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ANALYSIS OF GROUNDWATER REGIME ON THE BASIS OF STREAMFLOW HYDROGRAPH *

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Abstract. *During the drought the flow in streams is reduced and is dominated by base flow. Baseflows are characteristic of low flow periods and provide information on available water resources in the basin during the drought, particularly on the aquifer and retention basin characteristics. This paper deals with the possibility of analysis and simulation of baseflow, and the determination of the pattern of its changes based on the total registered streamflow hydrograph at the catchment outlet. The basis for modeling the base flow changes in the time were base flow values obtained from the streamflow hydrograph by application of the graphical local minimum method. Applying the simulation model developed in this study, simulations of base flow hydrographs were performed for three characteristic years (1970, 1985, and 1990). It was shown that discrepancies between values of the base flows obtained through application of the local minimum method and the model are within the limits of tolerance.*

Key words: *base flow, modelling, the local minimum method, the curve of concentration, recession curve*

1. INTRODUCTION

Due to the intense and irrational use of water there is a need for exploration of water resources, especially during low flow periods. The amount of base flow i.e. of groundwater flow of a basin is impossible to measure at the catchment outlet, but it can be analyzed based on the total registered streamflow hydrograph at the catchment outlet from which base flow values can be extracted using some of the graphical methods. Base flow hydro-

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graph contains important information on the qualities of aquifer and retention characteristics of a basin.

The model of base flows of the 340 km^2 Kolubara River catchment up to "Valjevo" water level monitoring station (w.l.m.s.), presented in this study, describes the rules of base flow changes in certain time spans based on the total registered streamflow hydrograph at the catchment outlet. This model enables base flow forecast in dry periods and estimation of retention capacities of the catchment under consideration and other catchments of similar characteristics.

Base flows are typical for low flow periods, and during periods of drought, total runoff is equal to the base flow. The base flow tends to gradually decline over time, and in extreme drought conditions complete exhaustion of water supplies in the basin or zero flow can occur. Occurrences of low flows usually are closely connected with problems in water supply to population, agriculture and industry. Low flow periods present potential dangers for degradation of the environment and can have long-term negative consequences on the bionetwork especially when water resources are used intensively and irrationally. In the existing literature and hydrological practice a large span is dedicated to runoff hydrograph analyses and development of models for simulation of flooding tides, which is a consequence of the necessity for flood protection instruments, for determining dimensions of dam overflows and other treatments concerning high level waters. Only recently, when problems of protection against floods have been more or less successfully solved, the interests of hydrologists focus onto detailed analysis of base flow, low flows and draughts, all of them representing a base for modern analyses of rational usage and protection of waters.

Due to the complex hydrogeologic conditions in the basin, which are highly variable even at small distances, it is very difficult to determine the amount of water that flows from unsaturated to saturated media. Taking into consideration that base flow is considered to be a rough estimate of groundwater recharge, i.e. the quantity of water flowing from unsaturated to saturated environment, the analysis of base flows on the basis of streamflow hydrograph contributes to information on groundwater recharge from the whole basin.

Following the work of Dausse (1842) and Boussinesq (1877), numerous studies have used recession of streamflow to estimate the contribution of groundwater to streamflow. Baseflow separation from streamflow hydrographs has long been a topic of interest in hydrology (Meyboom, 1961; Hall, 1968; Tallaksen, 1995; Toebes and Strang, 1964; Bevans, 1986; Nathan and McMahon, 1990; Moore, 1992; Rutledge, 1992) since the baseflow recession curve itself contains valuable information about the aquifer properties. The large number of existing techniques and the high level of subjectivity in separating baseflow contribution from total streamflow (Tallaksen, 1995) indicates that the problem is not fully understood.

Base flow characteristics depend much more on paedological and geological characteristics of the basin area, and to a much smaller extent on climatic qualities, so that base flow presents a more or less determined component of a hydrograph. That is why it is suitable for modeling and for determination of base flow changes in the course of time by analysing a streamflow hydrograph. However, in high precipitation areas, such as the area analysed in this study, the base flow may be subject to major fluctuations, as it depends on intensity of precipitation. In cases like this, it is more difficult to define the correlation suitable to express base flow changes in the course of time.

