CALCULATION OF SEDIMENT TRANSPORT IN RAKOVITSA TORRENT WATERSHED

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Abstract

The watershed of tributary Rakovitsa (747.5 ha) is a representative one in the middle part of the main stream of river Struma. The watershed is located in Blagoevgrad region, about 15 km south from the town.

Two methods were used for determination of sediment volume from watershed Rakovitsa. The average total sediment transport (suspended and bedload) using Poliakov-Kostadinov’s method is 340.0 m³.km⁻².y⁻¹. The data obtained by this method are more acceptable because they correspond with those from the small watershed situated in river Struma watershed too. It is important that Poliakov-Kostadinov’s method is verified for the watersheds in Serbia, i.e. in the similar geographical conditions as in Bulgaria.

It was established considerable differences in the results of two tested methods because the total sediment calculated using KINEROS2 model are 5583.0 m³.y⁻¹ whereas using Poliakov-Kostadinov’s method the sediment are 2540.0 m³.y⁻¹. The difference in the annual sediment transport, determined by mentioned methods, show the necessity of further investigations at the other regions in Bulgaria in order to verify fitting of methods and models to field obtained data.

Key words: Bulgaria, Rakovitsa, sediment transport, Poliakov-Kostadinov’s method, KINEROS 2 model

INTRODUCTION

The investigations concerning the sediment transport from the watersheds related to erosion estimation as well as possibilities for sedimentation of artificial lakes are subjected of special attention (Morgan, 1998; Chisci et al., 1998; Kostadinov, 1999; Bazzofri, Pellegrini, 2000; Verstraeten, Poesen, 2000; Lu et al., 2003; Meamarian et al., 2003). Previous engineering practice and experience shows that, in the design of all structures on the streams loaded with sediment, sediment regime must be seriously studied both the state before the construction and the conditions when the new structures are functioning. An average annual sediment transport was found as parameter with significant importance. It is well known that sediment transport in the torrents is very important for agriculture, waterpower engineering, water resources, energetic, traffic, urbanization and also for torrent control practice and science. Sediment transport in the torrents depends on many factors, such as parent materials, soil type, climate, vegetation
cover, etc., but the most important of which are: eroded material in the watershed (soil erosion intensity in the watershed), and transport capacity of the torrent bed (of the channel), which depends on hydrological and hydraulic characteristics of the flow.

In spite of the importance of sediment transport, the sufficiently exact and cheap methods for its measurement in the open streams, and especially in the torrents are not yet developed. The sediment transport is a very complex phenomenon and not enough studied in the point of view of the torrent hydrology and hydraulics. Due to the high concentration of sediment with a wide range of sizes particles (from the finest to the large pieces - more than 2 m in diameter), as well as due to high speeds of torrential flows, classical hydrological methods could not be applied for water discharge and sediment transport measurements. These kind of measurements are complicated and of a great expense. These are the reasons because of which for average annual sediment transport predicting (suspended and bedload) and for the watershed management practice in Serbia and Montenegro, Gavrilo and Polyakov (1972) and Polyakov (1948) methods have been used. Of recent years the modified Polyakov-Kostadinov's method, based on the newly introduced parameter of "pluvial-erosion index", is used (Kostadinov, 1985, 1990, 1993, 1999).

Considerable part of investigations, concerning sediments in the torrents in Bulgaria is related to sediment slope behind the technical facilities (barrages). A quantitatively dependences between sediment slope and slope of the torrent bed in a lot of torrents were established (Birochev et al., 1975; Zakov, 1988; Angelov, Marinov, 1984; Zakov, Marinov, 1995). Gergov et al. (2001) consider the sediments yield in the rivers in Bulgaria as an indicator for soil erosion in the watersheds. It was established that the average annual module of the sediment is around 125 t.y\(^{-1}.\)km\(^{-2}\) and eroded soil depth is 0.079 mm/yr. These values are suggested to be used as indicators for erosion processes in the watersheds.

