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RESERVOIR SEDIMENTATION AND HYDROLOGICAL EFFECTS OF LAND USE CHANGES-CASE STUDY OF THE EXPERIMENTAL DIČINA RIVER WATERSHED

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Abstract: Dams have always been a precious means of collecting, storage and managing of water resources throughout history. Today, there are about 845000 dams with a total volume of about 6000 km^3. Reservoir sedimentation is a very complex problem both worldwide and in Serbia. Natural conditions and anthropogenic activities have strong influence on sedimentation intensity and hydrological processes, which is represented at the experimental watershed of the Dičina River, in Western Serbia. Reservoir of 340000 m^3 was formed after construction of a 17 m high dam, in 1966. Sedimentation of the „Velika Dičina" reservoire was determined on the basis of a survey from October 1966 to October 2011, along longitudinal profile, 750 m upstream from the dam, with 15 cross section profiles (at a spacing of 50 m). Land use changes were analyzed on the basis of a comparison of watershed conditions in 1966 and 2012, using the CORINE methodology and the MapInfo software. Sediment yield of the area and intensity of erosion processes were estimated on the basis of the "Erosion Potential Method" (EPM). The hydrological conditions in 1966 and 2012 (after the performed Erosion and Torrent Control Works-ETCWs) were assessed on the basis of a historical overview of land use changes and their impact on computed maximal discharges. Total quantity of deposited sediment in the reservoir amounts to 18750 m^3. Intensity of sedimentation has continuously been decreasing since 2002 as the consequence of land use changes, performed ETCWs and depopulation. The values of computed maximal discharges and volumes of computed hydrographs are significantly reduced. Depopulation caused a decrease in the anthropogenic pressure on the agricultural and forest surfaces in the watershed. The realization of restoration works contributed to a decrease in the annual yield of erosive material from W_a=16007 m^3 to W_a=1930 m^3.

Key words: sedimentation, erosion processes, depopulation, land use, sediment yield, maximal discharge, erosion and torrent control works

1. INTRODUCTION

Dams and accumulations have been successfully used for collecting, storage and managing of water resources throughout history. Today, there are a large number of constructed dams with multiple functions, including the production of electric power, flood protection, water supply, irrigation, recreation, fishery and many others. Total capacity of water stored in accumulations in the world, is nearly 6000 km^3 (Sumi & Hirose, 2009). The total number of dams amounts to about 845000 worldwide, of which 45000 dams are higher than 15 m and they account for 97% of the total volume of dam storage capacity. Dams with a height of between 5 and 15 m represent 2%, and dams with a height smaller than 5 m account for only 1% of the total storage volume (Lempérière, 2009). Total reduction of the volume of dam reservoir due to sedimentation globally amounts to 567 km^3 (Sumi & Hirose, 2009). The average annual sediment yield varies from 20 to 5000 m^3·km^{-2} worldwide. The estimated total annual transport of suspended sediment to the world oceans is from $8.3 \cdot 10^9$ m^3 to $51.1 \cdot 10^9$ m^3. The highest values of mean annual specific suspended sediment yield for some rivers in the world range from $11.13 \cdot 10^3$ $t \cdot km^{-2}$ to $53.5 \cdot 10^3$ $t \cdot km^{-2}$ (Walling & Webb, 1996).

The annual level of sedimentation in the reservoirs of Southern Europe amounts to 0.25 km^3 (White, 2001). Reservoir siltation is a very complex problem in Serbia, both in big and small reservoirs. The huge Djerdap reservoir in the Danube River, on the border between Serbia and Romania, has a volume of $2 \cdot 10^9$ m^3, and traps $15 \cdot 10^6$ m^3 of sediment every year. However it has not been significantly endangered due to sedimentation yet (Petković et al., 1999). In contrast to that, the small Gvozdac reservoir at Goč mountain in Central Serbia, has a volume of $60 \cdot 10^3$ m^3 that is completely filled with sediment and out of function for water storage (Ristić et al., 2004). Sediment yield due to soil erosion depends on the complex interaction among a number of factors, including the natural characteristics of the area, population growth and fall rates, educational and cultural issues, the institutional conditions, as well as environmental and agricultural policy (Ananda & Herath, 2003; Ceylan et al., 2011). The intensity of erosion processes varies depending on storm conditions, hillslope aspect, lithological properties (Kašanin-Grubin & Rork, 2007) and human impact (Ristić et al., 2012a; Stefanescu et al., 2011). Absence of erosion control activities in the sediment source areas can cause very quick silting of the reservoirs, like in Romania where the Bascov and Pitești reservoirs were entirely silted in 2 years (Rădoane & Rădoane, 2005). Also, soil erosion can cause the abandonment of arable land due to declining productivity (Bakker et al., 2005).