In the year of 1980, the Institute of Hydrology in Great Britain (now it is the Centre for ecology and hydrology) has formulated a key indicator of influence of geological characteristics of land on values of low flow which is termed the index of base flow (BFI). The base flow index indicates the relation between the base flow volume and the total annual outflow volume. The values of BFI vary between 0 and 1, whereby lower BFI values correspond to lower infiltration capacity basins. Higher BFI values correspond to higher infiltration capacity basins. It was shown that base flow values are of significant importance in Serbia because the average annual values of the base flow index varied between 0.65 and 0.85 at the 100 most important profiles in Serbia (Radić et al., 1992). This means that the base flow values are for 5-10% higher than the values of direct flow and that the analysis of groundwater runoff must be given the significant attention.

2. STUDY AREA

The Kolubara River basin up to ”Valjevo” wlms (see Fig.1), situated in the central part of Serbia, comprises the upstream part of the basin of 340 km^2 together with the Jablanica River basin (152.79 km^2) and the Obnica River (187.21 km^2) basin.

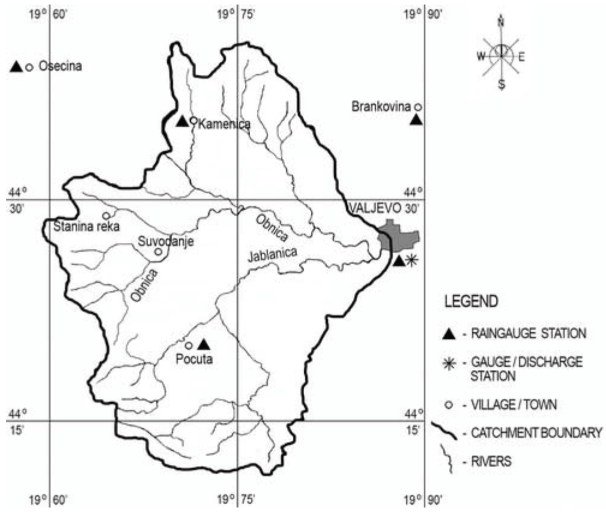

Fig. 1. Study area; Location of Kolubara River catchment up to ″Valjevo″ w.l.m.s.

This segment of the Kolubara basin is a very relief-outstanding area. The heights above sea level vary from 1100–1300 metres above sea level in the higher parts to 200–300 m in alluvial valleys of rivers. The vertical manifestation of this area makes it rich in streams and wells of different size.

Weather conditions in this region of Serbia are characterized by exceptionally high humidity and a high rate of precipitation of about 940 mm per year. Average annual temperatures are high, while the relative humidity is low, resulting in intensified evaporation.

From the studied basin, the following paedological types of soil were singled out: reddish-brown soil on a limestone base *(RBS)* (27%), brown skeletal soil covering schist

(BSS) (23.9%), rendzine *(R)* (13.87%), red soil *(RS)* (0.11%), parapodozol *(P)* (22.76%), alluvium *(A)* (2,22%), smonical *(S)* (5.62%), bare soil *(BS)* (0.98%) (see Fig. 2).

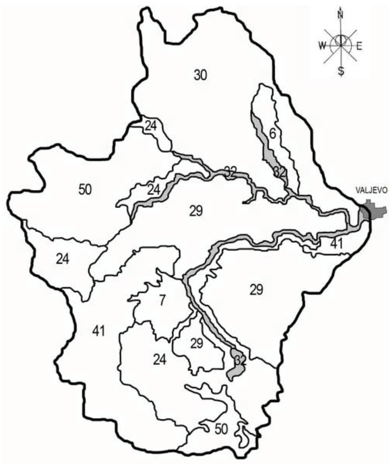

Fig. 2. Paedological map of the Kolubara River basin up to ″Valjevo″ w.l.m.s; Legend: 6,7 – smonical; 24, 29 – reddish brown soil on a limestone base; 30 – parapodozol; 32 – alluvial deposits; 41 – brown skeletal soil over schist; 50 – bare soil