Investigations on soil erosion in one of the largest watersheds in Bulgaria - Struma river watershed (Fig. 1) find out development of intensive erosion processes in the many of the tributaries (Kerenkova et al., 1968; Angelov et al., 1975; Mandev, 1984, 1996; Marinov, 1984; Martensson et al., 1998; Gergov, 2001; Marinov, Gruev, 2002). The presence of erosion is a result not only of the human activity in the past, but also of the natural factors of erosion, especially important of which are the topography, climate and bedrocks.

The watershed of tributary Rakovitsa is a representative one in the middle part of the main stream of river Struma. It was established that during the past years the average module of the sediment is 77 t.km\(^{-2}.\)y\(^{-1}\) in the section below the Blagoevgrad, where river Rakovitsa is running into river Struma. This means that the erosion processes were considerably reduced in result of the large-scale afforestation carried out during second part of the last century. The complex investigations of the influence of the separate factors on the erosion processes implemented in river Rakovitsa watershed were finalised in the project of the biological and technical strengthening of the watershed (Raev et al., 2002; Marinov, Gruev, 2002; Velizarova, Marinov, 2004, in press). The expected volume of behind-barrages sediment that the designed technical facilities could hold was determined (Liubenov, Marinov, 2003). However, investigations by direct measurement of the sediment transport using hydrometical methods have not been carried out, mainly because of the difficulties for such kind of measurements in the torrents, which pull with the others regions in the country so for the neighbor countries.

The purpose of the current investigation is to determine the annual average quantity of the sediment from river Rakovitsa that enters river Struma. The data obtained could be used for erosion assessment in the watershed as well as in design of activities for sediments transport reduction.

Fig 1. Situation of the Rakovitsa watershed
Empirical method

The annual sediment transport in this investigation was calculated using modified Polyakov's method, famous as Polyakov-Kostadinov method (Kostadinov, 1993). The main reason of using this method is that it is verified for the territory of Serbia i.e. in the similar geographical and natural conditions.

The modification of Polyakov's method consists of the calculation of average annual turbidity of water \( \rho_z \) based on the newly introduced parameter "pluvial-erosion index". Pez (Kostadinov, 1985):

\[
\rho_z = 0.2982 \cdot P_z + 0.0049
\]

\( r_a \) - average annual turbidity in kg.m\(^{-3}\);

Pez - pluvial-erosion index.

\( P_z = 100 \cdot \eta \cdot K_z \)

\( \eta \) - relation between maximum daily and annual precipitation,

\[
\eta = \frac{h_{\text{max}}}{H_{\text{year}}}
\]

\( h_{\text{max}} \) - average value of maximal daily precipitation in a year, in mm,

\( H_{\text{year}} \) - average value of annual precipitation, in mm.

\( K_z \) - part of watershed area affected by soil erosion (lowland, bare land, unproductive land and other land affected by soil erosion), in km\(^2\);

F - watershed area, in km\(^2\).

The main idea in the above expression is the attempt to link the main agents of sediment yield and transport, i.e. water (precipitation) and soil erosion processes in the watershed. It is known that total annual precipitation, \( H_{\text{year}} \), is not the decisive factor of soil erosion and sediment transport, a more significant influence is that of precipitation intensity. In the situation when there are no pluviographs in the watershed, but only simple rain gauges, this is the way (maximal daily rainfall in a year) to express the effect of precipitation. As sediment in torrents is transported only in flood waves occurring after heavy rains, this is a potential method of solving the problem.

