RESEARCH PAPER

MEASURING AND MODELING EROSION IN TWO SUCCESSIVE RESERVOIR CATCHMENTS ON THE DRIM RIVER IN NORTH MACEDONIA

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ABSTRACT. The catchments of the reservoirs Spilje and Globocica are positioned in the western part of North Macedonia. These catchments are situated in the higher part of the Drim/Drin catchment which is a transboundary catchment stretching in several countries. The two catchments were mapped for erosion according to the Erosion potential method by Gavrilovic. In order to assess the Erosion potential method, a bathymetric survey was also carried out. The two erosion maps created for the two reservoir catchments show very different results. The catchment of the reservoir Globocica is one of the most preserved catchments in the country from soil erosion point of view with average erosion coefficient of 0.21, specific annual production of erosive sediment is 394 m^3 km^{-2} yr^{-1}, the specific annual transport of erosive sediment is 247 m^3 km^{-2} yr^{-1} and the annual transport of erosive sediment is 74,543 m^3yr^{-1}. On the other hand, the catchment of the reservoir Spilje is one of the most erosive areas in the country, with average erosion coefficient of 0.44, specific annual production of erosive sediment of 776 m^3 km^{-2} yr^{-1}, the specific annual transport of erosive sediment of 541 m^3 km^{-2} yr^{-1} and annual transport of erosive sediment is 563,154 m^3yr^{-1}. The sedimentation of both of the reservoirs was measured only once in 2014 and 2015. The accumulated sediment in Spilje is 36.7 x10^6 m^3 or mean annual intensity of sedimentation is 815,555 m^3yr^{-1}. On the other hand, the Globocica reservoir has much lower values for sedimentation, 3.3x10^6 m^3 or mean annual intensity of sedimentation of 67,346 m^3 yr^{-1}.

KEYWORDS: Erosion rates, Erosion modelling, EPM, lake bathymetry, reservoir sedimentation, Drim/Drin

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INTRODUCTION

The soil and the water are the two out of three components of the natural environment. Water is a renewable resource, but the soil genesis on the other hand is long term process. So, in other words the soil practically is not a renewable resource (Blinkov et al, 2003). Soil erosion is deemed as the most important, most dangerous and most spread type of soil degradation and it is the limiting factor of the sustainable use of the land and development of the areas, states and regions.

Soil erosion has been occurring over the geological time. Inappropriate human activities accelerate this process. Soil erosion by water is a widespread problem throughout Europe. It is considered as one of the major threats to European soils, particularly in the Mediterranean areas (CEC, 2002). In order to effectively formulate mitigation strategies and implement conservation measures to counteract soil erosion, it is essential to objectively identify and quantify areas at risk (Gobin et al., 2002).

The South and Southeast regions of Europe are significantly prone to water erosion. In parts of the region, erosion has reached a stage of irreversibility and in some places, erosion has practically ceased because there is no soil left. Scientists from the Balkan countries faced with the erosion problem for years, paid significant attention to solving problems associated with erosion (Blinkov et al., 2019).

Construction of reservoirs is a priority for providing sustainability of the water resources. In the Republic of North Macedonia there are 23 big and over 120 small water reservoirs. On the other hand, erosion and filling the reservoirs with sediment is one of the main problems of reducing the lifespan of the reservoir. The total annual accumulated sediment in all the reservoirs in the Republic of Macedonia is 3,000,000 m^3 (Erosion map of RM, 1993).

Measuring sediment on natural flows is closely related to the examination of the soil erosion intensity in their respective catchments. The erosion intensity can be measured with direct bathymetric measurements of the reservoirs or with measuring the sediment discharge through one or many respective measuring hydrometric profiles on the stream or it can be estimated through modeling produced and transported sediment in the catchment (Gavrilovic, 1972).

Various methods for erosion risk assessment are used by various countries in Europe. Generally, three types of approaches exist to identify areas at risk (Eckelmann et al., 2006): qualitative approach, quantitative approach, and model approach. All these methods vary in their characteristics and applicability. All of the previously developed models were created for analog data use but in the recent period they are adapted to use with GIS enabled technologies. The most spread erosion type in the East and Southeast Europe as well as in whole continent is water erosion (Blinkov and Kostadinov, 2010).

The difficulty in applying the physically-based erosion models to natural landscapes lies in the fact that sediment yield predictions are still widely based on very simple empirical models developed by multiple regression methods between morpho-climate parameters and limited measurements of sediment yield and/or sediment fluxes (Jansen and Painter, 1974; Ciccacci et al., 1980; Mulder and Syvitski, 1996; Poesen et al., 2003, Lazzari et al, 2015).

