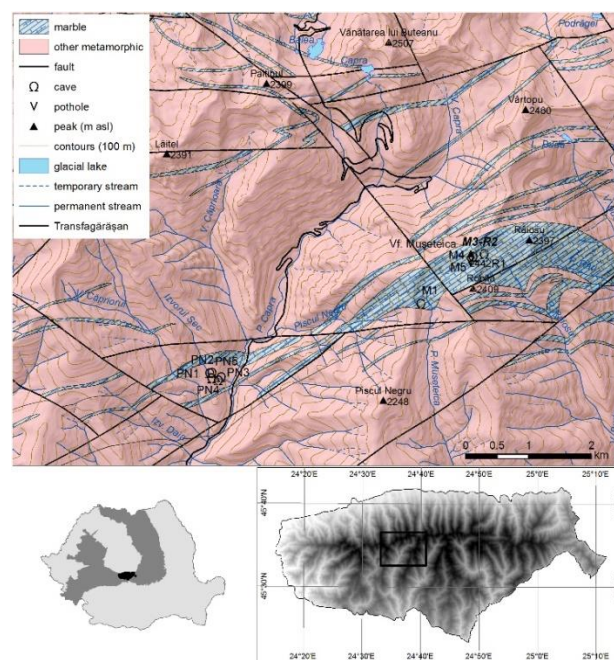


Figure 1 Geographic and geological setting of the caves in the upper valley of Argeș river, with M3-R2 outlined

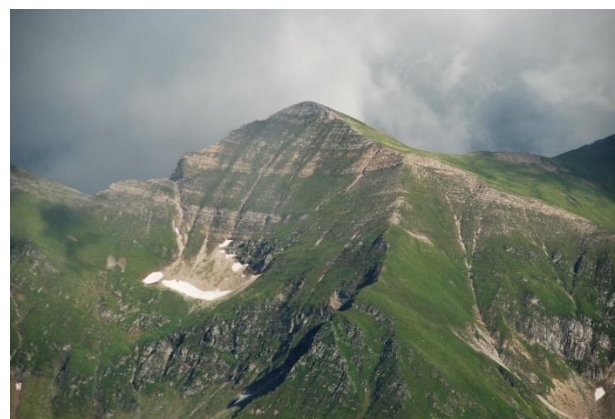


Figure 2 Mount Mușeteica (2442 m a.s.l.) displaying schistose metacarbonates

Results from continuous monitoring of microclimatic parameters in M3-R2 cave from April to October 2012 have shown that the air temperature is about 2-2.5°C during winter and variable after snow melting (up to 4.5°C), probably due to ventilation (Drăgușin, 2013). The shallow depth (10-15 m) and passage shortness makes it vulnerable to outer climatic changes.

3. Methodology

During field work we used a topographic map 1:25,000 (DTM, 1980) and the geological map 1:50,000 (Schuster, 1977). Structural measurements on joints, foliation planes and faults were performed using a Freiburger geological compass. Cave survey was carried out using a Disto™ X310 device from Leica Geosystems®, and professional speleological equipment. GPS measurements taken with a Garmin eTrex Vista® HCx were useful for the reassessment of cave elevation.

Cave survey data processing was performed using the open source Compass application. The resulted main survey lines, stations and depths served to further mapping (Fig. 3). We measured orientations of linear tectonic features in ArcMap™ using the ArcGIS 10 EasyCalculate 10 Add-Inn (Tchoukanski, 2010). The final map and profile were designed in Corel DRAW™.

Geomorphological mapping of subsurface karst features was made according to UIS symbology (Häuselmann, 2008), with details adapted from (Sencu, 1973). We created a detailed color map of M3-R2, given its modest size and morphological variety. Slightly different colors were used to emphasize the two main morphological components, speleothems and breakdown: white for calcite precipitation forms, and light grey (RGB code 245, 245, 245) for breakdown. Clayey sediment was emphasized by a light brownish color (217, 195, 139), and depth contours with annotations by a reddish-brown color (153, 102, 51). Passage walls and shafts were drawn using 0.5-width lines, 1st order morphology (e.g. steps) with 0.3-width lines, and 2nd order morphology (e.g. breakdown, contours) with 0.25-width lines.

Cave morphometry was calculated using the analytical techniques recommended by Povară *et al.* (1990). The module-based cumulative length was used to calculate cave development, the other parameters resulting directly from cave survey data. The map text box contains the projected distances representing cave development and extension. Orientation data were given in relation to magnetic north (N_m). Knowing that the magnetic declination of the cave location is +5.39° (positive), the geographic north should be considered in this sense.

4. Results and discussion

4.1 Cave morphology

The cave entrance has a NNE-SSW orientation (9.7°). In its immediate vicinity another two passage entrances can be explored, which obviously were part of the cave system in the past. Dissolution and gravitational processes have caused the formation of a collapse sinkhole at the intersection of the two remnant passages, which cannot be considered as being part of the cave at present. The collapse sinkhole has an ellipsoid shape (6.1 m in length, 3.2 m in width, and 0.5 m in depth) and its bottom is filled with rock fragments and clayey sediment. It is the highest-elevated sinkhole reported in the Romanian Carpathians. When it was surveyed for the first time, the '±0' level was taken at the B-lettered entrance, which makes logic if the cave passage was accessible through this passage. But this passage remnant is completely isolated from the cave by breakdown, so we reconsidered the setting of '±0' level.

This resulted in a different depth of M3-R2 cave, -18.15 m compared to previously reported depth of -20 m (Giurgiu, 2006). The cave is generally small, consisting in two main chambers separated by a 0.5 m-thick wall of rugged boulders cemented with calcite (Fig. 4). The cave entrance is very small (0.6 × 0.8 m), followed by a narrow, steep passage, which responds to the small chamber. A 1.3-meter double shaft connects it to the large chamber, which ends with an impenetrable ceiling-floor junction filled with sediment and breakdown up to 1.3 m in diameter.

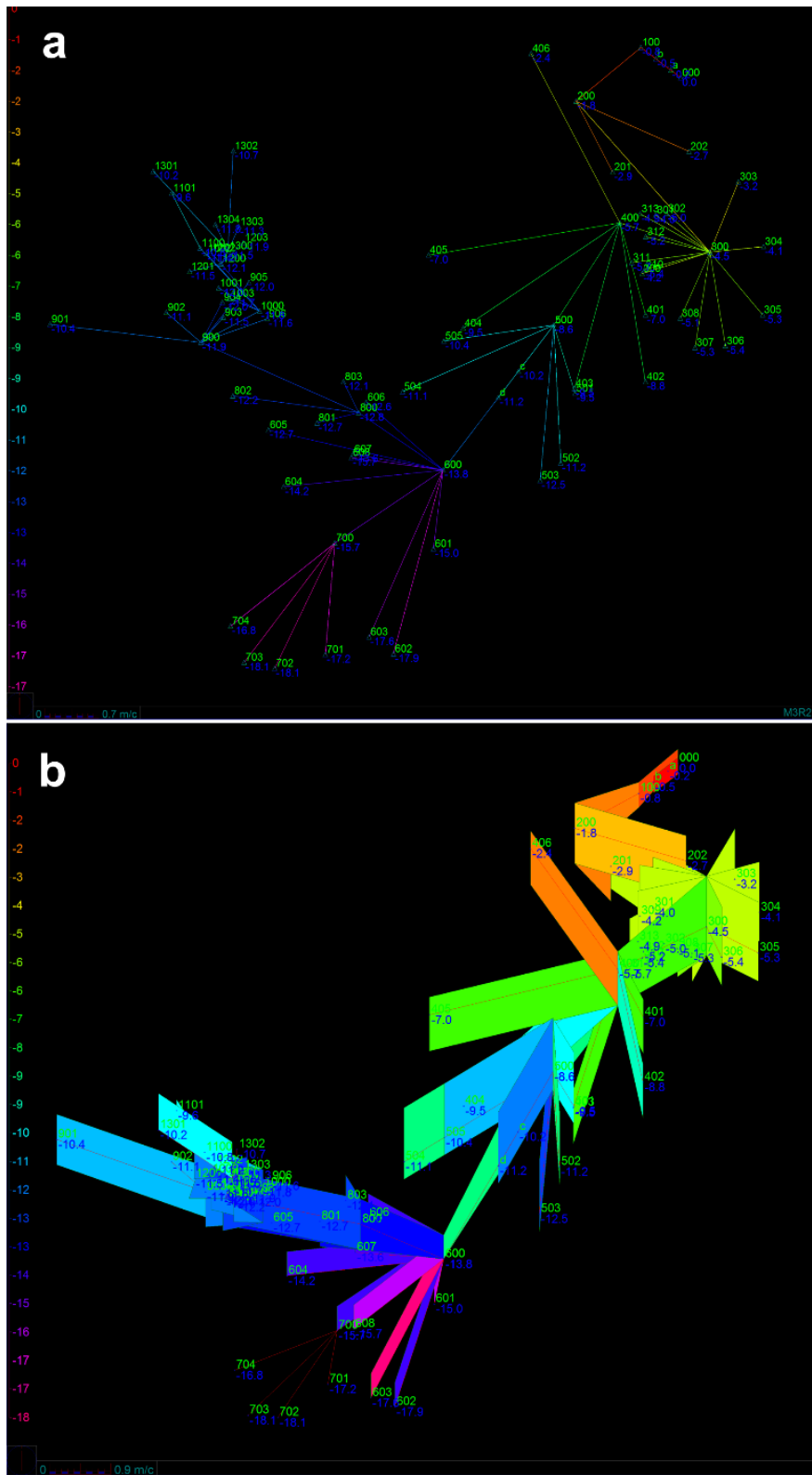


Figure 3 Modeling cave morphology in Compass (color-by-depth mode): a. Cave plan; b. Projected longitudinal profile