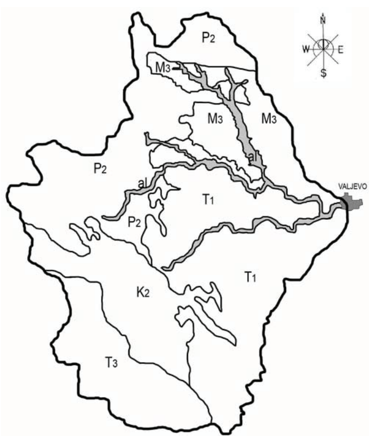

Fig. 3. Geological map of the Kolubara River basin up to ″Valjevo″ w.l.m.s; Legend: al – alluvium; K_2, T_1, T_3 – limestone; M_3 – clay; P_2 – clay schist

In the mountainous parts of the catchment soils on a limestone base as well as brown skeletal soils covering schists dominate, while smonical, parapodozol and alluvium dominate in the lower parts of the catchment. In the upper parts of the catchment deciduous forests prevail (36.5%), in the middle parts there are meadows (39.06%) and orchards (7.18%) while plowed fields (12.78%) are situated in alluvial valleys. The smaller part of the observed catchment area is defined by bare soil (1.05%), by urbanized areas (1.89%), and by river water surfaces (2.11%).

Various types of rocks prevailing in the Kolubara River basin up to the "Valjevo" wlms can be grouped in the following four categories: limestone (41.97%), schist (23.94), clay (28.38%) and alluvium (2.21%) (Fig. 3).

Groundwater recharge from different land types is different. The majority of soils in the basin under consideration are situated on limestone terrains, thus the limestone component seriously affects the runoff. Land on the limestones (reddish brown soil on a limestone base, rendzina) has good water-physical properties and high infiltration capacity. The limestone terrains in this part of Serbia are covered with karsts and there are numerous cracks allowing the best part of precipitation to infiltrate into deeper layers. Numerous karsts features make the defining of the actual ground water recharge very difficult. Due to their existence and their unknown physical characteristics and geometry, unknown groundwater reservoirs, their correlation and hydraulic functioning, it is difficult to define the quantities of water running off into groundwater as well as the size of the surface from which recharge originated. Groundwater recharge through the alluvial fans is also great, because their base is permeable and ground water is near the surface. Parapodozol and smonical are poorly permeable soil and the amount of water draining from the unsaturated environment of these types of grounds into ground water is very small.

3. Material and Methods

The basic input data used for the base flow modeling are the observed daily streamflow discharges registered at the "Valjevo" w.l.m.s. for the period 1961 through 1996, because much better fits are obtained when applying data processing from separation of hydrographs through periods spanning several years.

At first, the comparative analysis of results of base flow separation through application of the three graphical procedures i.e. using (i) the fixed interval method, (ii) the sliding interval method, and (iii) the local minimum method has been performed on the basis of measured daily mean stream discharges at "Valjevo" w.l.m.s. for three different annual periods with distinct climatic characteristics (an extremely rainy year – 1970, an average year – 1985, and an extremely dry year – 1990). The analysed graphical methods can be described conceptually as three different algorithms to systematically draw connecting lines between the low points of the streamflow hydrographs. The sequence of these connecting lines defines the base-flow hydrograph. The techniques were developed by Pettyjohn and Henning (1979). Base flow hydrographs obtained through application of the fixed interval method (Q_{b1}), the sliding interval method (Q_{b2}) and the local minimum method (Q_{b3}) during the period of three analysed characteristic years are shown in Figs. 4- 6.