Reservoir sedimentation is a serious consequence of soil erosion with large environmental and economic implications. Based on the existing data on reservoir sedimentation trapping rates, Mahmood (1987) estimated the global annual loss of storage capacity of the reservoirs was around 1%. According to the study by Wisser et al. (2013), global annual loss rates compared to original reservoir storage capacity were projected to range between 0.5 and 1%, equivalent to about 30 to 60 billion cubic meters per year.

Over time, sediments build-up in reservoirs and displace usable storage volume, which in turn negatively affects hydropower generation, reduces the reliability of the reservoir, irrigation, water supply, flood management services, and degrades aquatic habitat (Annandale et al., 2016; Icold, 2009; Rakhmatullaev et al., 2011). On the other hand, reservoir sedimentation also provides valuable information on erosion problems and sediment transport within a drainage basin. A reservoir can be considered as a large-scale experiment, as the outlet of a giant erosion plot (de Vente et al, 2000, Mincev, 2015).

The measuring of the deposited sediment in the reservoir is done on the basis of a reservoir bathymetric survey. In order to assess the rate of sedimentation of the catchment there should be constant monitoring of the filling up the reservoirs with sediment. This data is necessary for validation and calibration of the models for determining the sediment production and transport in the catchment.

The first erosion map of the country was finished in 1993 by the Institute for water economy (orig: Zavod za vodostopanstvo) in a process which lasted eleven years with extensive field validation and with traditional mapping techniques. After almost thirty years was updated in 2020 with contemporary mapping techniques (GIS, Remote sensing including field mapping using expert judgment approach as control of results of modelling). The latest erosion map was used in the analyses of this paper (Blinkov et al, 2020).

The aim of this paper is to show the difference between measuring sediment in the reservoirs Globocica and Spilje and estimating the sediment which is deposited in the reservoir by using established modeling schemes. The separate objectives are: (1) to measure the deposed sediment in the reservoir and to estimate the rate of sedimentation of the reservoirs, (2) to estimate the annual transported sediment in the reservoir using the EPM methodology, and (3) to compare the measured and modeled sediment estimations.

MATERIALS AND METHODS

Study area

The catchment areas of the reservoirs Spilje and Globocica are located in the western part of the Republic of North Macedonia. The Black Drim river basin connects with the White Drim in Albania and further flows as Drim (Drin) river up to the Adriatic Sea.

The Drin Basin is positioned in the south-east of the Balkan Peninsula with water bodies and watersheds which spread across Albania, Greece, Serbia, Montenegro and North Macedonia. It comprises the sub-basins of the Black Drin, White Drin, Drin and Buna/Bojana rivers, of the Prespa, Ohrid and Skadar/Shkoder lakes, the underlying aquifers, and the adjacent coastal and marine area (Fig.1). Water also flows through underground karst cavities from Lake Prespa to Lake Ohrid (http://drincorda.iwlearn.org/drin-river-basin/introduction).

The catchment area of Spilje reservoir is 985 km^2 and Globocica reservoir is 328 km^2 respectively, excluding the Ohrid Lake catchment. In this study, the catchment area of the Globocica reservoir is starting from the Ohrid lake. From sediment transport point of view, Ohrid Lake is not considered a sediment source, it is more of a sediment trap, and therefore the calculation of the sediment starts beyond the Ohrid lake. The main water source of the Globocica reservoir is the Drim River. The total storage of the reservoir is projected on $58 \times 10^6 m^3$.