After calculation of average annual turbidity, calculation of average annual sediment transport (total sediment) is possible according to the modified Polyakov's method (Polyakov-Kostadinov method):

\[
G_{\text{year}} = \frac{\rho_z}{10^3 \cdot \rho_l} \cdot \frac{M_o}{10^3} \cdot 31.536 \cdot 10^8 \cdot \left( 1 + \frac{\beta}{\rho_2} \right)
\]

where:

\( G_{\text{year}} \) - average annual sediment transport (total sediment), in m\(^3\) year\(^{-1}\),

\( M_o \) - average annual specific discharge, in m\(^3\) s\(^{-1}\);

\( W_0 \) - volume of annual runoff in m\(^3\);

\( E = F \cdot A \),

\( F \) - watershed area, in m\(^2\);

\( A \) - total annual runoff, in m (total annual runoff in mm was calculated according Keller's formula for the hilly-mountainous watersheds: \( A = H_{\text{year}} - 350 \) (Kostadinov, 1996);

\( \rho_l \) - specific gravity of suspended sediment, in t.m\(^{-3}\);

\( \beta \) - ratio of suspended and bedload sediment which is depending of stream slope, according the table of Polyakov (1948).

Model KINEROS 2

Determination of the mean year volume of sediments in Rakovska watershed was put into the practice by the KINEROS2 model (Smith et al., 1995). KINEROS2 is a hydrologic model, which upgrades an earlier version of KINematic Runoff and EROsion model (KINEROS) (Woolhiser et al., 1990). It is an event-based model, so that long periods of soil water redistribution, plant growth, and other inter-storm changes are not treated. A rainfall record describing the rainfall rate pattern is used to simulate the runoff over a catchment of rather arbitrary complexity. The catchment is described by an abstraction into a tree-like network sequence of surfaces and channels. Infiltration is described by a model, which includes small-scale spatial variability, a crust layer, and treatment of redistribution during rain hiatus (Gorardini et al., 1994). Runoff is routed with an implicit finite difference solution of the kinematic wave equation. Erosion is simulated as a simple transport process operating with erosive detachment from splash and hydraulic sources, in equilibrium with setting based on particle fall velocity (Smith et al., 1995). The model allows pipe flow and pond elements as well as infiltrating surfaces, and includes a partially paved element to use in urban area simulation. KINEROS can simulate the movement of eroded soil along with the movement of surface water; can account separately for erosion caused by rainfall in and erosion caused by flowing water, and continues the simulation through channel and pond elements. One necessary limitation is that, because a single mean particle size is used to characterize the eroded material, the effective soil particle size needs to be similar for all the eroding elements.

Parameters must be input to describe the network, the characteristics of each element, and the rainfall. Two ASCII files, in open format, describe the parameters and weather for the simulated storm. There is global data, such as temperature, and element
specific parameters for each kind of network element. In this exploration was applied most of input variables in parameter and rainfall files.

For the current study need only Plane and Channel elements in parametric file. The used parameters are: identifier of an upstream plane or channel element (ID), length of plane or channel in meters (LEN), area in square meters (AREA), slope of plane or channel (SL), Manning’s roughness coefficient (MAN), interception depth in mm (IN), fraction of surface covered by intercepting cover (CANOPY), saturated hydraulic conductivity, mm/hr (Ks), mean capillary drive, mm (G), pore size distribution index (DIST), porosity (POR), rain splash coefficient (SPLASH), soil cohesion coefficient (COH), particle class fractions (FR), lateral identifier(s) (LAT), channel bottom width in meters (WIDTH), bank side slopes (SS1, SS2), volumetric rock fraction (ROCK) (www.tucson.ars.ag.gov/kineros).

Land cover in the study area was used from CORINE Land Cover classification scheme and applied to NLCD (http://www.epa.gov/). This was important because for everyone of the land cover classes defined in NLCD are determining variables that influence to erosion process. The variable CANOPY in plane element of parameter file was computed by the type of land cover.

The soils in the investigated watershed are Luvisol (Velizarova, Marinov, 2004). Soil parameter was determinate by discrete measures in laboratory. The Ks and other parameters were defined according to the EUROSEM’s user manual (Morgan et al., 1998) classes relatively to textural class of the studied soils.

For DEM generation was digitized the paper maps from the study area at 1:5000 scale. GRID with 5 m resolution was build. DEM was used for determination of different characteristics of the plane and channel elements in parameter file. The schematic presentation of the planes and channels used in the KINEROS2 modeling is presented on Fig. 2.