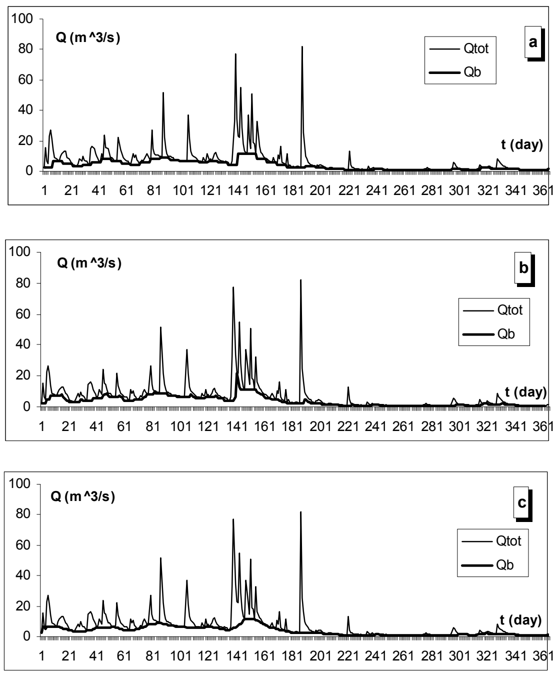

Fig. 4. Observed mean daily discharges and base flows obtained by application of the fixed interval method (a), the sliding interval mehod (b) and the local minimum method (c) (Kolubara River, ″Valjevo″ w.l.m.s., 1970)

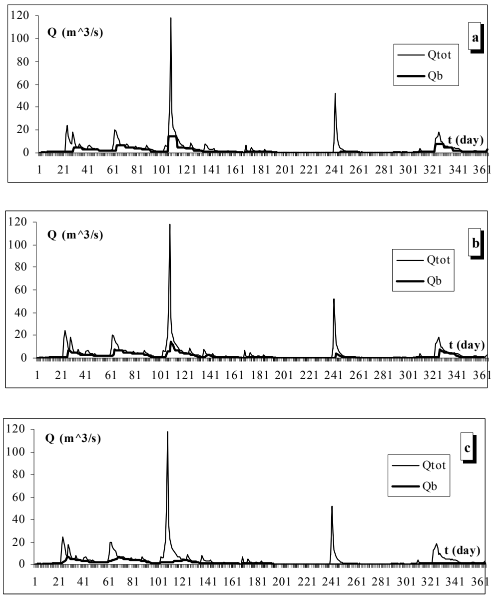

Fig. 5. Observed mean daily discharges and base flows obtained by application of the fixed interval method (a), the sliding interval mehod (b) and the local minimum method (c) (Kolubara River, ″Valjevo″ w.l.m.s., 1985)

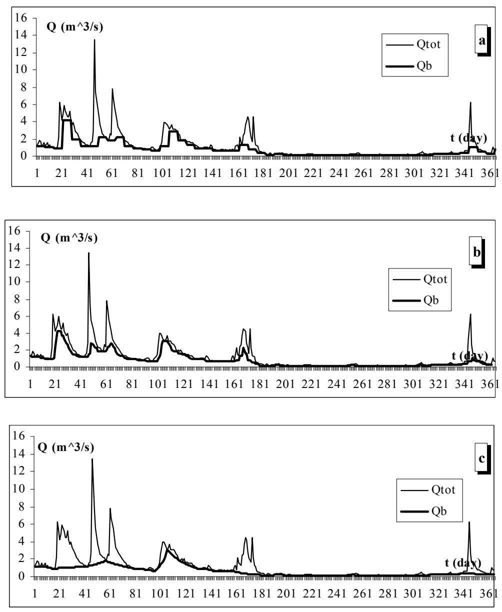

Fig. 6. Observed mean daily discharges and base flows obtained by application of the fixed interval method (a), the sliding interval mehod (b) and the local minimum method (c) (Kolubara River, ″Valjevo″ w.l.m.s., 1990)

Visual analysis of the base flow hydrographs obtained through application of the three different graphical methods led to the conclusion that through application of the local minimum method the obtained values of the base flow are in the best agreement with the physical character of groundwater discharge and the preceding theoretical analysis, and these base flow values were adopted as representative values for further investigations on the basis of which base flow changes in the course of time were modeled. Yet, the decision on which graphical method to apply as the most suitable one is a subjective matter, given the fact that values of base flow are impossible to measure, thus the choice of a certain graphical method as the most suitable one being not possible to support with measured base flow data.