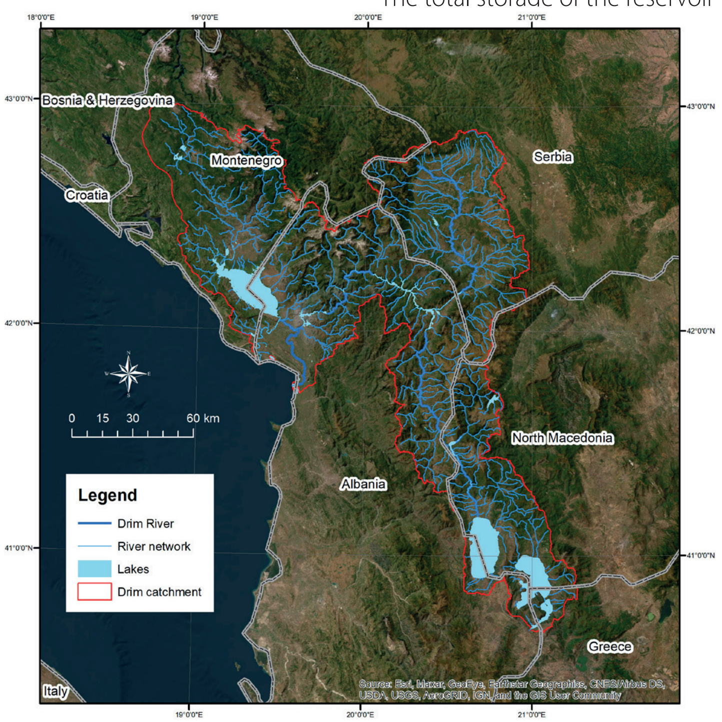

Fig. 1. Drim catchment within the administrative borders

The catchment area of the Spilje reservoir is constituted of two mayor catchment areas: Radika River to the north and to the south extends the catchment area of the river Black (Crn) Drim. Reservoir Spilje (Debar Lake) stretches east and south of the town of Debar. The dam Spilje is located on the Crn Drim River (Black Drin), 3.5 km south of the town Debar, about 300m upstream of the North Macedonian-Albanian border (Fig. 2). The total storage of the reservoir is projected on $543x10^6m^3$.

The climatic characteristics of the catchment of the reservoirs are strongly influenced by the location, orography, vegetation and hydrological conditions of the region. The lowest parts of the basins are affected by the sub-Mediterranean climate, hilly and upland areas are affected by moderate continental and mountainous climate and highland areas are affected by typical mountain climate. The average annual air temperature for the catchment is 7.1°C. The average annual rainfall sum is 860 mm within the analysed period (1981-2010) (Aksoy et al. 2020). The calculated R factor (rainfall-runoff erosivity factor according USLE) for the catchment is in range of 502 and 831 with average value of 633 MJ mm ha^{-1} h^{-1} yr^{-1}.

The catchment area of the reservoir Spilje has heterogeneous geological structure. In the catchment area of the reservoir is dominated by complex phyllites, metasandstones and conglomerates 24%, complex sandstones, clay, argiloshists and limestone 14% and 13% of limestone with chert, clay and massive limestones. As a result, the soil forming factors in the catchment can be found the following soil types: brown forest soils (eutric and distric cambisols) 30%, rankers 28%; calcocambisols 12% and lithosols 10% (Mincev et al, 2017).

The catchment area of the reservoir Globocica has similar geological and soil structure with some differences. Plate dolomite with chert, shale limestone and conglomerate 32%, alluvium 14%, sandstone, shale limestone and conglomerate 12%, marl clay, sands and gravel 11%, phyllite schists 8%, etc. The dominant soils are calcomelanosol 22%, brown forest soils (eutric and distric cambisols) 21%, complex of calcomelanosols, calcocambisols and dolomite 14% and molic fluvisols 11% (ibid).

The land cover in the catchment of Spilje is mostly dominated by broadleaved forest 40% (primarily of oak, beech or beech-fir forests), natural grasslands 36%, transitional woodland-shrub 10% and 6% agriculture area (Corine LC/LU 2018). The upper limit of the forest is dominated by alpine and subalpine meadows, rocky and massive rock formations. In terms of erosion, the existing vegetation basically provides relatively good protection of the land from erosion. The worst situation is in the vicinity of the inhabited areas, where the land use is significantly affected by human. On the other hand, the land cover in the catchment of Globocica is also dominated by broadleaved forest 38%, agriculture 29%, natural grasslands 9% and transitional woodland-shrub 13%. This catchment has more agriculture area but it does not contribute significantly to the erosion and sediment budget because is detached from the vicinity of the reservoir and it is on a flat area. Most of the agriculture area has the lowest erosion category (V).

Slope is a significant factor in increasing erosion and if the two catchments are compared: Spilje has an average slope of 50.2% and Globocica has an average slope of 30.8%. In combination of the slope with the unstable geological substrate on the shores of the Spilje reservoir there can be seen extreme erosive processes which significantly contribute to the reservoir sedimentation (Fig.3).

Bathymetric measurements of the Spilje and Globocica reservoirs

The main task of the echo-sounding measuring of the reservoirs is to determine the volume and the weight of the sediment between two consecutive measurements or from the beginning of the functioning of the reservoir till the moment of the measuring. From these measurements, also some other parameters can be calculated like the annual sediment yield and the reservoir lifespan (Hall, 2010). It is estimated that worldwide, annually, from 0.5% to 1% of the total storage of the reservoirs is lost because of filling up the reservoirs with sediment (White, 2001).