In the 60s of the 20th century over one hundred small reservoirs were formed in the hilly-mountainous regions of Serbia. These reservoirs were faced with a serious risk of sedimentation due to intensive anthropogenic activity in the watershed areas (IWRMJČ, 2001). However, already in the 80s of the last century the process of depopulation of rural areas was initiated as a result of the migration of people to cities, which reduced the pressure on the forest and agricultural areas. In the same period, Water Resources Management of Serbia performed large scale erosion and torrent control works (ETCWs), including technical works (check dams, bank protective structures, torrent training) and biotechnical works (afforestation, forest protective belts, silt-filtering strips, grassing, terracing and contour farming). In addition, spontaneous restoration of forests in large areas of abandoned arable land was observed in the hilly-mountainous areas characterized by intensive depopulation (Ristić & Nikić, 2007). The large-scale land use changes have produced some favorable effects, including decrease of sediment yield, less intensive reservoir sedimentation and reduced watershed potential for the formation of fast surface runoff. These phenomena were measured and analyzed at the experimental watershed of the Dičina River in Western Serbia.

2. MATERIALS AND METHODS

2.1. Study Site Description

Reservoir sedimentation and the hydrological effects of land use changes should be assessed at watershed scale, on the basis of complex investigations, including a historical overview of the process of erosion and land use changes, intensity of sedimentation, computations of sediment yield and maximal discharges, as well as detailed analysis of geology, soil and hydrographic characteristics of the watershed. This paper presents an investigation carried out at the experimental watershed of the Dičina River (profile P at the "Velika Dičina" dam), located in Western Serbia (Fig. 1). The dam „Velika Dičina" (made of stone with clay core) was built in the 1965-66 period, above the village of Gornji Banjani, as a water retention area for flood protection with a continuously open outlet. The main characteristics of the dam and reservoir are as follows: construction height of the dam, H_{br}=17.0 m; dam crown width, B=3.50 m; dam crown length, L_d=65.20 m; and volume of the reservoir, V=340000 m^3.

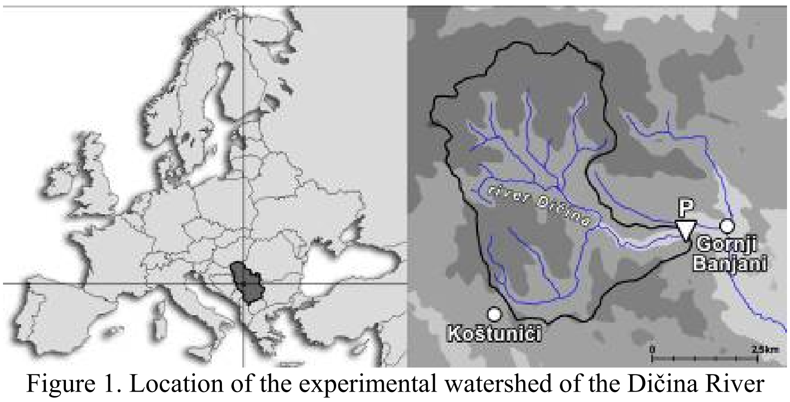

Figure 1. Location of the experimental watershed of the Dičina River

The main hydrographic characteristics of the experimental Dičina River watershed (up to the control profile P at the "Velika Dičina" dam), are presented in table 1.

Table 1. Main hydrographic characteristics of the experimental watershed

Parameter	**Mark**	**Unit**	**Dičina river**
Magnitude	A	km^2	21.98
Perimeter	P	km	23.64
Peak point	Pp	*m.a.s.l.	794
Confluence point	Cp	m.a.s.l.	492
Mean altitude	Am	m.a.s.l.	684.10
Length of the main stream	L	km	8.20
Absolute slope of river bed	Sa	%	3.68
Mean slope of river bed	Sm	%	2.05
Mean slope of terrain	Smt	%	23.99
Density of hydrographic network	D	$km \cdot km^{-2}$	2.57