Through application of the local minimum method simulation analyses of base flow were carried out in the period between 1961 and 1996. Based on the results of simulations, annual series of changes of the total flow and the components of the base and direct runoff are shown in Fig 7, as well as changes of the base flow index during the analysed period of time.

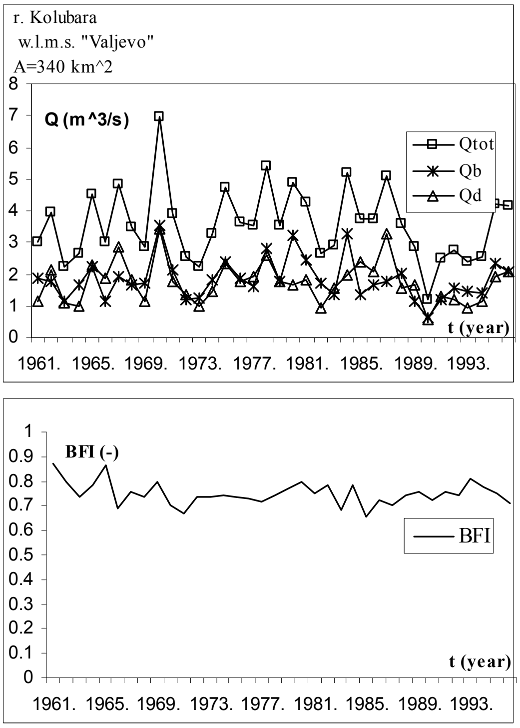

Fig. 7. Comparative survey of annual series of total flow (Q_{tot}), component base flow (Q_b), direct (Q_d) and the base flow index (BFI) for 1961. through 1996. period

It can be concluded that on the Kolubara river up to ”Valjevo” w.l.m.s., the base flow provides a considerable contribution to the total flow. Average annual base flow and direct runoff demonstrate their highest values during the year of 1970, and their lowest ones during the year of 1990. During the predominantly rainy year of 1970, the average annual flow was 6.94 m^3/s, i.e. twice as much when compared to average multi annual period flow during the analysed period 1961/1996, which was 3.58m^3/s. During the dry year of 1990, the average annual flow was 1.04 m^3/s, which is 3.44 times less compared to the average multi annual period. During the average year of 1985, the average annual flow was 3.71m^3/s, which was in near proximity to the average multi annual flow. Through the analysed time span from 1961 to 1996, variations of average annual values of the base flow index (BFI) were small and they ranged between 0.65 and 0.87, whereby the average multi annual value of the index was 0.75. By analysing the three characteristic years, it is obvious that during the dry year of 1990 the base flow was a dominant component of the total flow, whereby BFI value was 0.72. This is in accordance with the fact that base flow plays a dominant role in the total flow during low-flow periods. High values of the base flow index during the three characteristic years, as well as the high average multi annual value of this coefficient are a consequence of a predominantly karst-composed terrain in the basin resulting in high accumulation of groundwater.

Taking into consideration that runoff characteristics differ for rainy periods and rainless periods, the base flow models for these dissimilar periods differ, too. The simulation model developed in this study consists of two models, one of which is used to express base flow changes during precipitation periods, while the other one is used to express base flow changes following end of a precipitation period. For the purpose of determining the simulation model of base flows, all groundwater concentration curves and all recession curves of a streamflow hydrographs throughout the 1961 - 1996 period were analysed separately.

Analysis of recession curves enables simulation of water flow and water storage of a river basin during low flow and dry periods and droughts. Any hydrograph, as a consequence of a spell of rain, presents a short term event and its recession curve differs from any following recession curve depending on variations of groundwater recharge and the amount of precipitation, various preceding conditions and the season. Based on a certain number of hydrographs defining different outflow regimes and covering periods of different water accumulation modes, hydrographs are combined so as to produce the main recession curve. The median curve, covering many recession curves of the base flow is referred to as the main recession curve.