Acoustic echo-sounding relies on accurate measurement of time and voltage. A sound pulse of known frequency and duration is transmitted into the water, and the time required for the pulse to travel to and from a target

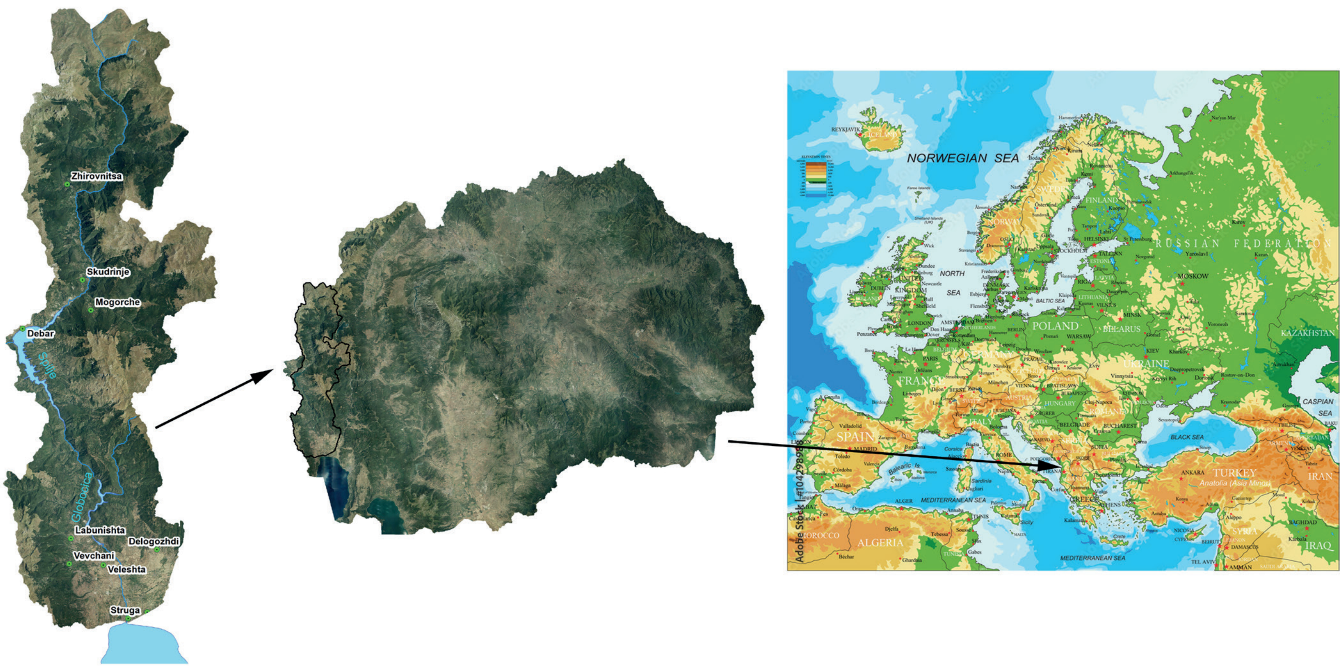

Fig. 2. Location of the catchments of Globocica and Spilje in the Republic of North Macedonia and Europe

Source for map of Europe: https://www.europosters.eu/europe-physical-map-f104298988 (e.g., a submerged object or the bottom of a water body) is measured. To acquire information about the nature of the target, intensity and characteristics of the received signal also are measured. Prior to conducting a bathymetric survey, geospatial data (including geo-referenced aerial photography) of the target lake are acquired, and the lake boundary is digitized as a polygon shape file. Transect lines are predetermined based on project needs and reservoir size (Fig. 4). Immediately before or after the bathymetric survey, elevation of the lake surface is determined (Jakubauskas and deNoyelles, 2008).

The reservoirs Spilje and Globocica were constructed in 1969 and 1965, respectively. The first and only sediment measurement was done in 2014 and 2015. The bathymetric measurement was done using combined transect and contour measurement.

Modeling transported sediment in the reservoirs Globocica and Spilje with the Erosion Potential Method (EPM)

There are several methods which are used for soil erosion estimation. The paper from Blinkov and Kostadinov (2010) give a review of several models for estimation of erosion: EUROSEM, USLE, PESERA, KINEROS, WEP, WEPP and EPM. All of the models provide an estimate of soil erosion, but only few deal with transport and deposition of the sediment: EUROSEM, WEPP and EPM.

