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Mountain river dominant formative discharge evaluation (through example of the Upper Tisa basin)

Abstract: Based on the comparative analysis of the two most commonly used techniques for the definition of dominant formative discharge for the Upper Tisa river, it has been established that technique by M.I. Makkaveyev can be used provided the availability of fixed-term discharge measurements or by means of the transition regional factors. Transition figure between the average daily rate and fixed-term discharge is recommended, which provides an opportunity to obtain reliable values of the dominant formative discharge in the full range of flow intensity change with low error (less than 10%).

Keywords: mountain river, dominant formative discharge, hydrodynamic system "flow-course -floodplain" comparative analysis, transition factors

1. Introduction

Existing approaches to the river bed evolution study were formed mainly on the results of observations of the lowland river channel flows. Such situation was caused by the historical course of the water industry development in the direction of water resources use and floodplain area development. Later, as a result of large-scale urbanization of the mountain river flooded areas the more thematic studies of the course of their bed evolution were held. The mountain rivers have much higher degree of manifestation discreteness and therefore, accordingly. a wider range of generation and dissipation of the flow energy.

Not for the first time N.I. Makkaveev (1973) pointed out the fundamental difference of the bed formation activity of water flows in the mountains and on the plains. In the second half of the twentieth century, a number of significant generalizations regarding the patterns of mountain river bed evolution were made by S.T. Altunin (1962), K.V. Grishanin (1974), V.F. Talmaza and A.M. Kroshkin (1968), V.V. Romashyn (1967), Z.D. Kapaliani and V.S. Tskhadadze (1972), R.S. Chalov (1997) and others.

The issues on bed formation processes of the rivers in Carpathian region were studied by I.L. Rozovskyi *et al.* (1976), M.N. Bukhin and V.V. Onischuk (1978), A.N. Kaftan (1983), Ya.I. Kaganov (1991), V.V. Onischuk (2012), L. Macura (1966), L. Zaharia (1997), K. Krzemien (2000) and E. Gorczyca and K. Krzemień (2006).

The abovementioned scientific achievements largely laid the theoretical foundations for the hydromorphological analysis of the mountain river bed evolution. However, the vast majority of the researchers tried to implement their developments as separate practical recommendations (Guidelines for the calculation..., 1977; 1989). However, the aspect of the environmental assessment of mountain river bed evolution and the consequences of the flow ravages affected by natural and anthropogenic factors as active restriction of the flow action are hardly manifested in the listed papers.

For the last decade, much more attention has been paid to the study of the environmental aspects in mountain bed formation (Chalov, 2008). In addition, the current publications have a systematic analysis of the river bed evolution factors in the context of flood protection of the urban flood-plain areas.

High floods in the mountain rivers which cause significant social and economic losses urge the need for fundamental research of the impact of natural and anthropogenic factors on the intensity of the bed formation process development. It is known that the hydromorphodynamic resistance of the course-flood-plain complex is determined by the nature of the dominant formative discharge course and conveying sediments and influence of the dynamic-kinematic effect on the rate of the course relief and floodplain formation.

2. Analytical review of current approaches to determining the dominant formative discharge

Currently, the determination of the dominant formative discharge and conveying sediments at levels proportional to the marks of channel edges (bankfull stage) usually uses formula of Schezi-Manning in its classic form. But practice of the mountain river hydromorphological state evaluation (Talmaza, Kroshkin, 1968; Makkaveev, 1973; Obodovskyi *et al.*, 1999; Onischuk, 2014) demonstrates that in case of significant anthropogenic effect, particularly against the background of irreversible deformation of the channel, in the course of bed calculations one shall approach from the standpoint of system analysis in the evaluation of hydraulic resistance as a reaction to the actions of various bank protection, protective and regulatory structures, quarries, etc.

Definition of the dominant formative discharge is one of the conditions that determine the features of the river channel regime and bed deformation development at different structural levels of "flow-channel-floodplain" system self-organization – from the channel as a whole (macroforms) to mesoforms of the channel relief. Therefore, they are formalized in terms of the flow capacity and act as one of the dominant factors of the channel process theory.