*m.a.s.l.-meters above sea level

2.2. Geology and Soil Characteristics of the Study Area

The watershed is characterized by diverse geological composition. Serpentinites spread over approximately 46% of the watershed area (the headwater and the center of the watershed) and they belong to the class of waterproof rocks. Bituminous limestone (Paleozoic sediments) accounts for about 4% of the central part of the watershed area. Mesozoic formations occupy 50% of the watershed area (the central and the lowest part of the watershed) and they include: layered and banked limestone, marls and sandstones, dolomite and dolomitic limestone, porphyritic breccias, tuffs with porphyritic flows, claystones and diabases (Filipović et al,. 1978). The soil in the watershed (Tanasijević et al., 1983) consists of Eutric Leptosol (53%), Calcic Cambisol (8%) and their eroded varieties (39%).

2.3. Methodology

The intensity of sedimentation was surveyed from October 1966 to October 2011. Sediment yield was measured by survey along longitudinal profile, 750 m upstream from the dam, with 15 cross section profiles (at a spacing of 50 m). The measurements were taken in 1966, 1997, 2001 and 2011, using a theodolite (from 1966 to 2000) and a laser total station (Topcon GPT-3100N) from 2001 to 2011.

Land use changes were analyzed on the basis of the existing technical documentation and the data collected from 1966 to 2012, field investigations, usage of aerial and satellite photo images, as well as topographic, geological and soil maps. Land use classification was made on the basis of the CORINE methodology (EEA, 1994) using the MapInfo software. The area sediment yield and the intensity of erosion processes were estimated by the "Erosion Potential Method" (EPM). This method was created, developed and calibrated in Serbia (Gavrilović, 1972) and it is still in use in all the countries which originated from former Yugoslavia.

The hydrological conditions were assessed on the basis of a historical overview of land use changes and computations of maximal discharges (for control profile P, Fig. 1). Assessment was based on the conditions from the end of the 60's of the last century (before performing of ETCWs) and spring of 2012. Maximal discharges were computed using the DM software (Malošević, 1995), which was applied to the combined method, which included the synthetic unit hydrograph theory (maximum ordinate of unit runoff, q_{max}) and the Soil Conservation Service (SCS, 1979) methodology (deriving effective rainfall, P_e, from total precipitation, P_b). The computation was performed for AMC III (Antecedent Moisture Conditions III- high content of water in the soil and significantly reduced infiltration capacity). Synthetic triangular unit hydrographs were transformed to synthetic (computed) curvilinear hydrographs of total direct runoff using the SCS basic dimensionless hydrograph (Chang, 2002). Maximal daily precipitation data were provided from the neighboring Gornji Banjani rain-gauge station (58 years of observations, 470 m.a.s.l.). The computations of maximal discharges included a regional analysis of lag time (Ristić, 2003), internal daily distribution of precipitation (Janković, 1994) and the classification of soil hydrologic groups for CN-runoff curve number determination (Đorović, 1984).

The aim of this investigation is to show how land use changes caused by ETCWs and lowered anthropogenic pressure can help improve the hydrological conditions in watersheds, mitigate erosion processes, decrease deposition of sediment and reduce the risk of torrential floods.

3. RESULTS OF INVESTIGATION

3.1. Land use changes

The land use changes were determined on the basis of comparison of land use maps from 1966 and 2012 in figures 2a and 2b. There are no settlements in the watershed. However, the villages of Koštunići and Gornji Banjani are located in the vicinity (Fig. 1). The inhabitants of these villages are the owners and the users of the land. The anthropogenic pressure on the soil in the watershed was very strong during the 1960s of the last century, because the population of the neighboring villages amounted to more than 1473 people or 67 persons per 1 km^2. In 2011, there were 747 inhabitants or 34 per 1 km^2 (SORS, 1971-2011).

The erosion and torrent control works (ETCWs) in the watershed started in the mid-60's of the 20th century. In the 1966–2012 period a wide scope of biological and biotechnical activities were performed. Dominant biological and biotechnical activities included: afforestation of bare land with *Pinus nigra* and *Pinus silvestris* (219 ha; steep, deforested and eroded slopes; 700-1100 seedlings per ha, two to three years old); systems of wattlings (197 wattlings were built in 21 gullies; average height - 0.8 m; material - *Salix alba* stakes and branches). The autochthonous forest cover dominantly consists of beech and oak trees. The beech forests are located at northern exposures, whereas the oak forests can mostly be found in the south.