The EPM was developed in the Balkan region, south Serbia, which is very similar in climatic conditions with North Macedonia and therefore it is well adapted to the study area. Also, the model has the ability to predict sediment transport and deposition and it was developed

Fig. 3. Gully erosion and extreme erosive processes on the banks of the Spilje reservoir

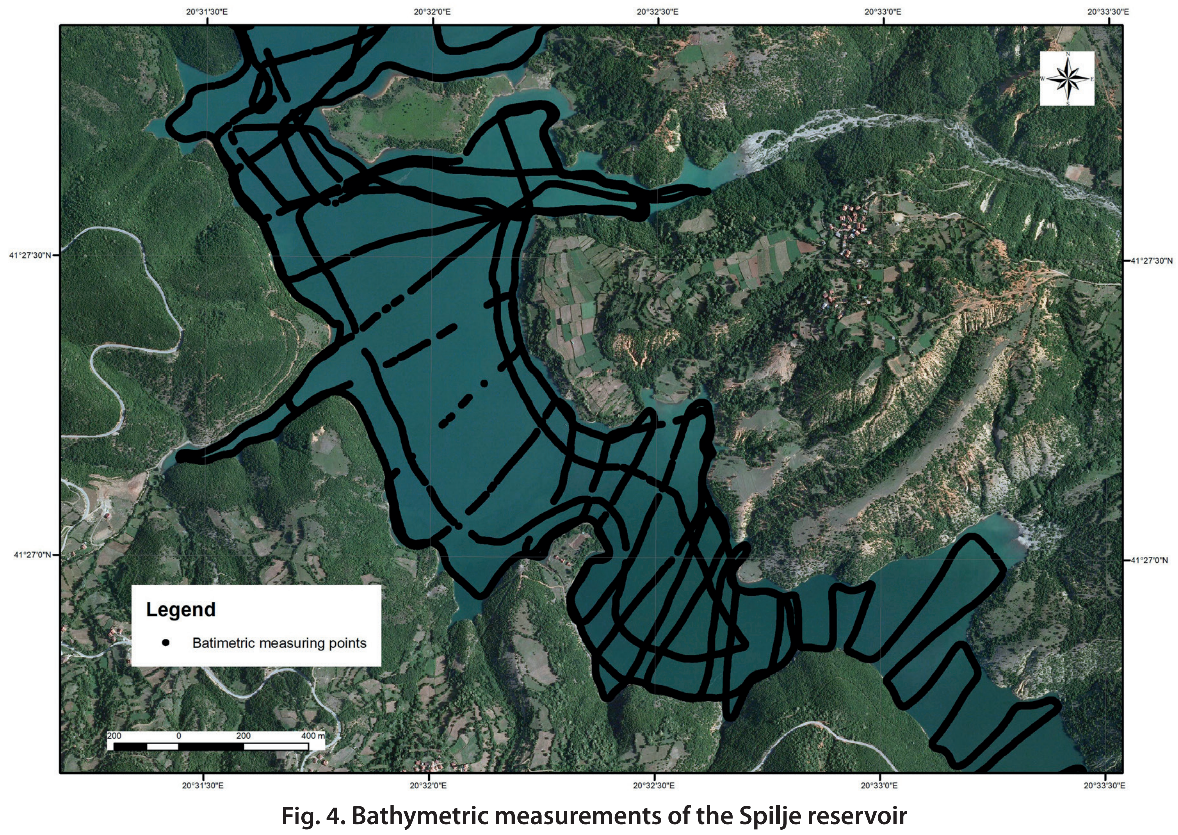

Fig. 4. Bathymetric measurements of the Spilje reservoir

with calibration of deposited sediment in the existing reservoirs. All of the previous studies were developed using EPM and therefore the results would be comparable and the methodology would be transferable (Mincev, 2015b; Blinkov & Kostadinov, 2010).

$$Z = \gamma * Xa * \left(\varphi + \sqrt{I_{sr}}\right) \quad (1)$$

$$G_{year} = T * H_{year} * \pi * \sqrt{Z^3} * F * R_u \quad (2)$$

Where:
Z – coefficient of erosion by Gavrilovic (dimensionless)
γ - reciprocal value of resistance of soils/rocks on erosion processes
Xa – protection of the catchment in natural conditions and after erosion control
φ - coefficient of visible processes of erosion
Jsr - mean slope of the catchment
G – quantity of transported sediments [m^3 yr^{-1}]
T – temperature coefficient
H – total annual precipitations [mm]
π – ludolph number
F – catchment area [km^2]
Ru – retention coefficient

There are several papers clarifying the EPM (see Mincev and Blinkov, 2007) and here only the approach will be shortly explained and the used data in the process and the used modifications will be clarified more elaborately. The EPM (by Gavrilovic) was originally designed to be used with hardcopy maps, and the mapping process itself was mainly done on catchment level. With the advent of the GIS tools and the large variety of geographic data available (Corine LC/LU, soil maps, geology maps, elevation data – DEM, etc.), the mapping process evolved on much smaller mapping units. These datasets can be with good quality but the production scale should be taken into account and they could be reclassified according the given classes in the methodology. It is recommended using global dataset because of the easy transferability and comparability of the results.