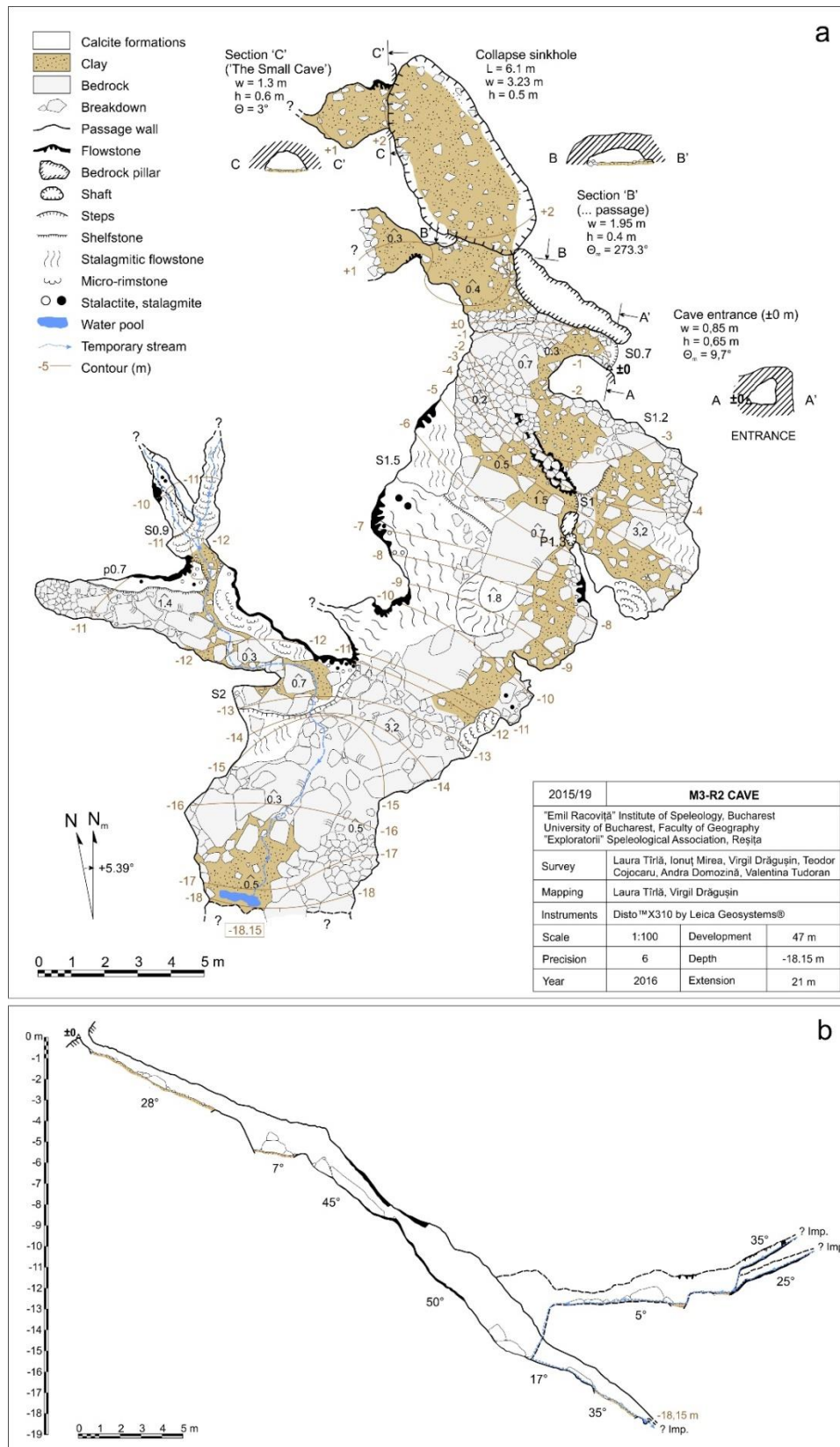


Figure 4 Cave map: a. Plan; b. Unfolded longitudinal profile

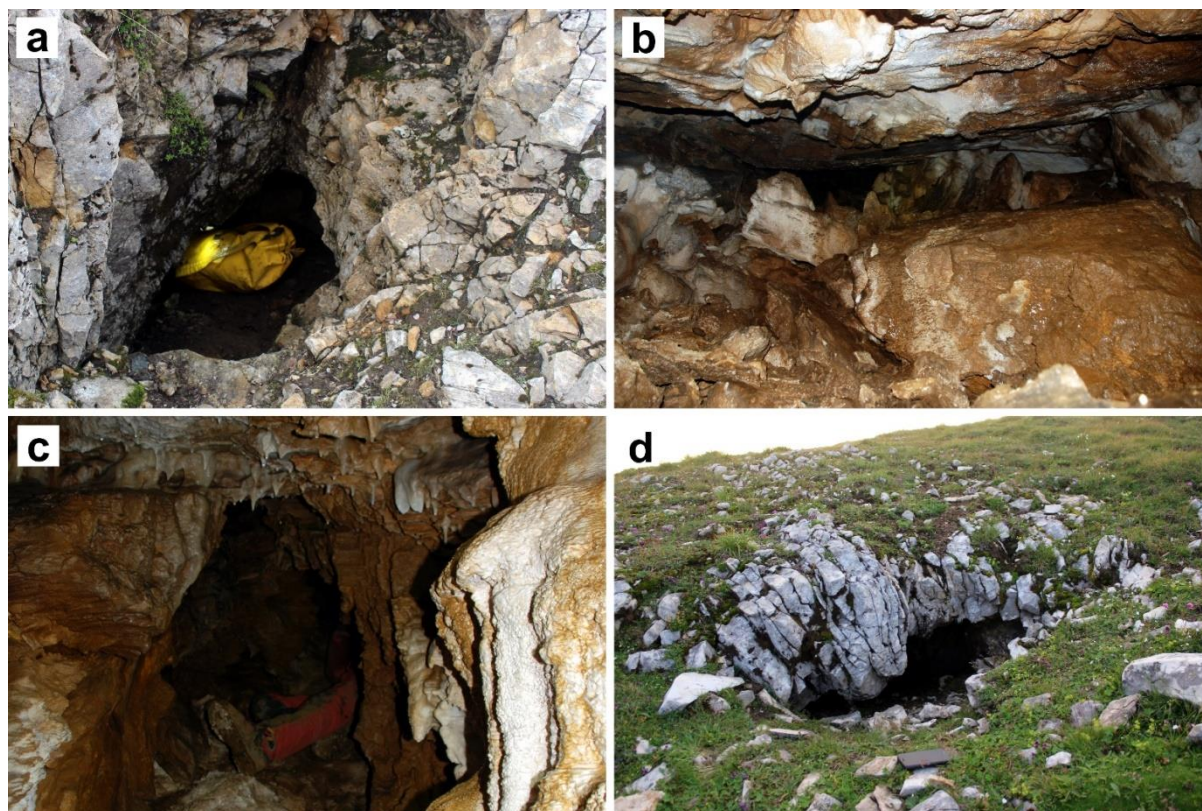


Figure 5 Cave morphology: a. Cave entrance (caving bag for size); b. The main chamber; c. 'The Pocket'; d. Entrance in a remnant cave passage ('The Small Cave'). Author credentials: I. Mirea (a), L. Tîrlă (b, c), N. Cruceru (d).

A clear difference between the shapes of cave ceiling and floor can be noticed. Ceiling morphology is quite uniform. Its planarity and dip indicate a structural control that we found to be directly related to foliation planes in the metacarbonate bedrock. In this idea, the cave most probably developed along the intersection of two planar features – a fracture opened along a foliation plane, and a fault. The floor is almost completely covered with breakdown interspersed with patches of clayey sediment. Several steps indicate tectonic floor breaks matching to ceiling breaks. The steps range between 0.9 and 2 meters in height. The Pocket's inclined floor is coated with calcite flowstone, slowly, but constantly fed by percolating water. Infiltration is active all inside the cave, mostly in this part, where a small creek forms and flows down over a 2-meters high step.

4.2 Speleothems

The cave is modestly decorated with speleothems, which is common for cavities developed in marbles.

The dense network of recrystallized calcite and increased quantity of impurities (e.g. argillaceous minerals) hamper marble dissolution and hence calcite precipitation (Ford & Williams, 2007; Onac, 2000). However, several speleothem types can be found here: flowstone draperies with serrated edges, micro-rimstones developed on the surface of flowstones, stalactites, straws, stalagmites, and helictites (Photo 3).

Draperies. Planarity and dip of the ceiling has favored calcite precipitation as asymmetric flowstones, commonly known as draperies (Field, 2002). In the M3-R2 cave, draperies have developed on the ceiling along fractures and joints and present saw-teeth serrated edges or fringes (Boga, 1997). This shape resulted by the organization of calcite crystalline network under the control of irregularities trapped on the drapery edge (Palmer, 2007).

Moonmilk. Abundance of active moonmilk is typical for this cave compared to other types of calcite precipitates. It is a microcrystalline aggregate found in M3-R2 as white patches of calcite

precipitation especially on flowstones and sided stalagmites. Frequently, moonmilk is the only speleothem present in cold, high-altitude or high-latitude caves, where massive calcite speleothems such as stalagmites do not form (Borsato *et al.*, 2000; Hill & Forti, 1997; Onac & Ghergari, 1993). Moonmilk has been attributed to a combination of both physico-chemical and biogenic processes (Onac & Ghergari, 1993), though scientific debates are far more complex, depending on each cave environment and setting.

Cacchio *et al.* (2014) stated that 'microbial activity at a constant and optimum temperature

appears to be a key factor promoting calcite precipitation and moonmilk formation'.

Stalactites and stalagmites. Only several stalagmites in the cave chambers are significant (about 5 or 6), most of them very old (MIS 5 or possibly older). One sampled stalagmite (M3-R2/01) was subject to detailed isotope analysis and U-Th dating by Drăgușin (2013), who found that it formed during the warmest period of the Last Interglacial (MIS 5e). These types of speleothems are more abundant in the 'Pocket' and its small adjacent passages, where active water infiltration contributes to calcite precipitation and speleothem growth.

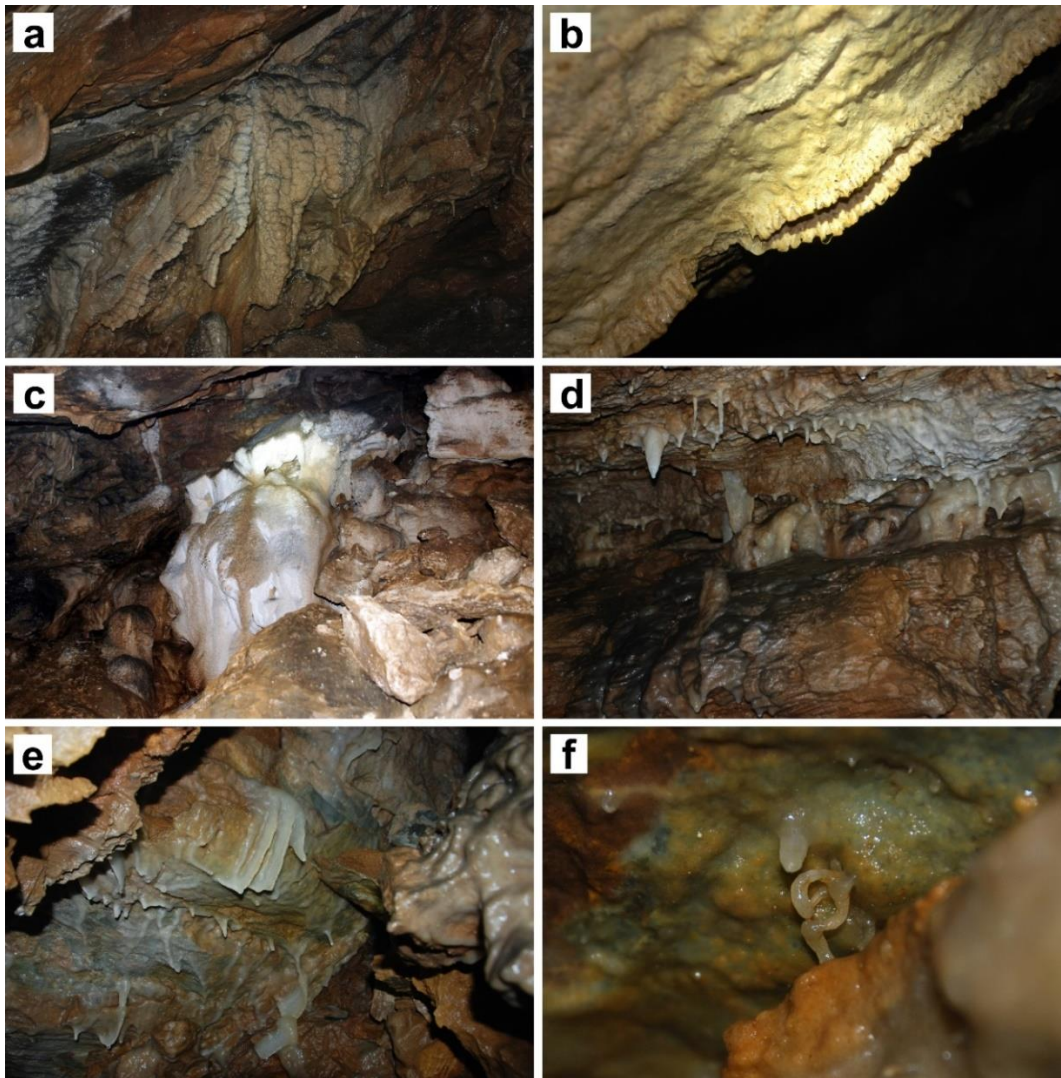


Figure 6 Speleothems from M3-R2 cave: a, b. Draperies with corrosion-shaped serrated edges; c. Massive flowstones covered by brilliant white moonmilk; d. Stalagmites and stalactites; e. Young draperies; f. Tiny helictite grown in a small niche from 'The Pocket' (water drops for scale).

4.3 Breakdown morphology

Breakdown morphology is typical for M3-R2 cave. Fallen blocks range from centimeter- sized small pieces to meter-sized slabs. Accumulations of breakdowns are frequently cemented with recrystallized calcite, particularly in the large chamber. Such type of breakdowns was taken as evidence for very deep freezing temperatures during the Pleistocene glacial maxima (White and White, 2000). Breakdown and slow calcite precipitation under the control of infiltration water are currently the most dominant processes that shape the cave main passage. Breakdown processes are most active during the enlargement and decay phases of cave development (White, 2012), the last being the most plausible in case of M3-R2 cave.

4.4 Cave morphometry

The cave pattern is simple, developed under the control of a rectangular fracture network inside the metacarbonate bedrock. Two quasi-perpendicular major fractures are visible, NW-SE- (155°) and NE-SW- (45°) oriented, respectively.

The main NE-SW-oriented fracture, where cave entrance is located, intersects the mountain topography, which leads to the assumption that most probably the cave's main passage was longer than at present, but it has progressively been eroded as the bedrock was removed by erosion. In this sense, speleothem morphology should also be considered. The most developed stalagmites and flowstones have grown in a stable underground environment, at depths and distances from the cave entrance where external climate oscillations could not have influenced them.

The microtectonic pattern of bedrock joint sets has revealed an orthogonal joint network reflected on passage orientations (Fig. 7). This is typical to extensional forces acting upon the bedrock, different from conjugate (shear) joint sets, which tend to merge with the first set at angles from 30° to 60°, often around 45° (e.g. Davis *et al.*, 2012).

Morphometric analysis was resumed by three main parameters, conventionally accepted as being essential for cave morphometry: development, extension, and depth (Povară *et al.*, 1990). The cave pattern is schematically illustrated in Figure 7. It consists in 10 segments or passages with various lengths and orientations (Table 1). The total cumulative projected length of cave passages is 47 m and represents the cave development. Additionally, calculations accounted for the tridimensional projection of all passages (Table 1, Fig. 7). Slope ranges from 5-7° to 45°-50°, averaging ~40°. It is comparable to measured foliations in the marbles dipping 27°-35°.

The length of the two remnant passages with entrances located in the collapse sinkhole was not considered, because they are not physically linked to the cave at the moment. Even if the B passage is part of the karst system, it is completely blocked with breakdown and access into the cave is not possible through it. Extension is given by distance between the extreme points of the cave, 21 m. Cave depth is -18.15 m. Previous morphometric data reported by Giurgiu (2006) were different compared to our results, especially the length of cave passages (86 m?). These may have resulted due to the lengths of all remnant passages (now disconnected from the cave), which were considered in the measurements, as well as to some morphological changes that occurred since the initial survey.