3.2. The process of erosion and sediment yield

Dispositions of different categories of destructivity of erosion processes (classification by EPM) in 1966 and 2012 are presented in figures 3a and 3b. Some characteristic outputs of computations of sediment yield are presented in table 2, as well as the representative values of the coefficient of erosion Z, before the ETCWs (1966) and at present (2012), including W_a-annual yield of erosive material and W_{asp}-specific annual yield of erosive material.

Table 2. Characteristic outputs of computations of sediment yield in the conditions before the ETCWs (1966) and actual conditions (2012)

Parameter	Before ETCW-1966	Actual conditions-2012
$W_a\,[m^3]$	16007	1930
$W_{asp}\,[m^3 \cdot km^{-2} \cdot year^{-1}]$	728.3	87.8
Z	0.439	0.187

3.3. Reservoire sedimentation

The sedimentation of the „Velika Dičina“ reservoire was determined on the basis of a survey conducted from October 1966 to October 2011 along longitudinal profile, 750 m upstream from the dam, with 15 cross section profiles, at a spacing of 50 m (Fig. 4). The total quantity of deposited sediment in the reservoir amounts to 18750 m^3, i.e. 15800 m^3 (509.6 m^3/yearly on average), in the 1966-1997 period, 2280 m^3 (570 m^3/yearly on average), in the 1998-2001 period and 670 m^3 (67 m^3/yearly on average) in the 2002-2011 period.

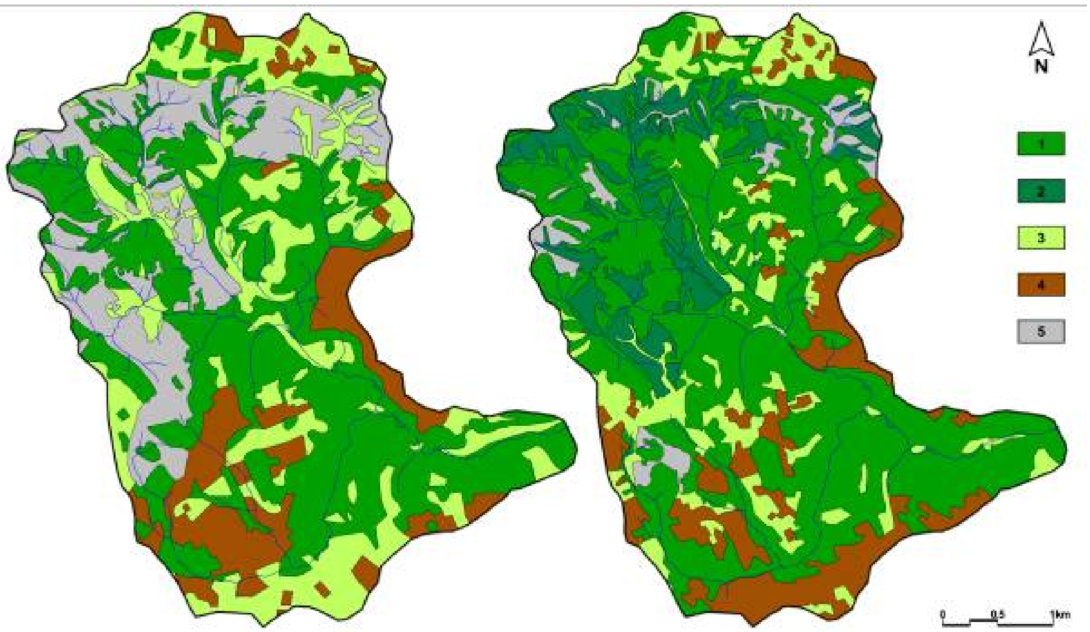

Figure 2a. Land use in the watershed of the Dičina river (1966): 1– Broad-leaved forest (9.58 km^2-43.58%); 3 – Pastures and grasslands (5.49 km^2-24.97%); 4 - Land principally occupied by agriculture, with significant areas of natural vegetation (2.94 km^2-13.42%, of which 2.34 km^2 are arable land and 0.60 km^2 are shrub land); 5 – Bare lands (3.97 km^2-18.06%)
Figure 2b. Land use in the watershed of the Dičina river (2012): 1 – Broad-leaved forest (12.53 km^2-57%); 2 – Coniferous forest (2.19 km^2-9.96%); 3 – Pastures and grasslands (3.25 km^2-14.79%); 4 – Land principally occupied by agriculture, with significant areas of natural vegetation (3.17 km^2-14.43%, of which 2.53 km^2 are arable land and 0.64 km^2 are shrub land); 5 – Bare lands (0.84 km^2-3.82%)

The maximal depth of deposited sediment close to the dam amounted to 3.1 m. The process of reservoire sedimentation starts at the distance of about 450 m upstream from the dam (profile 9, Fig. 4).