The most specific parameter in the EPM is the "Xa" parameter which is connected with the land cover of the catchment and presence of implemented soil erosion measures and works. The determination of the "X" part of this coefficient is done with the use of land cover/use map. The most commonly used land cover map is Corine LC/LU map produced by European Environmental Agency (EEA). This map is good for general purposes but in order to be used for erosion mapping it should be improved. The most obvious example is the class forest. If the class forest is with good cover and in good condition it should take value of 0.05, but in most of the cases the forest polygons are generalized and they do not have the full cover or in some cases there are gaps. To overcome this problem, it was included NDVI (Normalized difference vegetation index). The NDVI was extracted with Google Earth Engine and to each land cover polygon was assigned an average NDVI value. Then the highest values of NDVI were assigned the default Xa value of 0.05 and the lowest value was visually interpreted and assigned a value (Fig. 5). All of the other values in between were rescaled according the NDVI value. The same process was repeated for all of the land cover classes.

The input parameters used for the EPM were as follows: National soil map (scale 1:50,000); Land cover: Corine LC/LU 2018 (developed by European Environmental Agency, scale 1:100,000), later improved using visual photo-interpretation of aerial imagery with spatial resolution of 0.3 m (2019) Fig.5; DEM spatial resolution of 5 m; climatic parameters developed in spatial resolution of 20 m, analysed period (1981-2010) (Aksoy et al. 2020).