Table 1 The main parameters of cave passages

Passage ID	Projected distance (m)	Real distance (m)	Width (m)	Height (m)	Orientation (°)	Slope (°)
P1	1.7	1.9	0.8	0.7	110	25
P2	2.4	2.8	2.1	0.8	65	30
P3	7.8	9.5	4.2	2.2	148	35
P4	16.0	22.6	8.3	3.2	40	45
P5	2.3	2.3	1.7	0.7	125	5
P6	5.8	5.9	1.9	0.7	102	10
P7	3.4	3.4	1.2	1.5	165	5
P8	1.9	2.3	0.6	0.3	157	35
P9	2.9	3.2	0.5	0.3	143	25
P10	2.7	3.0	0.8	0.5	13	25

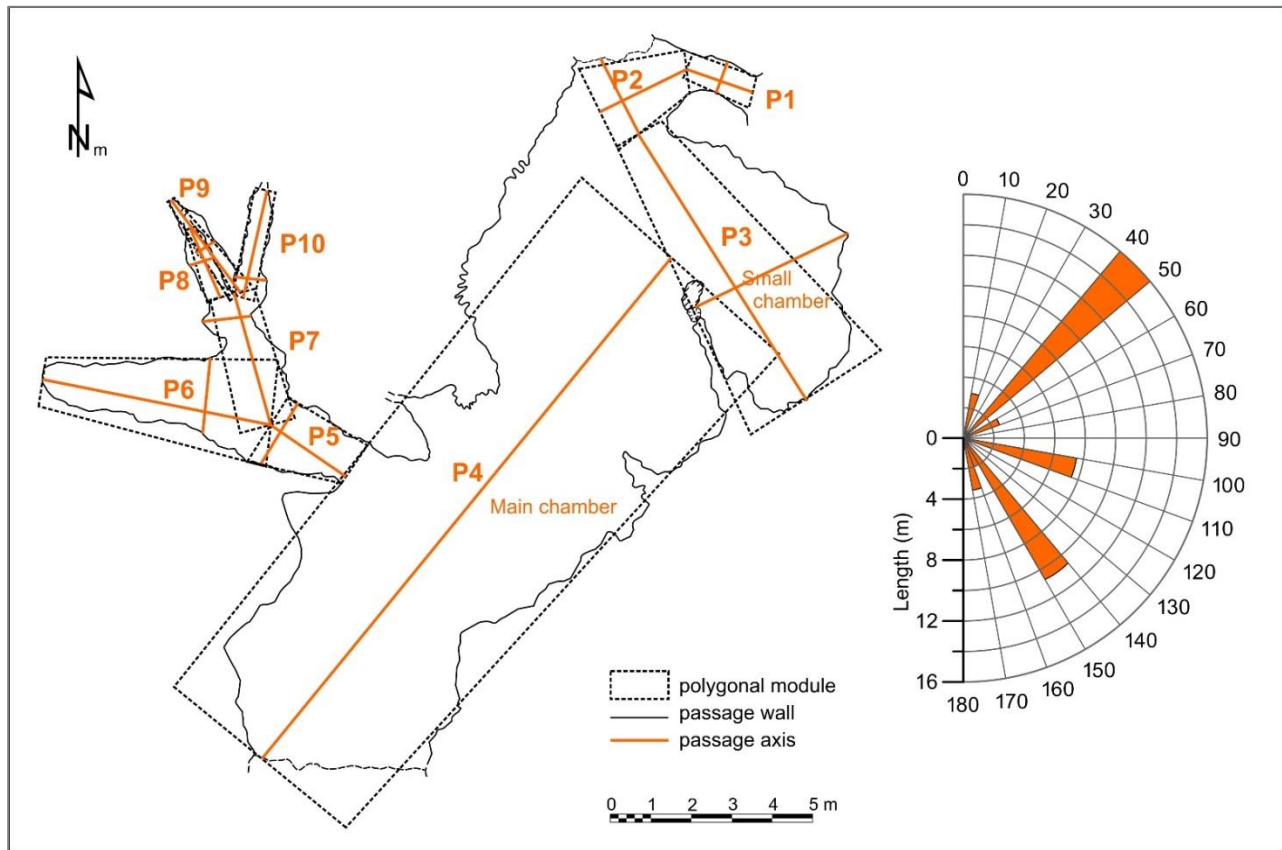


Figure 7 M3-R2 cave passages (P_n) and rose diagram showing orientations of cumulative lengths

5. Conclusions

A new map of M3-R2 was created using modern survey and mapping techniques. It shows the two main morphological components of the cave: speleothems and breakdown. Stalagmites, draperies and moonmilk are the most dominant forms of calcite precipitation. Biogenic activity in a cold, alpine environment is most probably responsible for moonmilk abundance. Breakdown morphology is the other dominant component. Agglomerations of breakdown were stabilized by cementation with recrystallized calcite. The floor is partly covered by clay formed by infiltration of impurities resulted from alteration processes in the marble bedrock.

Morphometric data indicate that it is a small cave, with no spectacular sizes. It has 47 m in length, 21 m in extension and -18.15 m in depth. It is a remnant of a probably longer karst system, reduced to several passages due to mountain slope retrogression caused by erosion. Formation of well-developed speleothems could not have been

possible unless in a stable underground environment, hardly influenced by external factors.

This study was prepared to serve for further research on karst in the central area of Făgăraș Mountains, considering the high potential of alpine karst to provide valuable information on the Quaternary evolution of South Carpathians.

Acknowledgements

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Paleodrainage network reconstruction on Miroč Mt. (Eastern Serbia)

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ABSTRACT

The paper represents a geomorphological study related to the transitional forms between fluvial and karstic process. Karst areas of eastern Serbia are distributed in a large number of relatively isolated segments, and therefore abound in contact karst features. In many cases, central parts of karst areas, away from the contacts, host a variety of relict and dry valleys. Morphological analysis of these valleys may reveal the remnants of paleodrainage networks and help to reconstruct the morphological evolution of the area. This is a case study of the karst of Miroč Mt. in north-eastern Serbia, where geomorphological analysis and relief visualization using the Geomorphological Information System enabled the detection of paleodrainage directions and patterns in the vicinity of the Danube Gorge. Three paleo-river systems were detected, the largest of which is that of the Suva Reka (51 km²).

KEYWORDS

karst morphology, paleodrainage networks, stream order, GIS, Serbia

1. Introduction

Carpatho-Balkan mountains of eastern Serbia have a relatively complex geological composition, consisting of the lithologies of almost all ages from the Proterozoic to the Quaternary. Several large

orographical units, stretching from the Danube Gorges (Iron Gates) on the north, to the Balkan Mt. and further to the south-east, are composed predominantly of carbonate rocks of either Jurassic or Cretaceous age. These carbonate mountains are characterised by dry slopes and plateaus, dissected by deep gorges of allogenic streams.

One of the most significant mountains of the eastern Serbian Carpathians is Miroč Mt. The aim of this paper is to analyze the elements of Miroč surface karst morphology in terms of detecting the extensive linear forms – relict valleys in karst. Most references attribute the origin of these valleys to the fluvial process, active prior to the onset of the karstic process. In certain cases, the linear morphologies are still visible on the mildly inclined karst surfaces, while in most other cases the suspected river network is totally disintegrated.

By the term "*paleodrainage network reconstruction*" we consider the detection of dry and relict valleys on karst, identification of possible thalwegs (e.g. Bočić *et al.*, 2015) and interpretation of possible sequence of geomorphological evolution. Most references claim the fluvial origin of this kind of valleys (Warwick, 1964; Bočić, 2003; Košutnik, 2007; Povara and Conovici, 2013; Petrović, 2015), while some refer to tectonic origin (Gams, 1998).

In Serbian literature, fluvial interpretations of linear forms on Miroč karst are dominant (Cvijić, 1921; Milić, 1965; Zeremski, 1988). However, detailed morphological analysis of the dry and relict valleys was missing. This paper gives one of the possible interpretations of morphological evolution of Miroč karst plateau, with the main aim of determining the directions of the former drainage.

2. Geological-geomorphological characteristics of the study area

Mt. Miroč belongs to the northernmost part of the Carpathian Mts of eastern Serbia (Fig. 1). It stretches in N-S direction for about 25 km, with maximal width of 8 km in W-E direction. The highest point in relief is the Veliki Štrbac peak (768 m a.s.l.), while the lowest points are situated on the Danube banks (68 m a.s.l. on average). The largest part of the mountain surface lies between 400 and 500 m a.s.l. Karst relief covers 143.5 km² and limestones are predominantly of the Upper Jurassic age.

Tectonically, Mt. Miroč is an autochthonous unit represented by the Miroč anticline. The anticline axis strikes approximately in N-S direction (Anđelković and Nikolić, 1980).

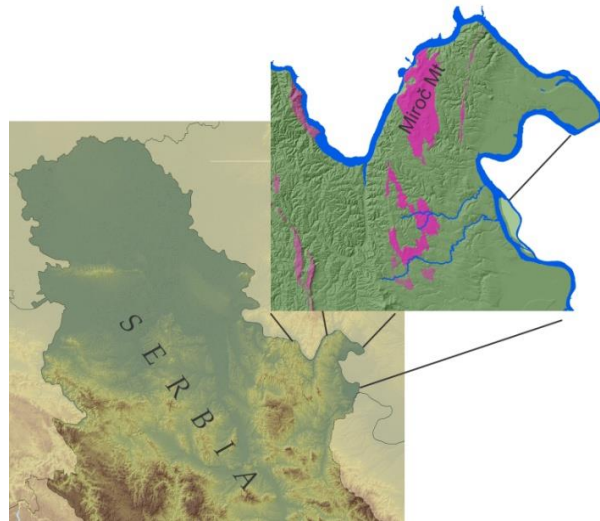


Figure 1 Location of the research area

On the anticline limbs, on the eastern and western side, there are remnants of the Gethic nappe that formerly covered the area. The anticline hinge is in one segment eroded to the Middle Jurassic marls, which are the oldest lithology on the plateau, representing a tectonic window (Anđelković and Nikolić, 1980). Central parts of Miroč consist of the Tithonian reef limestones (J33) (Fig. 2), surrounded by marly Cretaceous limestones and flysch (Bogdanović and Rakić, 1980). The core of the Miroč anticline consists of the Precambrian crystalline schists (Anđelković and Nikolić, 1980).

Tectonic setting of Miroč, with the dominant anticlinal form, led to the development of the systems of vertical ruptures in limestones, striking predominantly N-S along the anticline axis. Apart from those, structural-tectonic mapping carried out within the series of speleological explorations of the area revealed the ruptures striking NE-SW as well (Zlokolica-Mandić *et al.*, 1996; Mandić *et al.*, 1997).

In the surface morphology of Mt. Miroč, the forms of karstic and fluvio-karstic process clearly dominate: dolines, some small uvalas, and blind valleys. The karstic plateau Miroč – Ciucarul Mare (in Romania), which was once a continuous morphological unit, today is divided by the deep Danube gorge. Thus, the western rims of the Miroč karst plateau are represented by the high, steep escarpments towards the Danube (Fig. 3).

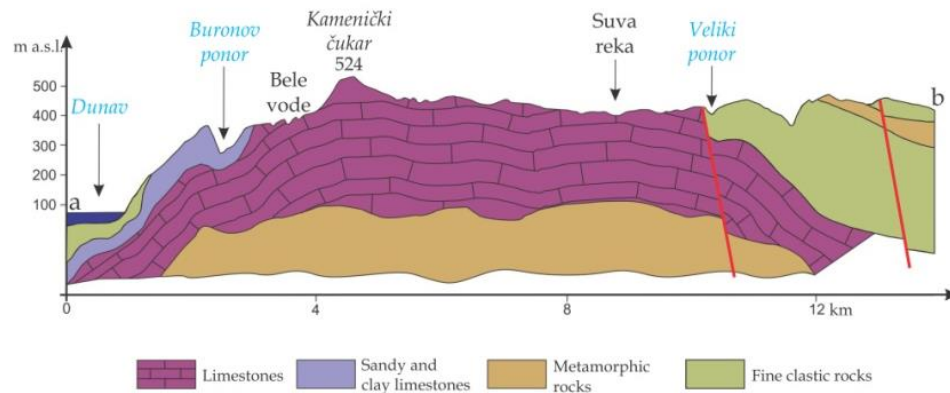


Figure 2 Structural-tectonic profile of Miroč Mt. (profile a-b on Fig. 5)



Figure 3 Steep escarpments of the Veliki Štrbac peak above the Mali Kazan gorge

Dolines are the most usual karst form on Miroč Mt. In a detailed morphological study, Telbisz *et al.* (2007) detected 3164 dolines, with an average density of 24.9 km². Distribution analysis shows that the dolines are grouped in several belts of N-S direction (Fig. 4), and are present on the surfaces with the inclinations of up to 12° (Telbisz *et al.*, 2007).

3. Methods

Reconstruction of the paleodrainage network on Miroč Mt. was done on the basis of fieldwork, geomorphological mapping and GIS analysis. The series of previous morphological studies in this area (to mention just a few – Zeremski, 1988; Mandić *et al.*, 1997; Djurović (ed.), 1997; Ljubojević, 2001;

Telbisz *et al.*, 2007; Mari *et al.*, 2007; Čalić (Ed.), 2015; Petrović, 2015) have covered the research of surface and underground forms of the Miroč karst. The results have depicted the mutual relations both between the surface karstic and non-karstic morphology, and the surface and underground karst. The fieldwork was the introduction to the geomorphological mapping of the Miroč karst plateau and the development of the Geomorphological Information System – GmIS (Petrović, 2015). Geomorphological mapping was carried out according to the standards of the Detailed geomorphological map of SFR Yugoslavia at the scale 1:100.000 (Gams *et al.*, 1985), and the symbols and colours in this paper follow these standards as well.

The basis for the GmIS was the digital terrain model (DTM), set up by digitizing of contours of 10 m vertical resolution and using interpolation techniques. For the development of the DTM, as well as for the complete GmIS, the *ESRI* package for geospatial data processing *ArcMap* was used.

The results of the mentioned studies and analyses (particularly the doline distribution) have helped in determination of particular parts of the drainage network in three types of valleys: active, dry and relict (cf. Bočić *et al.*, 2010; 2015; Petrović, 2015). Active valleys are those which host permanent or seasonal waterflows, the latter being much more frequent on Miroč. *Dry valleys* are without any water streams at the bottom, but they have a valley bottom of continuous inclination towards the former “mouth” into the main watercourse (Petrović, 2015). This type of valleys is

the least represented on Miroč and therefore are not visible in the figures within this paper, due to the scale. *Relict valleys* do not have a continuous inclination of the valley bottom, but the thalwegs host series of dolines, roughly indicating the fluvial pattern (Petrović, 2015; Bočić *et al.*, 2015). This is the dominant type of valleys on Miroč.

Reconstructed drainage networks on Miroč (and the valleys within them) were grouped in orders and shown on the map (Fig. 5) according to the Strahler method (Strahler, 1957), taking into account the frequency distribution of the length of the valley segments and relation of stream length to stream order.