The levels of reservoir sedimentation were measured in 1966, 1997, 2001 and 2011. Cross section profile 2, at the distance of 100 m upstream from the dam (Fig. 4, 5) has a deposited surface of 44.32 m^2 and a maximum thickness of deposited material of 2.1 m.

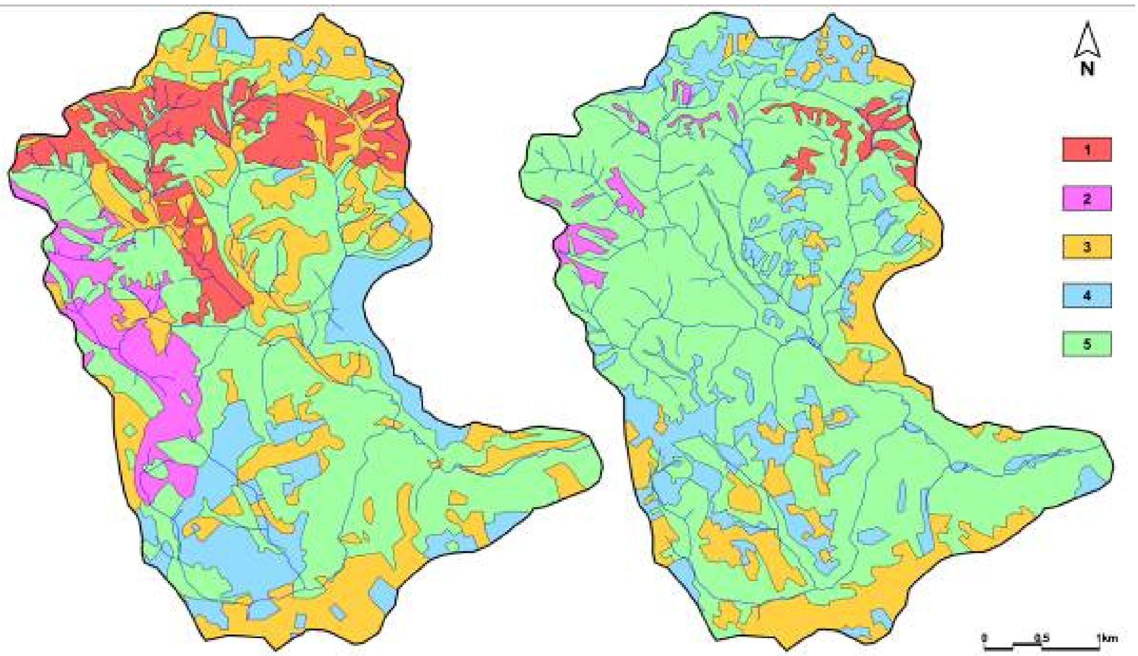

Figure 3a. The intensity of erosion processes in the watershed of the Dičina river (1966): 1 – Excessive erosion (2.42 km^2 - 11.02%); 2 – Strong erosion (1.55 km^2 - 7.05%); 3 – Medium erosion (5.49 km^2 - 24.98%); 4 – Weak erosion (2.94 km^2 - 13.37%); 5 – Very weak erosion (9.58 km^2 - 43.58%);

Figure 3b. The intensity of erosion processes in the watershed of the Dičina river (2012): 1 – Excessive erosion (0.36 km^2 - 1.64%); 2 – Strong erosion (0.35 km^2 - 1.59%); 3 – Medium erosion (3.11 km^2 - 14.15%); 4 – Weak erosion (3.24 km^2 - 14.74%); 5 – Very weak erosion (14.92 km^2 - 67.88%);