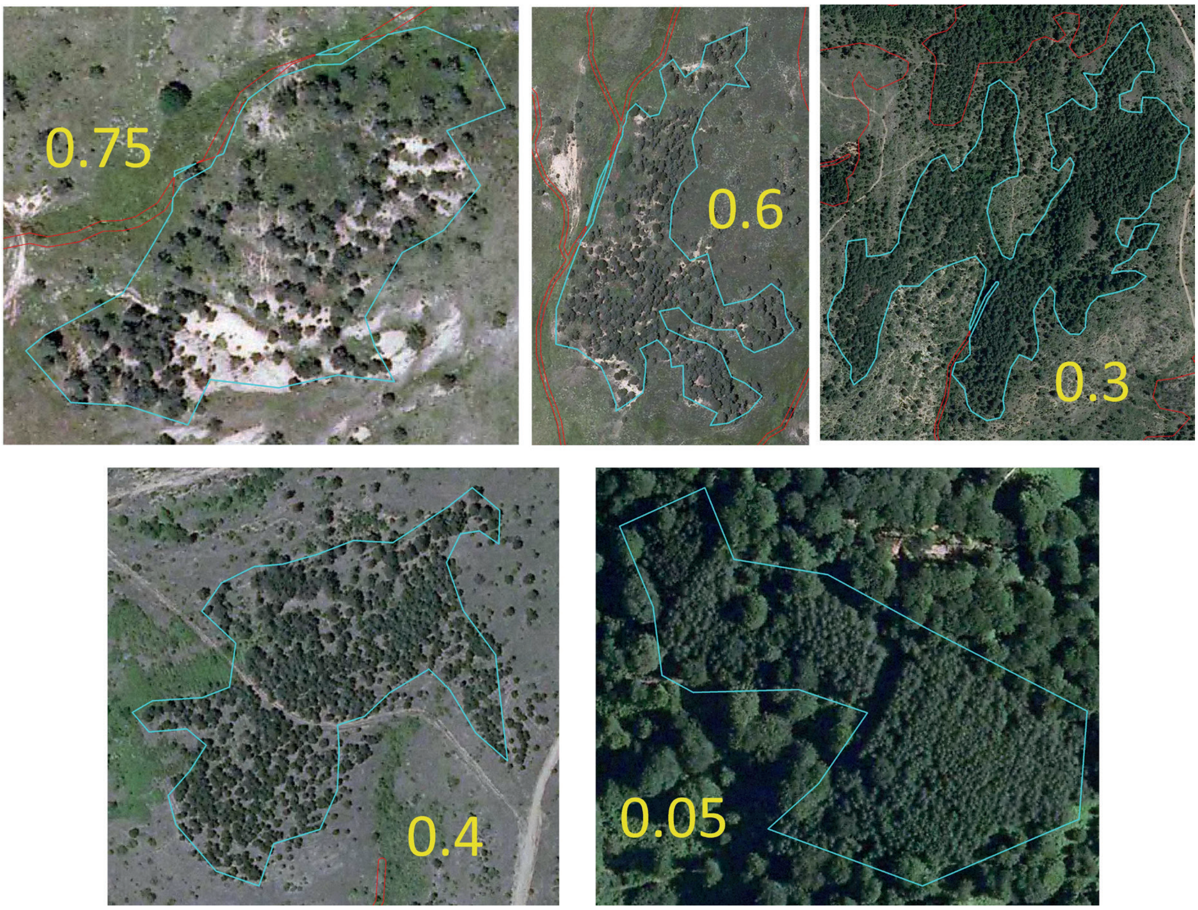

Fig. 5. Xa values for the land cover class forest

RESULTS AND DISCUSSION

The reservoir Spilje was designed with total storage of 543 million m^3. The bathymetric measurements in 2014 showed 36.7 million m^3 deposited sediment in the reservoir or annually 815,555 m^3 yr^{-1} or specific 827.97 $m^3km^{-2}yr^{-1}$. The reservoir Globocica was designed with total storage of 58 million m^3. The bathymetric measurements in 2015 showed 3.3 million m^3 deposited sediment in the reservoir or annually 67,346 m^3yr^{-1} or specific 205.32 $m^3km^{-2}yr^{-1}$.

The EPM model was conducted on both reservoir catchments. The catchment of the reservoir Globocica is one of the most preserved catchments in the country with average erosion coefficient (z) of 0.21, specific annual production of erosive sediment is 394 m^3 $km^{-2}yr^{-1}$, the specific annual transport of erosive sediment is 247 $m^3km^{-2}yr^{-1}$ and the total annual transport of erosive sediment (sediment yield) is 74,543 m^3yr^{-1}. On the other hand, the catchment of the reservoir Spilje is one of the most erosive areas in the country, with average erosion coefficient (z) of 0.44, specific annual production of erosive sediment of 776 $m^3km^{-2}yr^{-1}$, the specific annual transport of erosive sediment of 541 m^3 km^{-2} yr^{-1} and total annual transport of erosive sediment is 563,154 m^3yr^{-1}.

If the measuring and modelling results are compared there can be seen significant difference. Since these two reservoirs do not have continuity of sediment monitoring there can be expected such discrepancies. According the EPM at the moment, the annual transport of erosive sediment is 563,154 m^3yr^{-1} and the bathymetric survey shows reservoir sedimentation of 815,555 m^3 yr^{-1}. The difference is significant. There are two possibilities for this difference: error of the erosion modelling or error in the