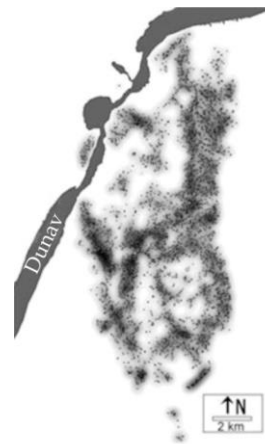


Figure 4 Doline density on Miroč Mt. (Telbisz *et al.*, 2007)

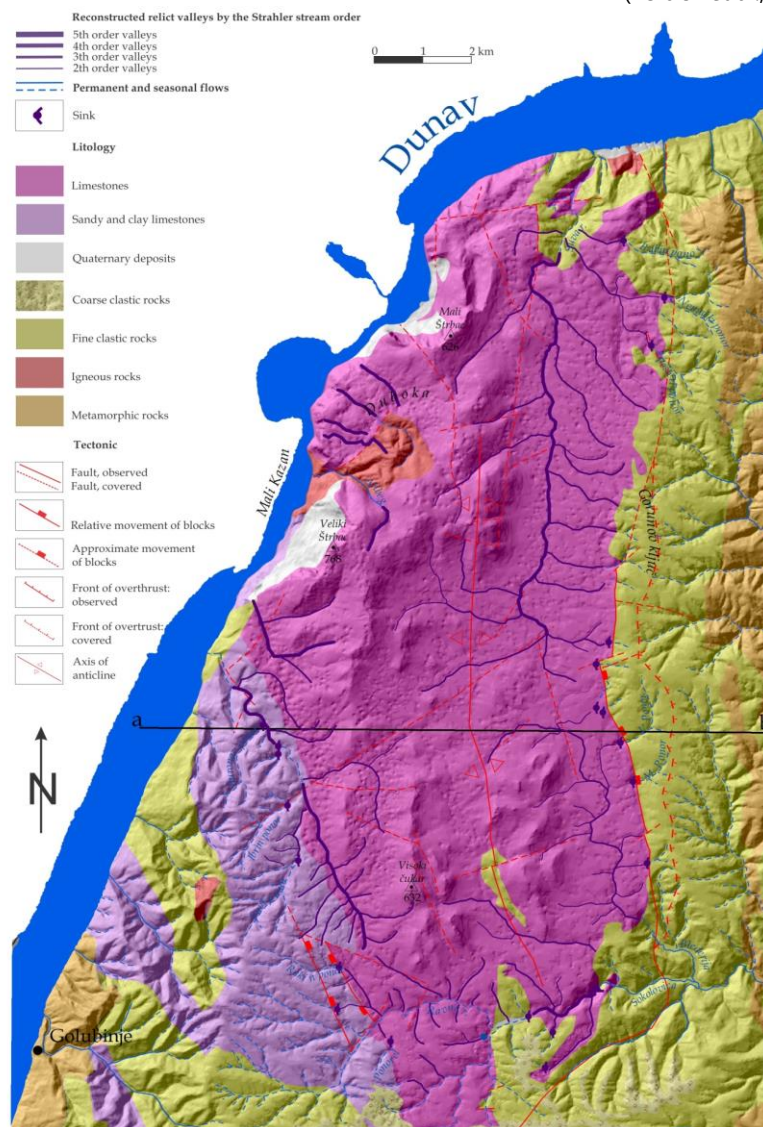


Figure 5 Map of Miroč Mt. with paleodrainage network

4. Results

Karstic plateau of Miroč is surrounded on three sides by impermeable rocks, so it can be said that its perimeter is characterised by contact karst. To the east and west from the karstic plateau, the area is somewhat higher. Therefore the short streams (1-1,5km) descend towards the limestones (Fig. 5). Considering the small quantity of water in temporary streams, they by rule sink on the contacts or immediately downstream from the contacts. Two long lines of blind valleys (western and eastern) were formed in this way (Petrović, 2015).

The eastern belt of blind valleys starts close to the Veliki Beljan village on south-eastern Miroč (Veliki Ponor and Mali Ponor), finishing on the north with Babin Ponor (Fig. 5). Downstream of these ponors, the relief most usually shows karstified valleys belonging to paleodrainage networks of Cvetanovac (on the south) and Suva Reka (on the north) (Fig. 6). These valleys with dolines along their bottoms are hanging 15-40 m above the final parts of blind valleys. Due to a considerable degree of karstification, they do not have the continuous inclination of the valley bottom, so they belong to the group of relict valleys. The direction of the blind valleys and their downstream parts (relict valleys) is determined by the existence of the "tectonic depression" on the eastern limb of the Miroč anticline (Zeremski, 1988). Structural-tectonic impact is responsible also for the asymmetric form of certain drainage areas, especially in the case of Suva Reka (Fig. 6). For that reason, Suva Reka had much more right tributaries than left tributaries (Fig. 5). It is the valley of the relict type as well, 12.5 km long, ending 260 m above the Danube. Suva Reka is developed along the mentioned tectonic depression on the plateau. The western line of ponors and blind valleys starts with Ponorel on the south and ends with Buronov Ponor on the north (Ljubojević, 2001).

As opposed to the eastern rim of the Miroč karst, characterised by the contact of limestones and fine clastic rocks (Fig. 6), the western contact lies in the zone where the Upper Jurassic limestones are present next to the Lower Cretaceous marly and clayey limestones in normal sedimentary superposition (Fig. 5).

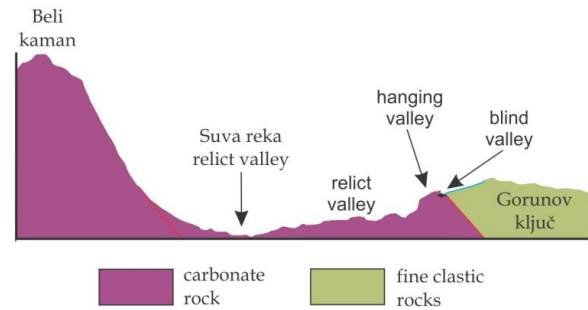


Figure 6 Cross section of the Suva Reka relict valley



Figure 7 Cvetanovac Ponor (photo: D. Smiljković)

Next to this contact, the dry/relict valley of Bele Vode and its drainage network are formed. The similarity between the Bele Vode drainage pattern and Suva Reka drainage pattern lies in the direction of the main valley and asymmetric shape of the drainage area. There are several differences as well. Apart from being karstified, the valley of Bele vode is more conspicuous in relief than the valley of the Suva Reka. In the central part, there is a weak watercourse, so the valley is not completely relict. The valley of the Bele Vode is 6.6 km long, ending about 100 m above the Danube. The valleys of the former left tributaries of the Bele Vode end blindly 10-30 m lower than the main valley bottom. They are slightly shorter (2-3 km) than the blind valleys in the paleodrainage network of the Suva Reka.

In the southern part of the Miroč karst plateau, there is the third paleodrainage network – Cvetanovac (Ravna Reka). It consists of active, dry, relict and blind valleys. The fact that two toponymes exist for this drainage area points to the different

characteristics of particular parts of the valley. The upstream segment of the Ravna Reka lies in impermeable rocks. Reaching the limestone part of the basin, the Ravna Reka sinks into the fissures on the valley bottom. Only during the floods, the flow reaches the downstream parts of Cvetanovac (Milić, 1965). This part of the valley is hanging 15 m higher than Cvetanovac. All the tributaries in the karstic part of the area are dry, with dolines along the bottoms. Cvetanovac is seasonally hydrologically active, fed by the karst spring of Fruseniš Potok. Alluvial sediments, into which Cvetanovac waters are sinking, cover the contact between impermeable lithologies and limestones (Fig. 7).

Downstream from the ponor, there is a relict valley of the main river, hanging on both sides, with the relict valleys of their paleo-tributaries. Cvetanovac waters emerge from the outflow cave Sokolovica (Zeremski, 1988) and feed into the Blederijska River. The valley of the former northern tributary of Cvetanovac, which was draining the south-eastern part of the Miroč tectonic depression, remained hanging high above the present spring of Blederijska (to see Fig. 5).

5. Discussion

The initial relief of Miroč Mt. was a central plain of a former marine strait that existed during the maximum of the Pontian transgression (Milić, 1965). The strait was subsequently used by the Paleo-Danube for the development of its epigenetic valley (the Kazan gorge). At that time, Bele Vode and Suva Reka were the right tributaries of the Paleo-Danube (Cvijić, 1921), which was subsequently feeding into the Dacian Sea. Ravna Reka (Cvetanovac) also flew to the Dacian Sea, to the south-east of Miroč.

All three rivers formed their drainage areas in impermeable rocks that were covering the limestones. Having in mind the lengths of the tributaries, the sizes of the drainage areas (max. 51 km², Suva Reka) and the fact that the main valleys belong to the 4th order in Strahler's classification (Strahler, 1957) (Fig. 8), we can conclude that these flows did not have considerable discharges.

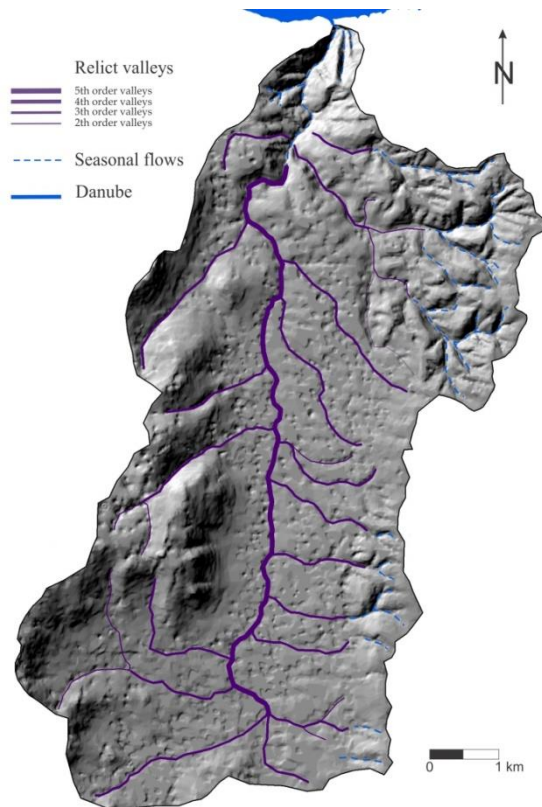


Figure 8 Paleodrainage network of the Suva Reka river reconstruction on central Miroč Mt.

The valleys of the Suva Reka and Bele Vode stretch in the N-S direction. Structural-tectonic influence of the Miroč anticline on the drainage pattern is evident. The further evolution of the drainage network caused the impermeable lithologies to be washed away. This process led to the development of fluvio-karstic levelled surfaces below the peak of Veliki Štrbac (Zeremski, 1988). After the recession of the Dacian Sea towards the east, faster incision of the Danube took place. This was the most important factor of the karstification of Miroč karst plateau, apart from the mentioned intense fissured porosity ("la fracturation particulièrement intense"; Ambert and Nicod, 1981), small discharge of the streams and the existence of extensive fluvio-karstic surfaces (Petrović, 2015). NE-dipping limestones enabled the groundwaters to drain towards the Danube, using the existing systems of fissures. Miroč limestones are deeply karstified, which is proven by the existence of strong karst springs (Pena, Pešter, Hajdučko Vrelo, Bele Vode), as well as by the depth and extent of major

caves, like Rakin Ponor, Nemački Ponor, Buronov Ponor (Zlokolica-Mandić et al., 1996). Their depths may exceed 200 m, with max.-285 m depth in Rakin Ponor (Čalić (ed.), 2015).

With gradual sinking of surface waters on Miroč, the fluvio-karstic phase finishes, giving the dominance to the karstic phase in relief formation. Due to intensive karstification, the bottoms of the valleys of Bele Vode and Suva Reka, together with their tributaries, turn to dry valleys and subsequently to relict valleys with dolines at their bottoms. Deep dolines completely changed the previously present relief forms, so a number of relict forms are difficult to distinguish. However, higher density of dolines (Fig. 4) point to the paleodrainage areas of Bele Vode, Suva Reka and Ravna Reka (Cvetanovac), within which one can reconstruct the former valleys of the main rivers and their major tributaries.

6. Conclusions

Former studies of karst relief on Miroč Mt. did not completely reconstruct the drainage pattern on the Miroč karst plateau. The reason was probably the fact that the relict valleys in karst were difficult to distinguish, due to the long-term impact of karstic process on the former fluvial relief. Usage of the modern geospatial analysis tools, as well as the formation of the GmIS, enabled the more precise reconstruction of paleo-drainage areas and paleo-drainage networks on Miroč Mt.

Suva Reka, Bele Vode and Ravna Reka (Cvetanovac) were short water courses with relatively small drainage areas (max. 51 km²). The first two were feeding into the Paleo-Danube, and Ravna Reka directly into the Dacian Sea. Development of the paleodrainage networks of these rivers turned from fluvial to fluvio-karstic phase after the erosion washed away the impermeable surface layers. Fast withdrawal of the Dacian Sea and, accordingly, incision of the Kazan Gorge of the Danube intensified the transition from fluvio-karstic to the karstic phase. Active streams disappear from the karst plateau of Miroč, while their valleys become dry. With the long-term impact

of the karst process, deep dolines develop along the thalwegs of the dry valleys, turning them into the relict valleys. Only the allogenic river of Ravna Reka remains active at some segments. Short streams from the impermeable parts of the former drainage areas sink on the contact with limestones or immediately downstream from the contact. These streams form two N-S oriented belts of blind valleys – eastern and western. Relict valleys of the Bele Vode, Suva Reka and Ravna Reka (Cvetanovac) remain in hanging positions high above the Danube and Blederiya.