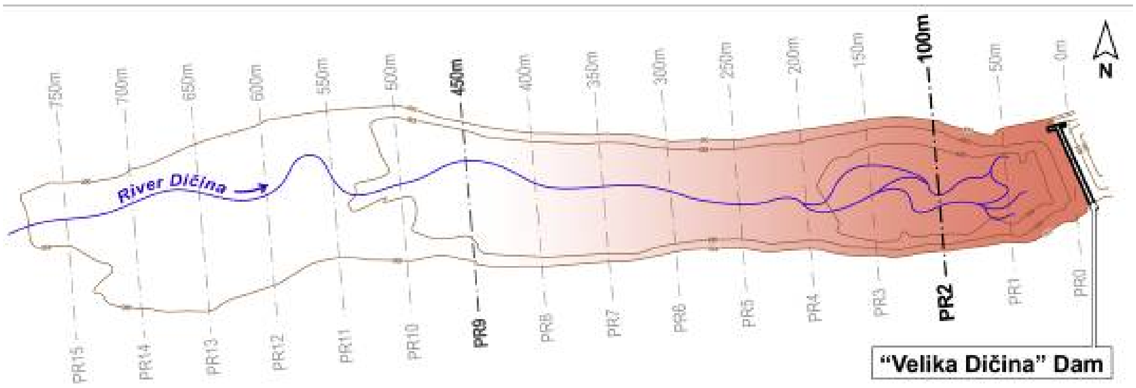

Figure 4. The disposition of the “Velika Dičina” dam, longitudinal and cross-section profiles and area of deposition (from profile 0 to profile 9)

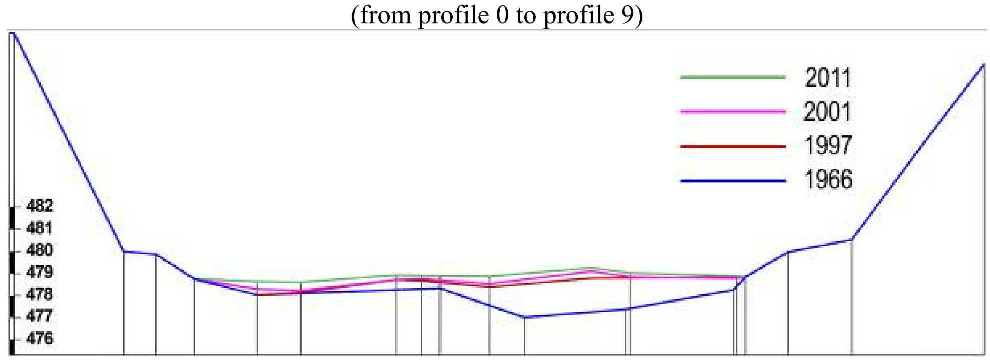

Figure 5. The cross-section of the profile 2 and levels of reservoir sedimentation in 1966, 1997, 2001 and 2011.

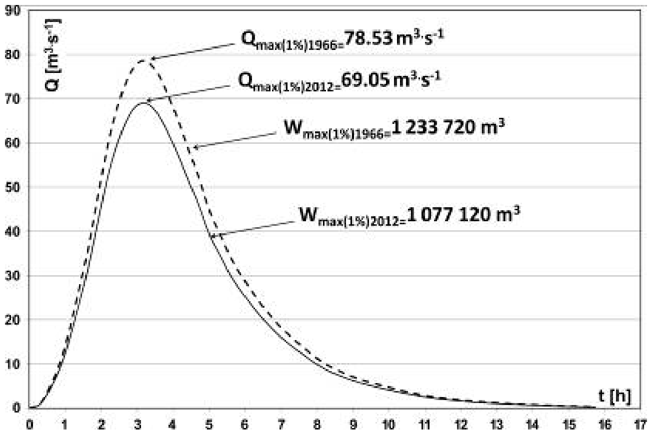

Figure 6. Calculated hydrographs of maximal discharges before (1966) and after (2012) the ETCWs

3.4. Changes of hydrological conditions

Hydrographs of computed maximal discharges for probability p=1% ($Q_{max(1\%)}$) are presented in figure 6. The value of computed maximal discharge calculated for the watershed conditions in 2012 ($Q_{max(1\%)2012}$=69.05 $m^3 \cdot s^{-1}$) is significantly reduced in comparison to the value of maximal discharge ($Q_{max(1\%)1966}$=78.53 $m^3 \cdot s^{-1}$) obtained for the watershed conditions in 1966. Furthermore, the volume of computed hydrograph of direct runoff in 2012 ($W_{max(1\%)2012}$=1077120 m^3) is significantly reduced in comparison to the volume of the computed hydrograph of direct runoff in 1966 ($W_{max(1\%)1966}$=1233720 m^3).