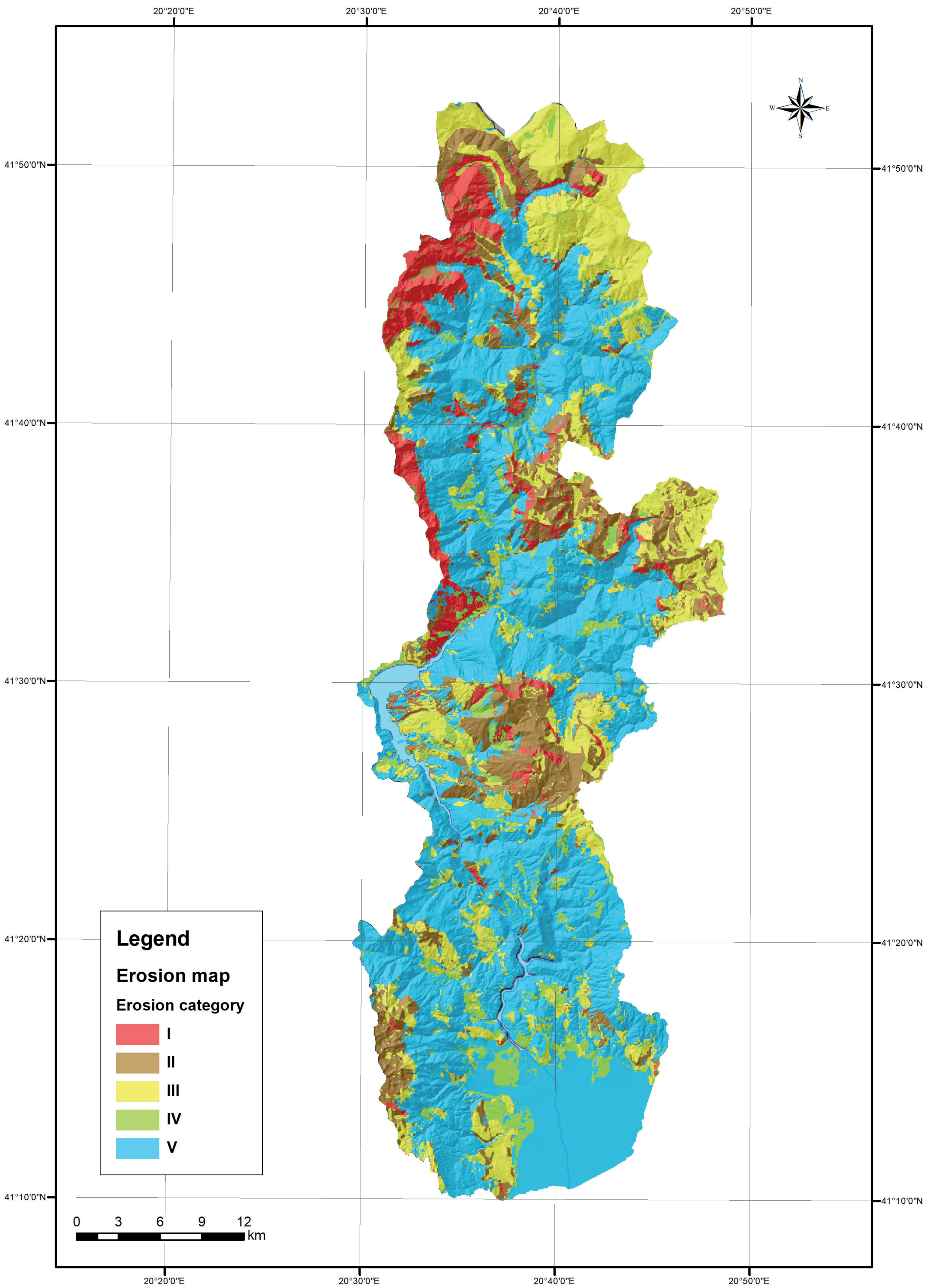

Fig. 6. Soil erosion map of the catchments of the reservoirs Spilje and Globocica

bathymetry. The northern part of the basin is characterized with specific Alpine relief conditions, where numerous so called "point" sources of sediments occur, i.e. rock weathering, landfalls, landslides, even coastal erosion on the lake banks (result of fluctuation level) that in a scale of modelling following the EPM cannot be expressed. It should be mentioned that EPM was developed in the area of old mountains with different relief conditions.

According to Minchev (2018), on a similar study done for the reservoir Kalimanci in the eastern part of the country, the sedimentation rate of the reservoir shows two rates of sedimentation from two periods, 1969-1984 and 1984-2013, in which the latest period has 2.5 times decreased rate of sedimentation. This can be accounted on the decreased pressure on the environment: decreased population, agriculture practices and animal husbandry and significant erosion control measures in the past (Mincev et al. 2019, 2023).

On the other hand, the reservoir Globocica does not have very big differences between the measured and modeled quantities. According to the EPM at the moment, the annual transport of erosive sediment is 74,543 m^3yr^{-1} and the bathymetric survey shows reservoir sedimentation of 67,346 m^3 yr^{-1}. The aforementioned pressures were not present here because this catchment is more natural and there are not so big disturbances and also as previously mentioned, this catchment has much gentler slopes.

CONCLUSIONS AND RECOMMENDATIONS

From the depicted results, it can be concluded that that measuring and modeling sediment does not yield the same results. The modeling results for the Spilje reservoir show that the annual transport of erosive sediment is 563,154 m^3yr-1 and the bathymetric survey measured reservoir sedimentation of 815,555 m^3 yr-1. The difference is significant. Several aforementioned studies show decrease in the severity of the erosive processes in the past decades. This can be accounted on the decrease of the population in the catchment and therefore decrease of the pressure on the environment. So according this theory, the rate of sedimentation of the Spilje reservoir in the past, up till the mid 1980's, was much higher according to Minchev (2018), on a similar study done for the reservoir Kalimanci.

On the other hand, the Globocica reservoir has similar quantities between the measured and modeled quantities. The model shows that the annual transport of erosive sediment is 74,543 m^3yr^{-1} and the bathymetric survey shows reservoir sedimentation of 67,346 m^3 yr^{-1}. This can be accounted on the absence of agricultural practices in the past, and most of the catchment was mostly covered with forest with gentler slopes.

The existing models which estimate sediment transport and deposition give close approximation of the state of the environment. Also, the choice of the model is dependent on the geolocation and site conditions. Another thing to consider is for what kind of purpose the models were developed.

Validation of the model with measured quantities is a prerequisite for a good model. There are a lot of papers which employ model modifications and they end up with just publishing results without any validation. The two catchments examined in this paper are a good example of using the same method of measurement and modeling and yield different results. The Globocica catchment has a good fit of the EPM with the sediment measurements and the Spilje catchment has higher measured values for the sedimentation. This can be accounted on the scarce sediment monitoring data, meaning that having only one measurement data per reservoir is not sufficient enough to assess the current rate of sedimentation. It is recommended that in near future another measurement be executed of the two reservoirs in order to estimate the current sedimentation rate.

Most of the developed theory is not very recent. In order to be implemented with the advances of the new technologies it should be modified. ■

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