There are not data for intensive precipitations in watershed Rakovitsa. We used the data of precipitations with quantity > 9.5 mm and \(I_{95} = 180\) mm min\(^{-1}\) which have duration over 30 min established for station “Igralishte” (Sandanski) where the natural conditions are similar (Ruseva et al., 2004). These intensive precipitations are characterized by following parameters: mean amount for single event - 24 mm, average annual intensity 18.9 mm h\(^{-1}\), duration - 84 min and yearly frequency 1.4.

RESULTS AND DISCUSSION

Characteristics of representative watershed

The watershed of Rakovitsa river is located in the Blagoevgrad region, about 15 km south from the town in the middle of the river Struma watercourse (Fig. 1). The area of Rakovitsa watershed is 747.5 ha, about 400 ha of which are used as arable and the rest as forest lands. The forest vegetation covers the steep and very steep slopes of the investigated region. These natural circumstances are a limiting factor for the vegetation development. The watershed is a part of the southern slopes of the Rila Mountain where the topographic conditions, climate and human activity provoke intensive soil erosion processes.

- Watershed Rakovitsa belongs to the group of hilly-mountainous watersheds.

The main characteristics of the representative watershed are:
- watershed area - \(F = 7.47\) km\(^2\);
- watershed perimeter - \(O = 14.99\) km;
- watershed length - \(L_g = 7.09\) km;
- watershed mean altitude - \(N_{av} = 686\) m;
- watershed mean slope - \(J_{av} = 41.1\) %;
- density of hydrographic network - \(G = 6.25\) km km\(^{-2}\);
- mean slope of main watersteam - \(J_1 = 9.8\) %.

Erosion of average degree of intensity is found for watershed Rakovitsa (Marinov, Gruev, 2002). The coefficient of erosion by Cavrilovic (\(Z_c\)) is 0.56. Significant part of the area - 26% of the total - is exposed to intensive erosion processes. Relatively equal in size parts of the surface - 32-34% - are subjected to either week or medium degree of erosion. On 55.0 ha (7.3%) excessive eroded area, the erosion control need to be undertaken urgently.

Calculation of Sediment Transport

For the calculation of total sediment transport were used average value of annual precipitation (\(H_{an}\)) of 650 mm and average value of maximal daily precipitation in a year (\(H_{an_{max}}\)) - 32 mm.

The following data were obtained:
- Average annual turbidity \(r = 0.9627\) kg m\(^{-3}\)
- Pluvial-erosion index Pez = 3.212
- Average annual specific discharge Mo = 0.00951 m³/s·km²

The total sediment transport (Gyr), determined by empirical Polyakov-Kostadinov's method is 2540.0 m³·yr⁻¹ and specific sediment transport (Gyr sp) is 340.0 m³·yr⁻¹·km⁻².

The following data were input for the calculation of the sediment in the KINEROS2 model:
- In the Plane and Channel file: a) land cover file; b) soil condition file; c) DEM of the area including characteristics of the main channel;  
- In the Rainfall file: a) the average annual number of the intensive precipitations with amount > 9.5 mm, intensity Icp: e” 80 mm/min and duration over 30 min is 1.4; b) average amount of such rainfall – 24 mm; c) average intensity of the intensive precipitations - 18.9 mm·h⁻¹.

The amount of sediment transport obtained using model KINEROS2 is 5583.0 m³·yr⁻¹ and specific sediment transport is (Gyr sp) is 750.0 m³·yr⁻¹·km⁻².