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Hydrogeomorphic exploration of a local headwater stream in low mountainous environment following detailed field survey protocol (Mecsek Mountains, Hungary)

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ABSTRACT

Comprehensive field survey of the physiographic context and channel morphology is a key to distinguish characteristic hydrogeomorphic reaches of a watercourse. In this analysis field data were collected during seasonal campaigns following a field survey protocol developed in the Polish Carpathian Mountains. Complementary information was conducted from cartographic materials and digital elevation model to map diverse sections of the semi-natural Váralja Stream in the Eastern Mecsek Mountains. Geological, geomorphological and anthropogenic effects had to be considered as decisive factors in recent fluvial development, with emphasis on the sediment transport influenced by woody debris. A total of 12 hydrogeomorphic reaches were identified along the stream by interpreting the spatial arrangement of channel forms and analysing the characteristics of the watershed environment. The mapped reaches are connected with transitional zones of different length. Step systems are typical on the upper reach of the stream, but they were found to be the result of the geological composition and structure of the region. It was also proven that woody debris accumulations, made up of tree trunks, branches and roots have significant influence on the channel evolution of the Váralja stream. Even though the presented field survey instructions were field-tested in alpine catchments the conducted research confirmed the applicability of such workflow in low mountainous environment. Furthermore, the results on the hydrogeomorphic conditions of this small watershed with intense relief provide useful information for understanding the flash floods occurring in the region.

KEYWORDS

field survey protocol, channel morphology, geomorphometry, woody debris, Mecsek Mts.

1. Introduction and objectives

More than 60 percent of cumulative length of the river network belongs to headwater streams, globally (Benda *et al.*, 2005). They play a great role in feeding lowland rivers with water and sediments and also in connecting hillslopes and fluvial processes (Galia and Hradecky, 2014). Beyond their geomorphological importance the hydrological and ecological studies also concern the headwater streams. The hydrology of small catchments and interacting subsurface runoff and channelized flow were analysed to model hydrogeomorphic system of a steep watershed (Sidle *et al.*, 2000). Forests have a great influence to development of headwater streams as living or dead dams (log and root) for small streams. Moreover, an intensive forestry and anthropogenic effects on land cover changes in mountainous environment can overmuch produce woody debris (WD) into channels. This process leads to a significant change in the sediment transport, longitudinal profile and the slope-channel system (Bilby and Ward, 1991; Harvey, 2001). These various hydrogeomorphic studies put headwater streams and watersheds in spotlight, recently.

Although the number of scientific papers concerning headwater (small) streams is growing a universal and simple definition of these features of the fluvial network is still missing (Benda *et al.*, 2005). According to the widely-used Strahler's (1957) definition a headwater stream has a first or second order channel, but it has to be mentioned that the Horton-Strahler (HS) channel ordering system depends on the basic map resolution or the ephemeral character of the streams during field observation. It is self-explanatory that distinguishing between stream orders is difficult on the field, especially in mountainous environment under canopy cover. Other supposed criteria (i.e. slope gradient, watershed area, transition zone etc.) are strongly modified by local settings, moreover a few of them is also time dependent. Thus, a classical evaluation developing for low gradient rivers is not applicable to classify mountain channels into various environments (Galia and Hradecky, 2014).

The formation and transformation of river beds, fluvial landforms and the spatial and temporal

changes of river channel patterns are indicative of the specific conditions of valley development and landscape evolutionary trends. Since the pioneering study of Leopold and Maddock (1953) to the present day a broad variety of channel classification systems were published almost yearly further investigating an ever-increasing number of parameters (Kaszowski and Krzemień, 1999; Lóczy *et al.*, 2012; Grecu *et al.*, 2014). However, the bed forms at the spatial scale of channel units in small streams were hardly studied (Grant *et al.*, 1990). Only few studies deal with systematically exploring channel units in non-alluvial or semi-alluvial channels at headwater environment (Halwas and Church, 2002).

The available classification systems consider dozens of criteria. The most commonly analysed parameters are channel pattern (e.g. Leopold and Wolman, 1957; Montgomery and Buffington, 1997), stability (e.g. Schumm, 1963), the channel material and transported sediments (e.g. Raczowska 1983) and the dominant processes (e.g. Kaszowski and Krzemień, 1999). Channel classifications and descriptions are typically based on the interpretation of aerial photographs, topographic and geological maps and hydrological data (Popov, 1969). Only few investigations supplemented the commonly applied laboratory methods with extensive fieldwork (Rudberg and Sundborg, 1975). Other approaches followed a standard guideline for channel analysis and mapping during the field survey (Krzemień, 1981; Kamykowska *et al.*, 1999).

In this study, we adopt the latter methodology to explore the morphometric characteristics and channel development of a semi-natural headwater stream in a Hungarian low mountain environment. The scale of this channel classification methodology was changed as most of the Hungarian streams located in the hilly and low mountainous environments are small. Main advantages of this method (straightforward, comparable, repeatable and scale flexible) were utilized to get a complex and comprehensive system to explore hydrogeomorphology of the analysed stream channel. Headwater streams and watersheds have been hardly studied in Hungary, it was the most easily acceptable standard method based on field observation.

There is a scientific need to analyse these small watersheds with headwater streams, because of the increasing number of extreme hydrometeorologic events in the last decade in Hungary (Horváth, 2005, 2015). The more frequently occurring flash floods require extensive research on these previously neglected watersheds and streams (Czigány *et al.*, 2010). Even though, many other factors influence the occurrence of flash floods (Czigány *et al.*, 2011), the topography and the channels draining the water are considered amongst the most important. Field observations on these small watersheds, a channel-reach classification and analysis of the spatiotemporal pattern of the landscape evolution is essential to the understanding and proper management of future flash floods.

The aim of this study was to evaluate the morphometric characteristics of a semi-natural headwater stream and explore the applicability of a

standard Polish channel mapping method in a Hungarian low mountainous environment. For this purpose, detailed information was recorded about the channel parameters and forms on the standard register form of the field survey protocol, moreover the forms were mapped using GPS devices and recorded on photos. The gathered information supplemented with geological and GIS-based data was interpreted to delineate characteristic reaches of the Váralja stream according to the method of Kamykowska *et al.* (1999). The research also focused on exploring the factors influencing the channel-reach morphology of the studied sections.

A secondary objective of the study was to present the scientific problems arising in case of the hydrogeomorphic interpretation of headwater streams in low mountains for wider and international professional audience was also aimed.

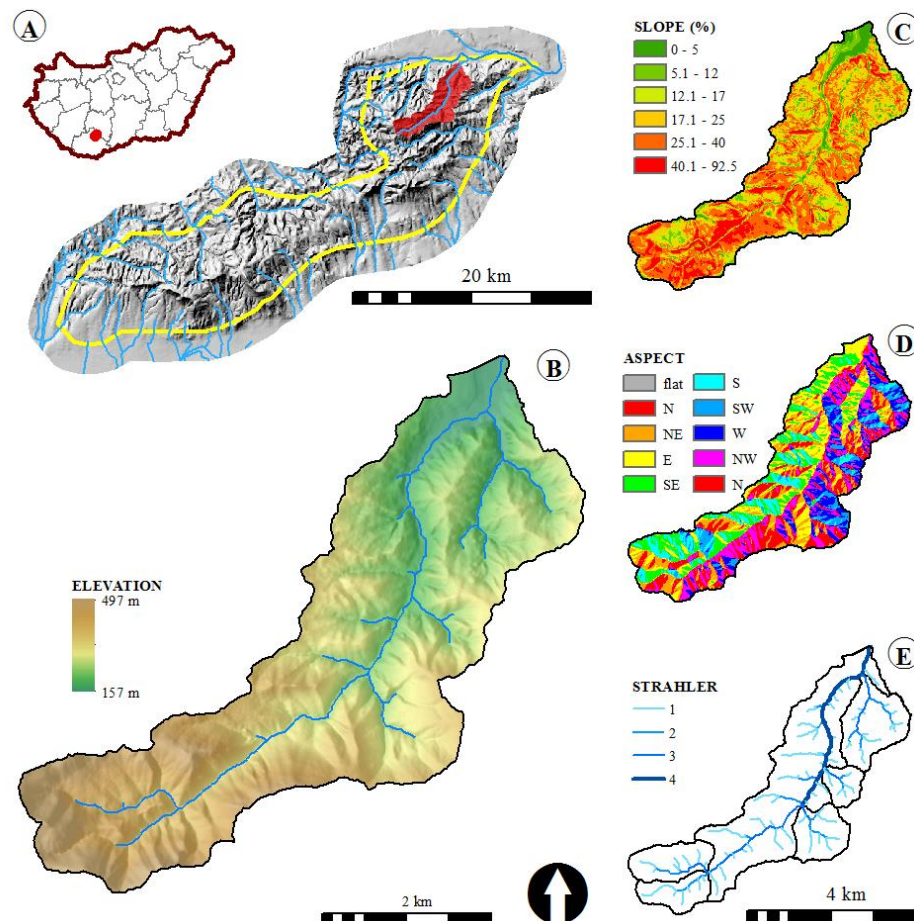


Figure 1 Location (A) and topography (B) of study area, slope (C) and aspect map (D), and ordered channel network (E) of the Váralja watershed (edited by E. Józsa).

2. Study area description

The studied Váralja stream is located in the northern part of the Eastern Mecsek Mountains, in Tolna County (Fig. 1). The watercourse joins the Danube water system through watercourses of local significance. The elongated catchment area of the stream covers about 15 km², the coordinates of the outlet: 46°16'35.2"N, 18°26'36.9"E. It should be noted that the watershed is uncertain around the outlet reach (cf. Table 1 and online web GIS application of HISSTWMD¹: <http://ddvir.ddvizig.hu:8000/ddvir/flex/ddvir.html#>). The second highest peak of the Eastern Mecsek Mountains (Dobogó, 593.7 m) is situated at the western boundary of the basin. Gradually lowering ridges and interfluvies are lined up symmetrically on both sides of the valley, e.g. Szamár Hill, Szószék, Csalán Hill, Nagy Hill, Közép Hill, Váralja Hill, Szarvas Hill. The mean elevation of the basin is 313 m above sea level.

The area is minutely dissected, in the upper valley relative relief is 200 m/km², while absolute relief reaches 446 m. Both the main channel and the smaller tributaries are deeply incised, therefore steep valley sides up to 5 to 10 m can be found in the basin. Analysing DEM to classify the slope gradient thresholds for erosion the 62.56%, 43.83% and 14.25% of the total area belongs to the slopes with >20%, 5–20% and <10% gradient, respectively.

Table 1 Morphometric parameters of the Váralja stream basin based on DEM and land cover characteristics from CLC2012.

Parameters	Value and unit
Catchment area (A)	14.9 km ²
Maximum catchment basin length (L)	10.4 km
Catchment shape index (C)	0.3
Form factor (F)	0.1
Valley system length	40.9 km
Drainage density	3.0 km/km ²
Integration index	2.7 km/km ²
Forested area	11.5 km ²
Woodiness index	76.7%
Grassland area	2.0 km ²
Arable land area	1.0 km ²

¹Hydrological Information System of the South-Transdanubian Water Management Directorate

Although c. 2/3 of the watershed has steeper slopes and erosional position, the moderately sloping transitional position is also remarkable. The basin is nearly symmetric; the proportions of northern and southern slopes are similar in the region (Table 1).

The bedrock of the Eastern Mecsek Mountains is dominated largely by Jurassic rocks with a lesser extent of Cretaceous – in particularly Early Cretaceous – formations (Fig. 2, Table 2). In the region Early Jurassic (Liassic) coal seams are found, and their excavation – besides its economic significance – led to the geologic exploration of a syncline structure (Haas, 2012). The basalt volcanism in the Cretaceous resulted in the pillow lava forms of the Márévár valley, while the subvolcanic activities produced phonolite in the region of the Szamár Hill (Lehmann, 1995). In the study area it only occurs on the south-eastern slopes of the valley head; not in the form of outcrops, but covered by debris.

Most of the rocks are not purely limestones, but calcareous, siliceous, sandy, silty limestones or marls, thus they are hardly or not at all karstified. As a consequence, the valley system is more diversified and developed compared to the Western Mecsek Mountains, and here the karst features are also missing. However, the numerous appearances of travertines prove the relatively rich carbonate content in the groundwater.

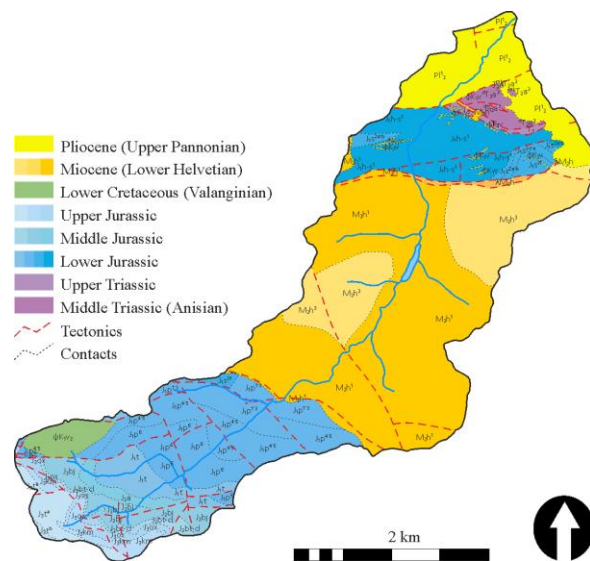


Figure 2 Revised geologic map of the basin (edited by P. Kalmár and E. Józsa).