4. DISCUSSION

The processes of erosion and sedimentation are related to the conditions in a watershed, including climate, topography, geology and soil characteristics, hydrology, population density and land use. The natural conditions in the watershed of the Dičina River are favorable for the development of the process of erosion, fast surface runoff formation and sediment transport. These natural conditions include frequent rainfall events of a short duration (2-3 hours) and strong intensity, I > 1 $mm \cdot min^{-1}$ (Ristić et al., 2012b), steep slopes of the terrain (S_{mt}=23.99%) and river bed (S_a=3.68%). In addition, the dominant part of the experimental watershed consists of waterproof rocks (serpentine) or erodible rocks (marls and sandstones, dolomite, porphyritic breccias, tuffs with porphyritic flows, claystones and diabases). The existing soil types (Eutric Leptosol and Calcic Cambisol) are characterized by a moderate water storage capacity and resistance to erosion under sustainable land use (dense vegetation cover, contour and terrace farming, limited number of live stock, controlled urbanization and forest cuttings). However, a significant part of the soil (39%) was eroded, during the 1960s of the last century, due to inadequate land use (massive clear forest cuttings, overgrazing, and straight row farming down the slope). The consequences were reduced water infiltration capacity and intensive sheet, furrow and even gully erosion.

The average population density in the vicinity of the watershed amounted to 67 persons per 1 km^2 during the 1960s of the last century and 34 per 1 km^2 in 2011. The comparison of the land use maps from 1966 and 2012 shows great differences in the structure of surfaces (Fig. 2a and 2b). Until the end of 1960s, the watershed of the Dičina River was covered with bare lands on 18.06% of the total area (3.97 km^2). The forests were used for timber and fuel. The meadows and pastures had a degraded grass cover and a compacted surface soil layer, because of the abundant cattle and sheep populations, while farming was carried out down the slope, in straight rows. Numerous activities initiated intensive sheet and rill erosion with embryos of gullies, and decreased water storage capacity of the soil. In this way, ideal conditions for fast surface runoff formation, development of the process of erosion and loss of soil were created. About 40 years later (spring of 2012), bare lands cover just 3.82% of the total area (0.84 km^2). In the same period, the broad-leaved forest area increased from 43.58% of the total area (9.58 km^2) to 57% of the total area (12.53 km^2). In addition to that, new coniferous forests were established in almost 9.96% of the total area (2.19 km^2), mostly on the former bare lands and abandoned arable land.

The depopulation caused a decrease in the anthropogenic pressure on the agricultural and forest surfaces in the watershed, so that the pastures and grasslands were reduced from 24.97% (5.49 km^2) to 14.79% (3.25 km^2) of the total area. In addition, 13.42% of the total area (2.95 km^2) containing mostly bare land, abandoned arable land and pastures became spontaneously overgrown with trees and shrubs.

The establishment of stable forest stands on bare land is a key anti-erosion measure applied to protect reservoir storage capacity from sedimentation. The effects of this measure are the following: increase of transpiration and interception, reduction in the loss of water by evaporation, the development of the soil and its infiltration capacity, as well as lower, but longer specific runoff. *Pinus nigra* on serpentine rock produced the above effects, 7 years after planting in the experimental site at Goč mountain in Central Serbia (Ristić & Macan, 1997). The performed ETCWs in the watershed of the Dičina River (afforestation of 219 ha of deforested and eroded slopes, systems of wattlings for gully restoration) helped decrease the sediment yield and balance the runoff regime.

Total sedimentation in the „Velika Dičina" reservoir in the 1966-2011 period, amounts to 18750 m^3 or on average 416.7 m^3/yearly, i.e. 19 $m^3 \cdot km^{-2}$ expressed as specific annual intensity of sedimentation. Deposition of the reservoir was more intensive (570 m^3/yearly on average, or 25.9 $m^3 \cdot km^{-2}$) in the 1998-2001 period, than in the 1966-1997 period (509.6 m^3/yearly on average, or 23.2 $m^3 \cdot km^{-2}$), as the consequence of the highly intensive and uncontrolled forest exploitation on steep slopes. The intensive afforestation of bare lands and restoration of gullies with wattlings, as well as better control of cuttings and depopulation, contributed to a decrease in the intensity of deposition in the 2002-2011 period to 67 m^3/yearly on average (3.05 $m^3 \cdot km^{-2}$). The total loss of reservoir volume in the 1966-2011 period amounts to 5.51%, or on average 0.122% yearly.