Seasonal characteristics have particular influence on the figure of decreasing, i.e. recession limb of the streamflow hydrograph. Losses in evapotranspiration from a river basin and a riverbed depend on the season, as well as on depth of groundwater level. Therefore, the main recession curve is determined especially for each season so as it was done in this study. It is impossible to construct the main recession curves in winter season for many streamflows, as due to frequent precipitation (rainfall, snowfall) periods and temperature fluctuations, values of surface run-off and base flow vary. It is, therefore, impossible to separate a sufficient amount of appropriate recession segments of base flow from a streamflow hydrograph. The majority of recession curves are derived in summer season (Gustard et al., 1989) when the flow in a surface stream is considerably reduced in relation to the average and when it is dominated by groundwater flow.

For the purpose of determining base flow changes during precipitation periods various linear and nonlinear (exponential, polynomial and logarithmic) rules connecting base flows in several consequent time intervals were analysed. Determination of rules of base flow changes is very difficult especially for the parts of hydrograph of the highest ordinates, and this is not possible to be defined precisely. It has been stated that the figure of the linear rules connecting the flows in adjacent time intervals (Q_t, Q_{t-1}):

$$Q_t = AQ_{t-1} + B \; . \tag{1}$$

is the best fit for the base flow values during the base flow hydrograph increase, obtained by the graphic method of local minimums. The linear connections of the base flow figures (1) were obtained for each limb of the base flow hydrograph increase through application of the smallest squares method.

The linear reservoir concept is based on analysis of the recession limbs of the streamflow hydrograph and has been used extensively for description of catchment responses during periods without rain (Linsley et al., 1988; Hornberger et al., 1991; Dingman, 1994). The model of linear reservoir is appllied in this study for describing base flow changes following end of a precipitation period. It is assumed that water flow (Q) from a basin, following end of a precipitation period, is in direct proportion with the quantity of water in the reservoir (S). This can be expressed with the following equation:

$$S = k \bullet Q \tag{2}$$

where k stands for the retention constant which represents the retarding time of the system. The depletion of such a linear reservoir can be described by an exponential recession:

$$Q_t = Q_0 \bullet e^{-(t-t_0)/k} \tag{3}$$

where Q_t stands for the outflow at any time t in m^3s^{-1}; Q_o stands for the outflow at time t_0 in m^3s^{-1}, and k for the retention constant with the dimension of time.

The retention constant k is not constant along the recession curve. The value of the retention “constant” is smaller for the upper part of a recession hydrograph and increases continuously with the recession of the discharge. The reason of this change lies in the fact that the recession flow is the superposition of different flow components, such as groundwater discharge and surface runoff. Recession curves of base flow can differ considerably depending on the period of year.

Median recession curves were determined for each season. For this purpose, streamflow recession curves of a minimum of seven recession days were analysed. Base flow values of each recession curve obtained applying the graphical method of local minimum were first transformed into a logarithmic scale and afterwards, applying the method of the smallest squares, the base flow values at the beginning, as well as the retention constants were determined. Median recession curves for each season as well as the main recession curve were determined on the basis of the average base flow values at the beginning of groundwater recession and the average retention constant values.

4. Results and Discussion

Through analysis of all groundwater concentration curves through the period 1961 to 1996, the median groundwater concentration curve was obtained. This median groundwater concentration curve may be expressed by the linear regression model of AR(1) type:

$$Q_t = 1.094 \bullet Q_{t-1} + 0.0075 \tag{4}$$

After extracting and analysing all recession limbs of streamflow hydrographs during the identification period, the median recession curves were obtained. These median recession curves for each season possess almost equal retention constant values of the basin. The parameters of recession curves for each season are set in Table 1. The recession curve parameters are considered to be the reciprocal values of the retention constants of the basin (marked as coefficient α) for each season, the base flow values at the beginning (Q_0), the number of the recession curves used for the analysis (N) and the total number of days of recession (T_r).