The data from the literature exhibit that the determined amount of the total sediment by empirical Polyakov-Kostadinov's method is approximately equal to that, established for small watershed (N 4) with area 0.551 km², situated in Drakovska river watershed, which is tributary of Struma river (Mandev, 1984, 1996). The total annual sediment transport from this watershed for 1971 to 1982 is 568 m³·km⁻²·year⁻¹ (595 t·km⁻²·year⁻¹), from which the bedload sediment are 83 % and suspended one 17 %. At that period the human activities had been rather larger in comparison with the years after this period. The geographical conditions in this small watershed are similar to these in the investigated one, where 53 % of lands are wooded, oak and beech forests are managed by branch-cutting manner and there are also free grazing lands. The difference between the small watershed (N 4) and Rakovitsa watersheds is in the existing in the first one of the arable lands - around 36 % territory, used in that period for cultivation of tobacco. The average annual amount of total sediment transport in small watershed (N 4) was 361 m³·km⁻²·year⁻¹ (598 t·km⁻²·year⁻¹) for the whole investigated period (1971 - 1993), where the percentage ration of bedload and suspended sediment where 80 % to 20 % (Mandev, 1996). As it can be seen the sediment transport quantity for the Rakovitsa watershed, established by Polyakov-Kostadinov's method, is thereabout the data obtained for the whole investigated period from the small watershed, which is situated in the river Struma watershed too. This allows us to accept the data for the amount of sediment, determined by this method as more accurate.

Some of input parameters used in the KINEROS2 model have been obtained from field surveying (vegetation cover, area and soil characteristics - SL, LEN, SLOPE, WIDTH, DEPTH, SS1, SS2), laboratory analyses (textural fractions quantity of studied soil, pore, ID, COH, SMAX INTER, CANOPY, LAT, ROCK, UP, SP), or from DEM analyses (slope, area, length etc.). Other necessary input parameters for the KINEROS2 model such as MAN, IN, G, Ks were taken from literature (http://www.epa.gov/). For example Manning's roughness coefficient is 0.015 for the three different types of

land cover - deciduous, coniferous and mixed forests. This could be a probable reason for an inaccurate data from modeling.

In the current study we used the data of precipitations with quantity > 9.5 mm and average intensity Icp = 10.8 mm·h⁻¹ which have duration over 30 min. Perhaps these limitations influence the accuracy of the KINEROS2 simulation too. Furthermore the precipitations data used in the model are established for the station "Igralitsa" which is located in the considerable distance from the studied watershed.

Taking into account the necessity for more accuracy in the input data for the KINEROS2 model, mentioned above, it could be suggested that the calculated data exceeds the real one. The probable reason for this exceeding could be also the lack of data for the intensive precipitation, measured in the studied region. Using the precipitation data determined for other watersheds reduces the accuracy of the applied methods regardless of the similarity in the geographical conditions. The interpolation of the intensive precipitation data from several meteorological stations situated near by the investigated watersheds is one of the possible approaches for increasing of the accuracy in determination of sediment transport by empirical methods and computed models.

The spatial distribution of sediment yield calculated by the KINEROS2 in the investigated watershed is presented on Fig. 2. The most intensive erosion and sediment transport occur in the low part of the watershed (planes 52, 43, 32, 33, 35). In the figure transport occur in the low part of the watershed (planes 52, 43, 32, 33, 35).

CONCLUSION

Two methods were used for determination of the volume of sediment from a watershed Rakovitsa. The average total sediment transport (suspended and bedload) using Poljakov-Kostadinov's method is 340.0 m³·yr⁻¹. It was established considerable differences in the results of two tested methods because the total sediment calculated using KINEROS model are 5583.0 m³·yr⁻¹ whereas using Poljakov-Kostadinov's method the sediment are 2540.0 m³·yr⁻¹.

On this stage of investigation the data for sediment from Rakovitsa watershed obtained by Poljakov-Kostadinov's method are more acceptable because they correspond whith those obtained from the small watershed situated in river Struma watershed too. It is important that this method is verified for watersheds in similar geographical conditions as in Bulgaria. The difference in the annual sediment transport, determined by mentioned methods, show the necessity of further investigations at the other regions in Bulgaria in order to verify fitting of methods and models to field obtained data.

The KINEROS model advantage consists in the possibility to receive information about the space-temporal characteristics of the water discharge during the intensive
precipitations that could be used as preliminary information for designing of technical facilities for erosion control.

Acknowledgement: This work was financially supported by MEW and MAF - NFR.

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Received: 30.03.2004