The initial state of the process of erosion (1966) was characterized by the coefficient of erosion Z=0.439 (medium erosion). ETCWs were carried out in order to decrease the yield of erosive material, increase water storage capacity of the soil and reduce flood runoff. The present state of the process of erosion is characterized by the coefficient of erosion Z=0.187 (very weak erosion). The realization of restoration works helped decrease the annual yield of erosive material from W_a=16007 m^3 to W_a=1930 m^3 (Table 2). The comparison of erosion maps from 1966 and 2012 shows great differences in the intensity of the process of erosion (Fig. 3a and 3b). Until the end of the 1960s, the watershed of the Dičina River was endangered by excessive erosion (the hardest category of terrain destruction with deep gullies, landslides, and removed soil) on the 11.02% of the total area (2.42 km^2), while in the spring of 2012 it amounted to 1.64% of the total area (0.36 km^2).

The effects of hydrological changes were estimated by the comparison of computed maximal discharges in 1966 (before ETCWs) and 2012 (after ETCWs). The computed value of the maximal discharge ($Q_{max(1\%)2012}$=69.05 $m^3 \cdot s^{-1}$) is significantly decreased in comparison to the maximal discharge ($Q_{max(1\%)1966}$=78.53 $m^3 \cdot s^{-1}$). This indicates the improvement of hydrological conditions, as a direct consequence of the ETCWs and land use changes. In addition, the volume of the computed hydrograph of direct runoff in 2012 ($W_{max(1\%)2012}$=1077120 m^3) is significantly reduced (12.69%) in comparison to the volume of the computed hydrograph of direct runoff in 1966 ($W_{max(1\%)1966}$=1233720 m^3). By contrast, other significant parameters, including physical characteristics of the watershed (magnitude, mean slope of terrain, mean slope of river bed) and total precipitation remained the same. Some characteristic outputs of hydrologic computations (Tab. 3) indicate more favorable hydrological conditions of the post-restoration environment (2012) in the watershed of the Dičina River, including reduced values of the maximal ordinate of sinthetic unit hydrograph (q_{max}), runoff curve number (CN) and effective rain (P_e).

5. CONCLUSIONS

The experimental watershed of the Dičina River still has the natural potential, in terms of climate, topography, geology and soil characteristics and hydrology, for the development of intensive processes of erosion, sediment yield and reservoir sedimentation. Soil erosion in the watershed, during the 60s of the last century, was initiated by the removal of forest (clear cuttings, trunk transport down the slope) and inadequate agricultural activities (straight row farming down the slope, overgrazing). In addition to that, population density, educational and cultural conditions contributed to the process of degradation.

The anthropogenic impact was significantly reduced after the ETCWs and the change towards sustainable land use. The depopulation contributed to a significant decrease in the pressure on agricultural and forest surfaces in the watershed. The ETCWs in the watershed of the Dičina River (afforestation of 219 ha of deforested and eroded slopes, systems of wattlings for gully restoration) helped decrease the sediment yield and balance runoff regime. The establishment of forest stands on degraded surfaces and appropriate technical works in the hydrographic network are effective anti-erosion measures for the protection of reservoir storage capacity from sedimentation. In order to minimize the impact of erosion, it is necessary to perform afforestation with adequate species and form stable forest stands, at least 7-10 years before the beginning of the water reservoir exploitation.

Once extremely disturbed watershed with intensive sediment yield is now restored after large-scale biological and biotechnical ETCWs, which were performed in the 1966-2010 period. Land use changes in the watershed helped balance the runoff regime by increasing the low discharges (their amount and duration) and decreasing the maximal discharges. The intensity of the process of erosion has been reduced from medium erosion (Z=0.439) before the ETCWs, to very weak erosion (Z=0.187). Most of the former bare land, abandoned and degraded arable land and pastures were transformed into forest surfaces or transitional woodland- shrub land. This transformation and the restoration of 21 gullies with systems of wattlings helped decrease the sediment yield about 8 times.

The total sedimentation in the „Velika Dičina" reservoir, in the 1966-2011 period, amounts to 18750 m^3, and accounts for 5.51% of the total reservoir volume. The most intensive deposition of sediment was recorded in the periods of very intensive and uncontrolled forest exploitation on steep slopes, and high pressure on the agricultural land. The ETCWs, controlled forest cuttings and adequate use of agricultural land, as well as the process of depopulation helped in the restoration of the watershed and slowing down of the reservoir sedimentation.

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