Table 1. Recession curve parameters for certain ceasons (Kolubara river, water level monitoring station Valjevo, 1961-1996)

season	α=1/k	Q_0	N	T_r
spring	0.04082	2.717	78	1189
summer	0.04231	1.0053	72	1086
autumn	0.0400	1.433	51	647
winter	0.0415	2.985	50	732

The main recession curve can be expressed with the following equation:

$$Q_t = 1.813 \bullet e^{(-0.0412 \bullet (t-t_0))} \tag{5}$$

The model describing base flow changes in the course of time was obtained by combining the equation (4) describing the base flow increasing limbs and the equation (5) describing the base flow recession. The base flows follow the equation of the limb of the base flow increase until the moment when runoff ceases. After this moment the equation of the main recession curve applies. Applying the simulation model developed in this study, simulations of base flow hydrographs were performed and compared to the results obtained through application of the local minimum method for three characteristic years (1970, 1985, and 1990). Fig. 8 sets out a comparative picture of the changes of the total flow and the base flow obtained through application of the graphic local minimum method and the developed model for the three characteristic years - 1970, 1985, and 1990.

Analysis of Fig. 8 leads to the conclusion that discrepancies between the base flow values obtained through application of the graphic local minimum method and the developed model can be neglected. Table 2 sets out computed total annual volumes of the base flow obtained through application of the local minimum method and the developed model, as well as discrepancies occurring between these values for the three characteristic years.

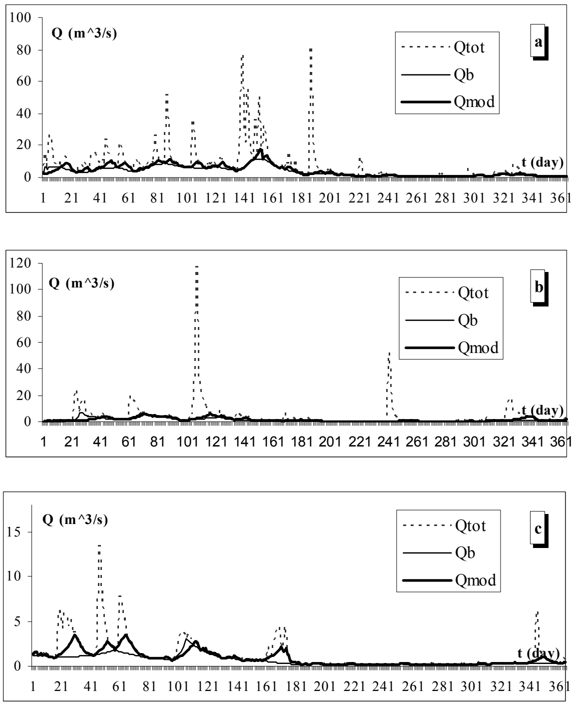

Fig. 8. A comparative picture of total streamflows (Q_{tot}) and a series of base flows obtained through application of the local minimum graphic method (Q_b) and the formed model (Q_{mod}) for three characteristic years 1970 (a), 1985 (b) i 1990 (c) (Kolubara River, "Valjevo" wlms)

Table 2. Annual volumes of the base flow obtained by application of the local minimum method and the developed model and discrepancies occuring between these values

The approach of calculating the base flow values	1970	1985	1990
local minimum method	111,314	41,917	19,721
model	132,926	48,033	26,766
rel. error	19,415	14,590	35,700

The discrepancies between values of the base flows obtained through application of the local minimum method and the developed model for all three characteristic years are within the limits of tolerance. The relative error of estimation of the total annual base flow volume is about 15% in the average year, while it is about 20% in the rainy year. From the position of general hydrological accuracy these values of errors are accepted. A significantly bigger error of estimation of the total annual base flow volume of about 35% is obtained only in the dry year, but simulation of base flows in low-flow periods (summer months and the first autumn month) is completely satisfactory. These discrepancies in the year of 1990 would be much lesser if the graphic method of fixed intervals or the graphic method of sliding intervals were applied as the representative graphic method with which the modeled values of base flows could be compared.