Table 2 Geology of the morphostructural sections of the Váralja stream based on the geological map at scale 1:25 000 (former key) and Gyalog (ed.) 1996, 2005 and Kercksmár *et al.* 2015

(revised key and <i>cf.</i> Fig. 3) No.	Geological formations	Former key	Revised key	Characteristic rocks and sediments
G1	Fonyászó, Kisújványa and Várkonyi Limestone Fm	J ₃ ox J ₃ km	^f J ₃ ^k J ₃ ^v J ₃	siliceous limestone and radiolarite, nodular, cherty limestone
G2	Dobogó Calcareous Marl Fm and Óbánya Limestone Fm	J ₂ ^{bt-cl}	^d J ₂ ^ó J ₂	marl (with limestone nodules), calcareous marl and nodular limestone, clay marl and siliceous calcareous marl
G3	Komló Calcareous Marl Fm	J ₂ bj	km _{J₁₋₂}	grey, mottled, bioturbated, ammonite-bearing silty marl, calcareous marl and clayey limestone
G4	Komló Calcareous Marl Fm	J ₂ a	km _{J₁₋₂}	laminated marl and clay marl
G5	Óbánya Siltstone Fm and Komló Calcareous Marl Fm	J ₁ t	^ó J ₁ km _{J₁₋}	sandstone, siltstone and spotted marl
G6	Kecskehát Limestone F mand Mecseknádasd Sandstone Fm	J ₁ p ¹⁻³ J ₁ p ⁴⁻⁵ J ₁ p ⁶	kh _{J₁} ^m J ₁	siliceous crinoidal limestone, siliceous sandstone and breccia complex
G7	Szászvár Fm and Szászvár Member (Gyulakeszi Rhyolite Tuff)	M ₂ h ¹ M ₂ h ³ (λM ₂ h)	^{sz} Me-o ^{sz} _s Me-o (^g Mo)	variegated siltstone, sand, sandstone, gravel and conglomerate with rhyolite tuff intercalations
G8	Mecsek Coal Fm	J ₁ h-s ¹	mk _{T₃-J₁}	sandstone, foliated clay, and claystone, black coal intercalations
G9	Mecsekjános Basalt Fm and SzamárhegyPhonolite Member	ψK ₁ v	^m K ₁ ^m _{sz} K ₁	subvolcanic and submarine volcanic complex, alkali basalt and phonolite
G10	Dunántúl Fm group (former Upper Pannonian)	Pl ₁ ²	^D Pa ₂	fluvial, lacustrine and paludal sand and clay

The climatic conditions of the study area are not significantly different from the average values of Hungary. The annual sunshine duration is 2040–2060 hours, while annual mean temperature is 9.5–10°C, closer to the peaks only 9°C. Due to the low mountain environment the annual amount of precipitation is above the national average, 680–800 mm. Precipitation maxima typically occur in early summer or autumn, but with the decrease in the number of days with precipitation intense rainfall events are becoming more frequent. According to

the classification by Péczely (1979) the climate of the studied catchment is moderately cool – moderately wet and cool – moderately wet.

Stream discharge is based on the information available from the HISSTWMD. Annual mean discharge is 0.066 m³/s at the outlet and 0.012 m³/s at the confluence of the two headwaters (8,420 m from the outlet). The total length of the stream is 10,131 m and the elevation drop is 369 m. In 1977 three water reservoirs were constructed on the stream for recreation and flood protection purposes

on the section between 3980 m to 4640 m from the outlet. In spite of that, the calculated flash flood risk of the watershed is 4 and 5 in a 1–6 ranged scale (Czigány *et al.*, 2010).

A large part, 76.7%, of the area is covered with forests, dominantly oak-hornbeam associations, on the higher regions with northern exposure beech stands also appear. On the valley bottom hydrophilic alder species occur. The lower parts of the basin belong to the outskirts of the village Váralja with mainly arable and grassland cultivation.

3. Materials and methods

The research objectives required extensive field surveys to map channel characteristics and auxiliary information from expert-based topographical and geological maps to interpret the field notes. The primary review of the morphological and geological characteristics of the study area was based on the 1:10 000 scale unified Hungarian topographic maps and geological maps at different scales (1:10 000 and 1:25 000). A contour-based digital elevation model with 5 m horizontal resolution from the FÖMI (National Institute of Geodesy, Cartography and Remote Sensing) was used to represent the topography of the drainage area and automatically derive hydrogeomorphic parameters and basin metrics. Basic hydrological information on the Váralja stream were also available from the web-based HISSTWMD.

The channel mapping and description methodology consisted of the integrated classification system introduced by Krzemień and research group (Kaszowski & Krzemień, 1999; Kamykowska *et al.*, 1999). This mapping technique was successfully adopted in different geomorphologic settings, e.g.: high mountains and their foreland (Krzemień, 2003), glacial trough (Krzemień, 1999), following catchment capture (Chelmicki & Krzemień, 1999), Holocene volcanism influence (Krzemień, 2004), following extreme and flash floods in middle mountains (Izmailow *et al.*, 2006; Gorczyca, 2007), river training (Korpak, 2007), lowland late-glacial system (Angiel, 1999). Therefore, it was expected to provide correct results for the investigated basin. The morphometric and

hydrogeomorphic survey was carried out following the guideline by Kamykowska *et al.* (1999), recording the information in a specifically designed report, including: preliminary information (1), description of the channel (2), hydrogeomorphic characteristics of the stream (3), hydrometeorological conditions of the research period (4) and morphometry of the river drainage basin (5) (Krzemień *et al.*, 2015). The full description of this method can be found in the above cited papers, discussion of the steps in detail is out of the scope of the present study.

The significant landmarks, characteristic landforms and geologic features were mapped along the channel using a Dakota 20 Garmin handheld GPS. Field observations, notes and photos about the channel and valley forms and materials were gathered and arranged according to the instructions. A total of 150 pebbles were randomly collected at ten characteristic profiles of six sections and all three axes were measured by ruler. The width and depth of the channel were also measured at those points. Zingg's shape index (Zingg, 1935) was computed to analyse and classify roundness of transported gravels. The particle size index based on the nominal diameter $D_n = (a \cdot b \cdot c)^{1/3}$ were calculated for every measured cross section.

4. Results and discussion

The hydrogeomorphic sections of the stream were delineated in three steps. First by analysing the detailed topographic map in scale 1:10 000, thereafter deducing from the geological maps, and finally mapping the sections based on the modified version of field survey methodology of Kamykowska *et al.* (1999). Based on the characteristic changes in the topography 8, according to the geologic units 10 (Table 2) and interpreting the results of the channel mapping technique 12 reaches were separated on the stream (Fig. 3). The reaches delineated according to the topographic map and the other two methods rarely match. The reason for this is mainly that the map contains little information on the terrain characteristics, the available scale is not detailed enough; the contour lines representing the topography and the drawing of the watercourses are generalized.

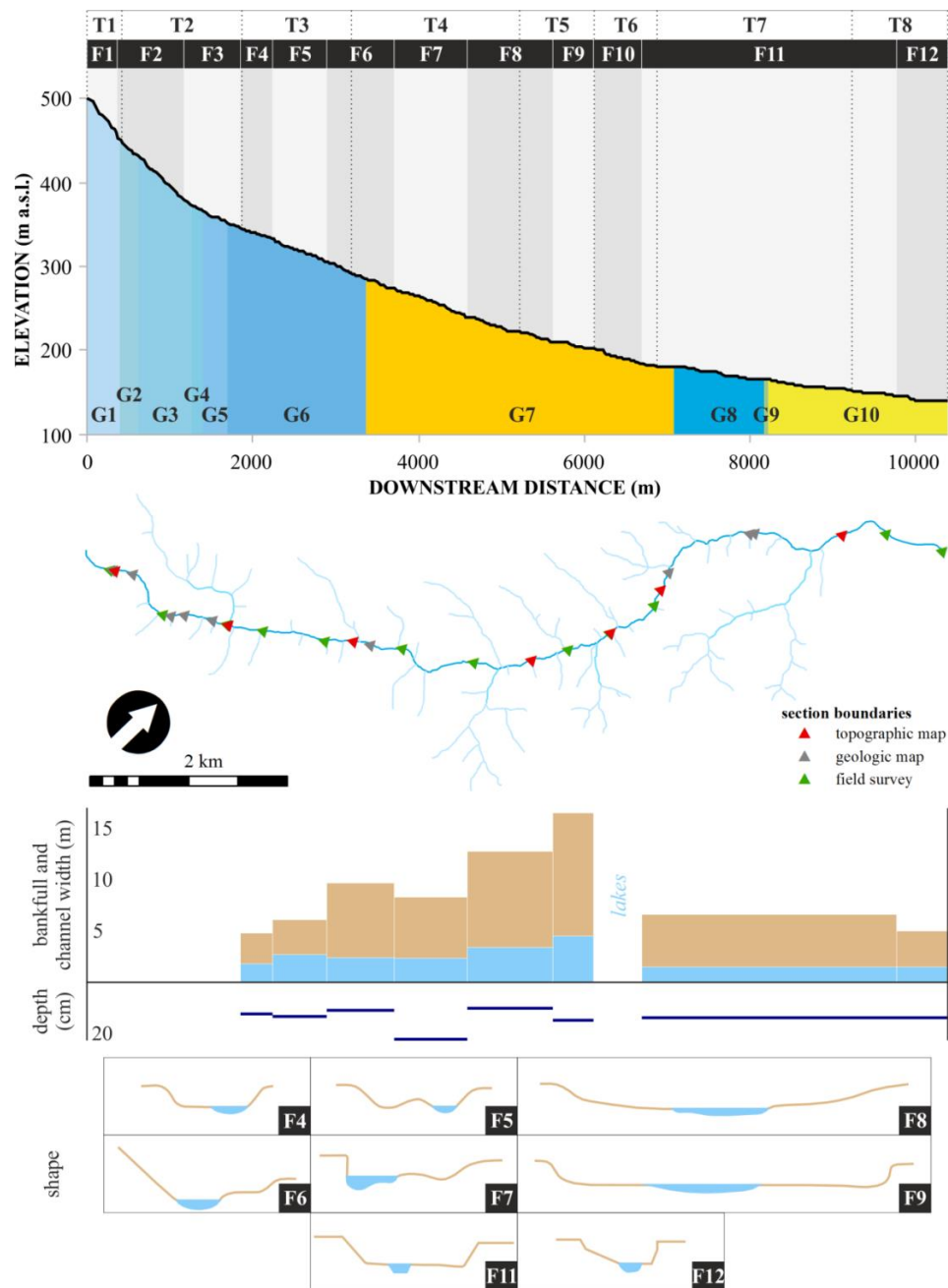


Figure 3 Long profile and sections of the Váralja stream. T1–T8 based on topographic map, F1–F12 according to field survey, G1–G10 by geologic units.

On the upper sections of the stream, where the steps and step systems are decisive, the reaches based on the topography and geology, show many similarities. On the lower stretch the stream reaches the bedrock only locally, so the geological conditions are less important in the development of the channel, accumulation forms are getting typical, e.g. woody debris and bars. The field observations

and the above-mentioned field reports provided sufficient information for the most accurate delineation of section boundaries. Section F1–F2, as the steepest reach with hollows differs significantly since the channel has a colluvial character and some bedrock steps. Section F3 is characterised by bedrock channel and step-pool system and an asymmetric steep valley profile due to the

combination of the geological settings (Fig. 1) with higher discharge. Therefore, in these sections channels can hardly be identified. Similar slope process dominated section was mapped at F5 with narrow V shaped valley and outcrop step-pool reaches after the confluence (1.9 km) of two source channels.

The mapped channel forms are summarized in Table 3. Based on the number and size of the occurring landforms the following characteristics can be highlighted. Steps and step-pool systems were found along the total length of the stream. The number and size of these features widely vary, while their shape and layering show similarities (Photo 1). Relative to the river course the pattern of the steps

is transverse or oblique and matches the strata dip. The size of the steps varies from 5–10 cm to 150 cm; the most frequent values are 20–30 cm.

The upper part of the steps is a hard, flat surface, and downstream the steps there are small pools where finer bedload is accumulating. In this finer sediment 5–10 cm or in some cases even 50 cm deep pools were formed. On the lower section, below the lakes the stream is flowing across young (Miocene, Pliocene) loose sediments (Fig. 2, Table 2). An interesting phenomenon here is that the barriers formed by tree roots are leading to hydrogeomorphic conditions similar to what the steps cause (Photo 2). Pools with 30–40 cm depth and 2–3 m width also occur on this part.



Photo 1 Steps on the stream (Photo by P. Kalmár 2014)



Photo 2 Higher energy part at tree roots and the formed erosion hole (Photo by P. Kalmár 2014)

Riffles were mapped on the middle and lower sections of the stream, but channel unit distinctiveness was poor compared to downstream sections. The morphology showed transitional character between plane bed and pool-riffle semi-alluvial channel-reaches. A common phenomenon is that the larger blocks transported by mass movements from the valley sides is mixed with branches and leaves, and creates dams. In case of intense rainfalls likely these stone blocks with a diameter above 30 cm are also entrained and the material is becoming more classified, which promote the formation of riffles and rapids (Lóczy, 2012).

The banks appear in diverse forms. On the upper sections (F1–F2) they are not typical; the valley is more like a gully with indefinite bed (cf. Fig. 1E). 20–40 cm high banks occur on the section F3, as the bedrock outcrops are getting more frequent and compelling the stream to change direction, thus lateral erosion becomes predominant. On the sections F4–F7 vertical erosion is intense, 1–1.5 m high banks can be observed (Photo 3). Below the F8 section the valley is getting wider, lateral erosion is becoming the typical process and alluvial character also occurs. These can be large forms (relative to the studied stream), even 10–15 m long and 5–6 m wide. Bars were found all along the stream except from upper sections (F1–F4), although with varying materials and sizes. On the middle sections (F6–F7)

they are formed from the finer sediments deposited downstream the steps and upstream WD dams and boulders. These channel-reaches have a "forced alluvial" character (Montgomery and Buffington, 1997) with some small semi-alluvial forms. These bars are usually smaller (50 cm long and 40 cm wide on average) and temporary features, displaced or destroyed by increased discharges. On the lower sections, we observed point bars built up from cobbles that can have a diameter of even 10–15 cm (Photo 4). Smaller islands appear on the sections F6–F7 and F9, where between the separated channels they are often only temporarily surrounded with water, in case of higher water levels. They can reach 15–20 m length and 6–8 m width.