The main reason causing significant discrepancies between the base flow values obtained through application of the simulation model developed in this study and through application of the local minimum method lies in the large and frequent amount of precipitation at the analysed basin, which significantly influences base flow characteristics and can induce great fluctuations of changes of base flow values. In cases like this, it is much more difficult to define correlations fit to express base flow changes in the course of time.

5. Conclusion

The simulation model of base flows of the Kolubara River catchment up to the ”Valjevo” w.l.m.s. is formed in this study starting from the supposition that only measured data of streamflow discharge at the outlet catchment point were known.

Based on the described analysis of separation of total flow into base flow and direct flow as well as the existing methods and models for the simulation of the recession limb of the streamflow hydrograph, it can be concluded that the base flows on annual level at the analysed basin of the Kolubara River are on the same level as the direct flow, meaning that the analysis of the base flow deserves the same attention as the analyses of flooding tides. In the hydrological practice to this date (oriented towards the protection from floods) it was not the case. As in low - flow periods the majority of flow is composed of the base flow, the development of adequate models of this component of a streamflow hydrograph becomes of the prime significance during the phase when the focus of hydrological analysis is directed towards the necessities of working out the models of managing procedures for the consumption and protection of water. In order to develop adequate base flow hydrograph models, it is necessary to examine the complete dynamics of the process of origination of the base flow which understands changes of periodical phases of recharge of the ground reservoir and a continuous discharge being the function of the current level of water in the ground reservoir. In order to develop an adequate base flow model it is necessary (during the phase of calibration) to possess information on continuous series of the base flow. As it is impossible to measure the base flow separately, it is necessary to possess an adequate model for the separation of the base flow component from the total flow hydrograph registered on a hydrological profile.

Preliminary analyses of the base flow based on the recorded total flow have proved that it is possible to develop an adequate model for both the phases of increase and the phases of decrease of the base flow hydrograph. Thus, it is possible to closely monitor changes of groundwater flow. Taking into account that the analysed basin is characterised by a large quantity of precipitation and significant fluctuations of the base flow, the model appears to be more complex in comparison with models describing base flow changes in areas with moderate precipitation. In order to provide efficient application of this model in practice for estimation of water storage reserves in the considered basin, it is required to reformulate the model for simulation of the base flow so as to function in accordance with the actual situation in the basin. Based on these results, it is further necessary to continuously keep separating the base flow in order to apply the model of increase or decrease of the base flow hydrograph.

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ANALIZA REŽIMA PODZEMNIH VODA NA OSNOVU HIDROGRAMA OTICAJA

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U toku suša proticaj na vodotocima je smanjen, i dominira bazni proticaj. Bazni oticaji su karakteristični za malovodne periode i pružaju informacije o raspoloživim vodnim resursima u slivu u toku suše, posebno o osobinama akvifera i retenzionim karakteristikama sliva. Ovaj rad se bavi mogućnošću analize i simulacije komponente baznog oticaja, kao i determinisanjem zakonitosti u njegovim promenama, do kojih se može doći analizom registrovanih hidrograma ukupnog oticaja u dužem vremenskom periodu. Osnova za modeliranje promena baznih oticaja u toku vremena bile su *vrednosti baznih oticaja dobijene iz hidrograma ukupnih oticaja primenom grafičke metode lokalnih minimuma. Primenom formiranog modela urađene su simulacije hidrograma baznog oticaja tokom tri karakteristicne godine (kišne -1970., prosečne – 1985. i sušne – 1990) i pokazano je da su odstupanja u odnosu na vrednosti baznih proticaja dobijenih primenom metode lokalnih minimuma u granicama dozvoljenih.*

Ključne reči: *bazni proticaji, modeliranje, metoda lokalnih minimuma, kriva koncentracije, recesiona kriva.*