According to Zingg's classes the 44, 27, 19 and 10% of collected pebbles has discoidal, bladed, rods and spherical shape, respectively. A relationship between the channel length and the shape was not detectable. Though, a not too strong relationship ($R^2 = 0.41$) exists in the resulting linear trend: $D_n = 0.52C_w + 4.2$, where C_w (in meters) is channel width. On the other hand, no relationship could be identified between particle size index and channel depth or between the computed average channel gradient and particle size index ($R^2 < 0.1$). The ratio of particle size index to water depth (D/D_n) is above 1.0 in every section with one exception at F7. As other small channels this also has a higher relative roughness.

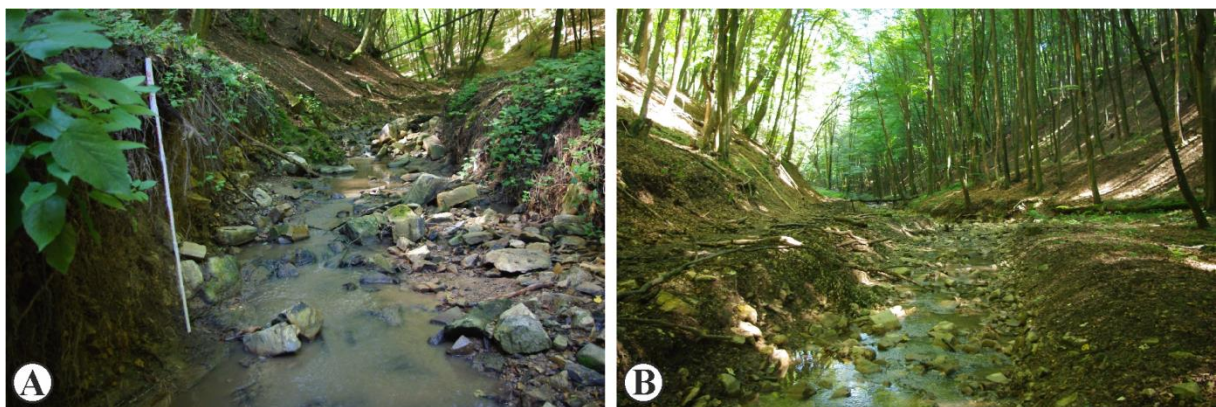


Photo 3 Examples of deeper vertical erosion on sections F4–F7 (Photo by P. Kalmár 2014)



Photo 4 Cobble bar and cut bank on section F11 (Photo by P. Kalmár 2014)

Although it is not part of the applied method (Kamykowska *et al.*, 1999) to analyse woody debris (WD), but as three quarters of the basin are covered by forests, the tree trunks and branches have a significant influence on landscape evolution. There are two sources of WD: the naturally decaying vegetation and forestry waste, which is getting to the valley bottom from the steep slopes of the higher hills. These materials accumulate in the main channel and jammed to form dams, the larger of which can exist possibly for longer periods (even years), as we observed channel relocations due to these WD dams (Photo 5). These woody materials have a significant impact on the flora and fauna of the stream, and they also alter the formation of natural transition zones between the drainage basin and the watercourse (Bilby and Ward, 1991). Based on the observed woody debris and dams, on various reaches of the stream only great floods are considered to be adequate for further transport.

During the last decade, the years 2010 and 2014 were extremely humid, as the annual precipitation has exceeded 900 mm. The highest monthly total precipitation at Váralja (255.4 mm) recorded during May of 2010. This humid period is supposed to be responsible for recent WD transport and dam formation.

The village of the same name and the cultivated valley bottom are at the lowest sections of the Váralja stream, so channel regulation and flood control works were carried out. The watercourse was artificially deepened and gabions were placed for

protecting the banks (Photo 6). Even though these anthropogenic structures are not preventing the natural transformation of the stream, they considerably slow down the bed-forming processes. However, the effect of the flash floods is the strongest in this area, as a result of the elongated catchment area and the significant decrease of elevation drop in this section (Fig. 1).

The hydrogeomorphic characteristics explored in this study reveal that the development of each stream section and their spatial order is not closely related to the low mountain environment of the basin. The 12 sections identified based on the bed and valley forms are not separated by clear boundaries, but they are connected with transitional zones. In fact, the so typical step systems were not formed by the stream, but they are a result of the geological composition and structure of the region. The sections with knickpoints and the steep, convex slopes are evidence for the recent uplift of the Eastern Mecsek Mountains (Dunkl, 1992). These steps were only exposed by the stream and the processes forming the valley, which means that the step systems control the hydrogeomorphic dynamics of the watercourse along these sections.

Even though the presented method has been developed for mountainous and alpine environments, our study proved its applicability in a low mountainous region as well. In our opinion, the decisive condition for the application of this method is not the terrain characteristics, but the size of the analysed watercourse.

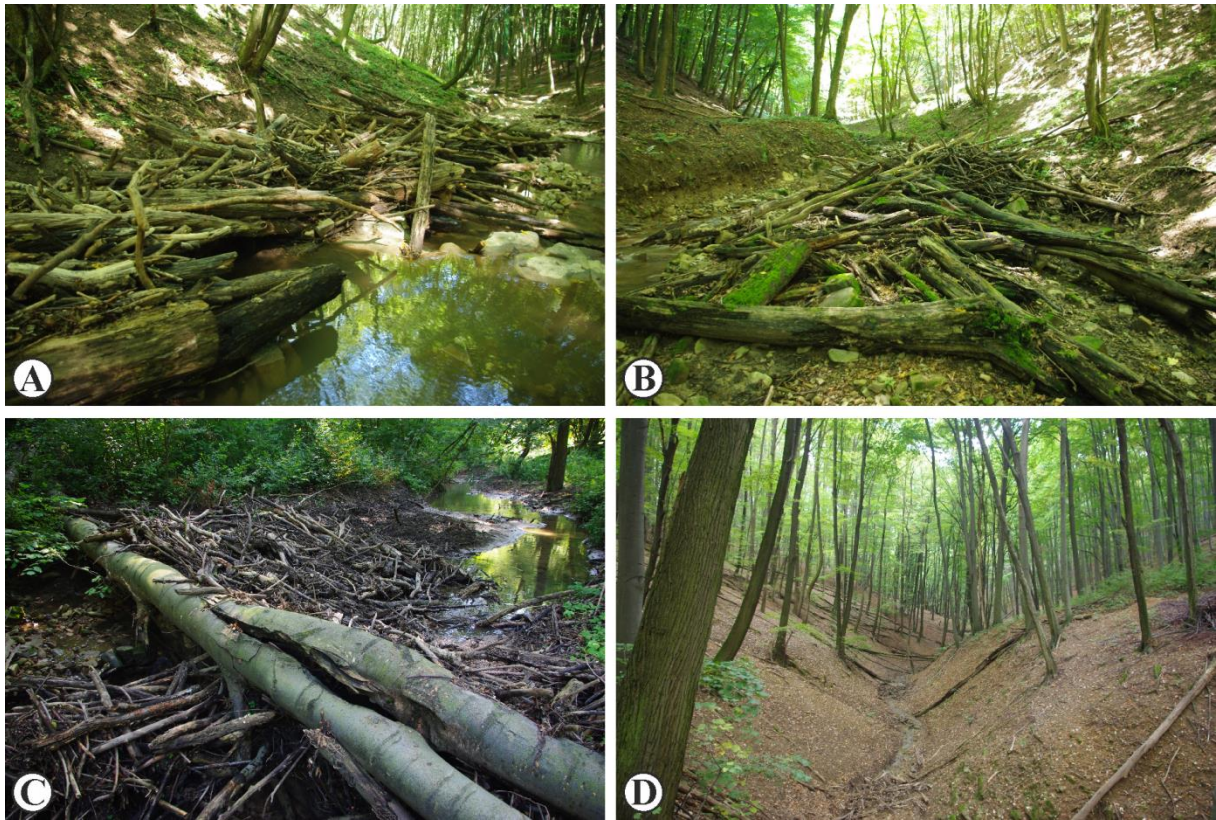


Photo 5 Woody debris in the channel (A – left sided; B – middle bedded; C – dam type) and the source of the material (D)
(Photo by P. Kalmár 2014)

Table 3 Characteristic size of the mapped channel forms in the Váralja watershed

No.	Steps		Pools		Cut bank		Bar & island		Woody debris	
	n	Height	n	Depth	n	Height	n	Length	n	Length
F1	–	–	–	–	–	–	–	–	–	–
F2	8	0.3 m	4	0.1 m	–	–	–	–	10+	2 m
F3	10	0.25 m	7	0.2 m	6	0.5 m	–	–	4	1 m
F4	9	0.4 m	5	0.3 m	10	0.8 m	3	2 m	4	2 m
F5	20+	0.45 m	10+	0.3 m	8	0.8 m	2	1 m	6	4 m
F6	5	0.2 m	3	0.2 m	10+	1,2 m	2	6 m	10+	8 m
F7	1	0.15 m	2	0.4 m	6	1,2 m	4	6 m	8	6 m
F8	–	–	2	0.3 m	2	0.4 m	6	4 m	4	2 m
F9	–	–	4	0.5 m	8	1 m	6	4 m	4	1 m
F10	–	–	–	–	–	–	–	–	–	–
F11	2	0.2 m	–	–	10+	2 m	4	2 m	1	1 m
F12	–	–	–	–	4	2 m	–	–	–	–



Photo 6 Simple makeshift bank revetment (A) and gabion protection (B) of banks (Photo by P. Kalmár 2014)

5. Conclusions

In the present study, we explored the applicability of the channel classification method by Kaszowski and Krzemień (1999) and Kamykowska *et al.* (1999) in the case of a headwater stream drainage basin in Southern Hungary. Based on the available topographic and geologic maps and the GIS-based morphometric parameters we gathered preliminary information about the study area. During several field surveys, we recorded the parameters of channel and valley forms according to the guidelines of the methodology presented and mapped their location using a handheld GPS device along the entire stretch of the Váralja stream. Due to the extensive forest cover the vegetation plays a key role in river bed evolution and recent development of the valley. For this reason, we concluded that it is necessary to supplement the report with recording the changes in the channel caused by WD.

Taking into consideration the geological and anthropogenic factors influencing the characteristic landforms and valley evolution we delineated 12 dynamically distinct sections with transitional zones. For the upper section of the stream (to the end of the Farkas ditch, F1–F3) the presence of steps, step systems are specific. The occurrence of WD from the valley slopes and side valleys is frequent in sections F2 and F6. There is a risk that the stream can only transport WD during floods after intense rainfalls, so the deposition of the woody material is often associated with channel migration. On the lower sections of the watercourse the anthropogenic

elements tend to be decisive in the dynamic processes. Right above the fishing ponds the watercourse loses a significant portion of stream power, so the accumulation forms become dominant. Intensive incision can be observed in section F10, where the stream leaving the dams formed steep banks. For the protection of the village the watercourse was regulated on the last two sections. On the lower course (F9–F12) the river bed cannot be regarded as semi-natural. According to the explored hydrogeomorphic properties Váralja stream has some headwater and a few semi-alluvial characters.

Considering the results of our study we conclude that the detailed analysis of other catchments with the presented field survey methodology would be helpful to provide accurate information about the processes and evolution of small streams with various geographical backgrounds. Understanding the large-scale changes occurring during catastrophic periods and exploring the factors influencing the level of vertical erosion and geomorphic evolution of a stream is essential information for the proper management of flash floods increasingly threatening built environments.

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Miscellanea

Symposium

Romanian participation at the 18th Joint Geomorphological Meeting Chambery, France, June 27th –29th, 2016

JGM – Joint Geomorphological Meeting is an international conference, in the event list of the IAG (International Association of Geomorphologists) and organized every two years by one member of the joint group of geomorphological associations from France (Groupe Français de Géomorphologie), Italy (Associazione Italiana di Geografia Fisica e Geomorfologia), Belgium (Belgian Association of Geomorphologists), Greece (Hellenic Committee of Geomorphologists), Romania (Asociația Geomorfologilor din România) and for the first time, Switzerland (Société Suisse de Géomorphologie).

After the conference of Liège, Belgium (June 2014), the 18th edition of the JGM was organized by the French geomorphological community (Groupe Français de Géomorphologie), at Chambery – department of Savoie - in the Northern French Alps. The venue was the University of Savoie-Mont Blanc with the CNRS-EDYTEM laboratory (Environnement – Dynamiques – Territoires – Montagne), wellknown as an important centre for the research of the mountain environmental dynamics.

JGM was a part of a geomorphological event week (June 27th - July 1st, 2016), organized at the University of Savoie-Mont Blanc in Chambery, followed by the conference of young geomorphologists (Journées des Jeunes Géomorphologues) and a special conference focused on the periglacial phenomena (Journée de l'Association Française du Périglaciaire, with a special session dedicated to prof. Albert Pissart, one

of the pioneers in this field of geomorphologic research).

This edition was focused on erosion and sedimentation phenomena (Source to sink, from erosion to sedimentary archives), but the papers and posters followed a diversity of derived topics, from dating of sediment deposits, land erosion, geomorphic mapping and modelling, to applied geomorphology issues in different environments, from temperate to tropical and glacial-periglacial, and of course in tectonic active mountain regions (Alps, Pyrenees, Carpathians, Balkans, Himalaya).

Five invited lectures were from France (E. Cossart – modelling of sediment fluxes in mountain catchments), Italy (M. Gugliemini – Italian rock glaciers as archives in paleoclimatic studies and landscape evolution), Greece (S. Pechlivanidou – source to sink in tectonically active areas catchments on rift areas), Switzerland (C. Scapozza – sediment transfer in Southern Alps during and after the last glaciation in Ticino, Southern Switzerland) and Belgium (V. Vanacker – antropogenic disturbances in morphodynamics in Western Mediterranean in the context of selected cultural landscapes).

Seven lectures followed these presentation. They were selected on the criteria of relevance to the conference thematic and had different themes of approach: soil erosion and lake sedimentary archives (M. Bajard *et al.*), GIS-based geomorphic mapping in Italian Western Alps (M. Giardino *et al.*),

reconstruction of flash flood events in Rwenzori Mountains, Uganda (L. Jacobs *et al.*), the periglacial morphodynamics of permafrost affected walls in Mont Blanc Massif under the pressure of summer heat waves (L. Ravanel *et al.*), the analysis of suspended sediment fluxes in Meuse and Scheldt Rivers, Belgium (J. Van Campenhout *et al.*). The Romanian group of geomorphologists was represented by the oral presentation of Bogdan Olariu in collaboration with Bogdan Mihai and Ionuț Săvulescu, from the University of Bucharest, Faculty of Geography, Department of Geomorphology-Pedology-Geomatics (Human-induced soil degradation in Bucegi Natural Park, Romanian Carpathians). This communication focused on the GIS modelling of the soil erosion processes on Bucegi Plateau.

Following the tradition of past events, the JGM had a special poster session (25 papers), a part of them presented by the authors in the conference room. Marina Rujoiu-Mare, PhD students from the University of Bucharest, Faculty of Geography, had an oral presentation of the poster focused on mapping of land erosion in Subcarpathian area with the help of the recent Sentinel-2 satellite imagery (in collaboration with Bogdan Mihai and Ionuț Săvulescu).

The Romanian delegation was represented by geographers from the University of Bucharest, mainly from the Faculty of Geography-Department of Geomorphology-Pedology-Geomatics (Prof. Florina Grecu, Prof. Laura Comănescu, Prof. Alexandru Nedelea, Prof. Bogdan Mihai, Assoc. Prof. Ionuț Săvulescu, Lect. dr. Robert Dobre, Assist. Mădălina Teodor) Lect. dr. Daniela Strat from the Department of Meteorology and Hidrology and the doctoral school "Simion Mehedinți" at the Faculty of Geography (Marina Rujoiu-Mare, Bogdan Olariu – PhD students). From the University of Iași, Assoc. Prof. Dan Dumitriu also joined the conference.

There were nine papers from Romania, presented during this session, with different topics: sediment systems in Romania (D. Dumitriu *et al.*), river channel, floodplain morphodynamics and flood risk (F. Grecu *et al.*, L. Comănescu *et al.*, and A. Nedelea *et al.*), slope morphodynamics and transport infrastructure projects (R. Dobre *et al.*), snow regimes and skislopes development in Romanian Carpathians (L. Ilie *et al.*, M. Teodor *et al.*).

Two days of fieldtrips, organized by our French colleagues followed the scientific programme. These were targeted on the essential geomorphic issues from the Northern French Alps, in the context of postglacial, Holocene and present-day morphodynamic evolution. The first trip focused on Bauges prealpine Massif – 2217 m altitude, East of Chambéry (karst landscapes, cave morphology and evolution, glacial and periglacial morphodynamics) and the second focused on the high alpine morphodynamics under glacial and periglacial regimes (Mont Blanc Massif – 4810 m with Chamonix glacial Valley and Mer de Glace Glacier with the severe glacial retreat and the active morphodynamics of granite rock slopes around the highest peaks – a stop to Aiguille du Midi, 3842 m).

The conference was a real successful event, a new occasion for scientific exchanges between geomorphologists and a possible opening of new research projects in the future. Our colleagues from the EDYTEM laboratory (L. Astrade, P. Deline, S. Jaillet, L. Ravanel, F. Hobléa) organized a high-level scientific meeting, focused on the latest research issues in geomorphology.

(Mihai BOGDAN, Faculty of Geography, University of Bucharest, Romania
November 2016)

Symposium

Workshop on Urban Geomorphological Heritage Rome, Italy, October 27-29, 2016

The conference Workshop on Urban Geomorphological Heritage held in Rome, Italy,

between October 27-29, 2016 under the auspices of the International Association of Geomorphologists –

IAG and the Geomorphosites Working Group, and the Italian Association of Physical Geography and Geomorphology (AIGEO) and its partners (ProGEO, G&T associations).

It was an exploratory scientific event, with an innovative theme, organized by the geomorphologists from the University of Rome – La Sapienza, the host institution, represented by dr. Alessia Pica, in collaboration with the University of Modena and Reggio Emilia (Italy) – represented by dr. Paola Coratza, together with the University of Lausanne (Switzerland), Institute of Geography and Sustainability, whose director, professor Emmanuel Reynard had the idea of the workshop.

The topics of the conference were: the geomorphological analysis in urban environment, the methodologies for the assessment and mapping of urban geomorphosites, the urban geotourism, the interpretation and the popularization of urban geomorphosites, the relationship between cultural and geomorphological heritage in cities, the conservation of geoheritage and the urban growth, the geoheritage and the urban planning.

The programme included three different activities. The first day was focused on an intensive course in urban heritage mapping and analysis

(Methods for urban geomorphic mapping and geoheritage analysis). The second day was the scientific session, while the third one was the fieldtrip in Rome historical core, focused on urban geoheritage.

The scientific session gathered together about one hundred researchers from Europe (Italy, France, Switzerland, Portugal, Poland, Czech Republic, Poland, Slovenia) and Northern Africa (Morocco), specialized in geomorphology and other sciences like geology, archeology, history and urban planning. After the opening ceremony (speeches from G. Scarascia Mugnozza, M. Soldati, P. Coratza and P. Fredi) there were 30 oral presentations and posters, organized in four topics: a plenary session focused on the achievements in this research topic (presentations by E. Reynard, D. Spizzichino, C. Giusti, M. Del Monte and P. Migoń), anthropic geomorphological evolution (P.Brandolini, B. Mihai, C. Guerra, P. Mozzi and B. Commentale), urban geomorphosites (C. Portal, F. Badiali, J. Tičar, L. Meelli and Z. Zwolinski) and urban geotourism (L.Grangier, M. Górka-Zabielska, M.L. Rodrigues and L. Kubalíkova). There were also displayed 12 posters with the above mentioned topics.



Fieldtrip at the first stop at Circus Maximus and the explanation on valley morphology transformation by Dr. M. Del Monte (Photo B. Mihai).

Fieldtrip was focused on the geomorphological heritage of the city of Rome and was coordinated and guided by Dr. M. Del Monte and Dr. Alessia Pica, from the host University of La Sapienza Roma 1. It was a real experience to discover the old urban sites of the seven hills of Rome (Septimontium). Four of them were visited, from Circus Maximus (close to Palatino Hill) to the Aventino hill and Tiberine Island on Tiber River. The excellent walking tour used a documented geomorphic map and other representation in order to understand the closer relationship between the antique and the newer urban structure of the city with the geological and geomorphological background. A new mobile application on the geoheritage of Rome was also introduced by the colleagues.

From Romania, there was an oral presentation by dr. Bogdan Mihai in collaboration with dr. Constantin Nistor from University of Bucharest, in partnership with Liviu Toma and Irina Cârlan, PhD students at the same institution and GIS analysts at GISBox Srl company (Photogrammetric modelling for medieval site mapping. A case study from Curtea

de Argeş, Romania). The colleagues from the University of Oradea (dr. D. Ilieş), joined another oral presentation in partnership with geomorphologists from the University of Modena and Regio Emilia (F. Badiali, D. Castaldini), focused on the geoheritage in Oradea town. A poster focused on geotourism in Bucharest was also displayed (L. Comănescu and A. Nedelea, University of Bucharest, Faculty of Geography).

In conclusion, the first edition of the Workshop on Urban Geomorphological Heritage, was a challenging scientific meeting that opens a new research field at the border between geomorphology and other sciences, with potential output in basic scientific approaches like geoarcheology or urban history and in applied directions like urban planning and geoheritage conservation for geotourism development.

(Mihai BOGDAN, Faculty of Geography,
University of Bucharest, Romania
November 2016)

Symposium

National Geomorphology Symposium, 32nd Edition Piatra Neamţ, 19-22 May 2016

The National Geomorphology Symposium (NGS2016), 32nd Edition, of was organized by Romanian Association of Geomorphologists (AGR) in collaboration with: *Alexandru Ioan Cuza* University of Iasi (UAIC), *Ştefan cel Mare* University of Suceava (USV) and *Stejarul* Biological Research Center from Piatra Neamţ. **NGS 2016** represented a perfect occasion for *celebrating 60 years since the founding the Stejarul Biological, Geological and Geographical Research Station*. The beginning of NGS2016 manifestations was marked by the touching speech of *Professor Constantin Grasu* which was focused on founding and evolution of *Stejarul* Research Station as an incursion in time on "brightness and twilight of an institution".

The symposium took place during 4 days. There have been registered 6 sessions of plenary

communications (33 oral presentations and 24 posters), 3 fieldwork applications (**1**: Royal Court Visit; Ascension on Cozla Mountain – Considerations on relief evolution in the contact area between Carpathians and Sub-Carpathians and the history of Piatra human settlement) (20 May), **2**: Lake Cujejdol (21 May), **3**: Bistriţa Valley (22 May).

After the AGR Council Meeting and AGR General Assembly, on 21st of May took place the rewarding of best poster (Mădălina Ristea) and best presentation (Răzvan Popescu) from NGS2016.

The topics discussed were varied, identifying the main research directions of Romanian Geomorphologists: mountainous, coastal, fluvial geomorphology, palaeogeomorphology, hillslopes processes, dendrogeomorphology, etc.



Natural dam Cuejdel Lake, filled in 1991. In front, AGR team at 32nd Edition of GNS

Final conclusions from the end of NGS2016 showed that the Symposium from Piatra Neamț reconfirmed the strengthening of Romanian geomorphology and sync with international trends regarding especially, the rigorous working methods used and high technological applications for fieldwork research. It was reconfirmed the need to preserve the format set in 2015 for SNG: (i) plenary

communications; (ii) rigorous selection of oral presentations; (iii) discussions focused on research topics through questions and comments. Also, there were discussions about the necessity of enlarging the interest area of geomorphology by inviting experts from neighboring scientific fields and personalities from abroad.



"Blue moon" phenomenon seen from Cozla Mountain
21 May 2016

Other details regarding SNG2016 32nd Edition, can be accessed at the following address: <http://geomorfologie.ro/sng/>.

Book Review

Landform dynamics and evolution in Romania **Rădoane, Maria, Vespremeanu-Stroe, Alfred – Editors (2016)** **Springer International Publishing Switzerland**

ISBN 978-3-319-32589-7, DOI 10.1007/978-3-319-32589-7
Library of Congress Control Number: 2016942904, 867 p



The book *Landform dynamics and evolution in Romania* has appeared in September 2016 and is part of Springer Geography Series. The volume was coordinated by Maria Rădoane, professor and researcher affiliated to the Department of Geography of Ștefan cel Mare University of Suceava, president of the Romanian Association of Geomorphologists (AGR) and by Alfred Vespremeanu-Stroe, reader and researcher at the Faculty of Geography, University of Bucharest (vice-president of AGR).

In the 34 chapters, totaling a number of 867 pages, this book represents the contributions of 52 authors, experienced researchers and young researchers in the domain of geomorphology, geology, pedology, palaeoclimatology and palaeoecology, the majority being affiliated at the

most important universities and research institutions in the country.

The aim of this work is to present the progress achieved in the knowledge of landforms from Romanian territory in a manner synchronized with international geomorphology evolution. The validity of the results presented in this volume lies in the material and methods used; many of them were based on direct measurements, large databases, on statistical or automatic modelling and absolute dating to establish the age of certain landforms, modelling processes or climatic events which impact them.

The volume is structured in 8 parts, and 7 correspond to the main types of relief that occupy the Romanian geographical space. In the first part were traced the main landmarks which delineate relief study in the present volume, respectively, defining the time frame (namely, the last 15,000 years) and spatial area of interest. There were presented the latest results and interpretations on the formation of Romanian Carpathians and an overview on climates and vegetation post Glacial evolution.

The second part of the paper contains recent studies from the domain of mountainous geomorphology, including the problem of mountain massifs deglaciation, the distribution and characteristics of forms specific to glacial and periglacial landforms and recent evolution of mountain permafrost. The third part discusses the problem of mass movement processes, with special attention on landslides from the Moldavian Plateau and Curvature Sub-Carpathians area, and debris

flows on mountain hillslopes. Fourth part treats the soil erosion processes from sheet erosion to gully erosion, and consequences they generate in land degradation on the territory of the Moldavian Plateau. Fifth section of the volume presents studies from the domain of fluvial geomorphology where the evolutionary trends of rivers and channels are discussed at different time scales, closely related to climatic modifications and also, with human disturbances. Sixth part is dedicated to the evolution and present dynamics of Danube Delta and Romanian coast of the Black Sea, by presenting a new vision on the formation of the Danube Delta, the shoreline evolution in the last 150 years and coastal landforms behavior derived from continuous monitoring in the past 20 years. Seventh part considers the sediment transfer in different geomorphic systems, with applications in the present sediment transport for river channels and palaeo-environmental reconstructions of conditions

for forming the sedimentary deposits. The last part of the volume addresses the geomorphological hazards (avalanches, landslides, floods, coastal storms) in terms of generating processes and associated risks, and the impact on human communities, respectively.

We believe that the appearance of this work represents an event for the Romanian geomorphology evolution, mainly because the dynamics of Romanian landforms is seen in the wider context of knowledge evolution on the European continent, subject to conjugated actions of climate changes and unprecedented human interventions. We are convinced that both academic geoscientists and specialists in other fields will find concrete information, checked and of wide diversity regarding the dynamics and evolution of landforms, also necessary for future prediction of landscape changes.

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