River stream and channel wherein it flows are in constant interaction. Despite the fact that the flow continuously shapes its bed, the intensity of this process is primarily closely linked to its water content and frequency of discharge recurrence, which determines its conveying capacity. And therefore, in order to characterize the interaction of the flow and deformed channel the concept of the dominant formative discharge is used.

Later there were a considerable number of interpretations of such term and, therefore, approaches to its definition. Certainly, it is proposed to define this characteristic as an appropriate water discharge passing at the channel edges (bankfull discharge – bankfull stage), proportional to the average value of annual maximums or provisions (50, 10, 5, 1%), etc. Analysis of these approaches is presented in many papers of national and foreign authors, including those listed below.

For the channel calculation and evaluation of the emergency channel situations both scientifically justified definition of dominant formative discharge of any watercourse and corresponding ranking of the floods and land flood in the basins, i.e. their classification are important. Flood passing within the edges may be considered as bed-building discharge since in such case the system is in dynamic equilibrium. According to R.S. Chalov (2008) the dominant formative discharge objectively reflects the intensity of the erosion-accumulative process course in the watershed located above.

At the same, the dominant formative discharge is an integral characteristic of "flow-channel" hydrodynamic system (HDS $_{f\text{-}ch}$) subject to its dynamic equilibrium. It stipulates the most stable operation of this open system at the highest level of structural self-organization (Obodovskyi et. al., 2002).

Each section of the channel has its own specific structural level and water discharge in terms of which the most intense deformations of its depression and shores occur. The impact of any discharge on the channel relief formation is determined not only by the value of discharge and slope, but also the duration of a certain level of standing water (Makkaveev, 1973).

The methods of determination and the interpretation of the concept of dominant formative discharge still have a lot of discussion points that require further studies. In hydraulic engineering practice, the water discharge corresponding to the level of its outflow to floodplain was often taken as the main and most important for the river bed relief formation. Likewise, these discharges are calculated by foreign researchers, for example, L.B. Leopold and M.G. Wolman (1957), D. Rosgen (1996). However, according to N.S. Lelyavskyi (1904), the flood destroys the bed forms, which are created by previous low water level, and the next low water level resumes them. F. Schaffernak (1950) proposed to calculate "dominant formative discharge" as the discharge which corresponds to maximum pulling force of the flow stipulated as the result of its depth on the slope of the free surface. According to his calculations the maximum value of such force is accounted for discharge with coverage of 7.5 days per year, i.e. close to the maximum.

The proposals of N.I. Makkaveev (1955), R.S. Chalov (Makkaveev, Chalov, 1986) are the most developed and logically reasonable, which are based on the proportionality of bed deformation and sediment discharge (or some set of characteristics that reflect the flow of sediments). They enable to determine the dominant formative discharge at typical levels of changes in the specific capacity of the watercourse within the structural development of "flow – channel – floodplain" system. According to these methodological approaches the calculation of the dominant formative discharge is carried out using maximum values on the function curve

$$Q_f = f\,(\sigma\, Q_0^n\, PI), \tag{1}$$

where σ – coefficient which takes into account the width of the flood flow (σ = 1 prior to water outflow to the floodplain; σ = 0,9 if the floodplain width is less than two widths of the channel; σ = 0,5 if the width of submerged floodplain exceeds ten widths of the channel); Q_0 – average water discharge for each interval into which the entire range of discharge in calculated cross section is divided (in such case the daily water discharge is taken into account), m³/s; n – index of degree depending on the coarseness of the channel alluvium (n = 2,5 for rivers with gravel-pebbly bottom; n = 3 for boulder-pebble bottom); P – probability of exceeding the daily discharge for their corresponding interval, %; I - the average slope of the free watercourse surface for the corresponding discharge interval. Certain amendments to this methodology were made by O.G. Obodovskyi (1998).

In addition to this approach, the informative characteristic of the "flow-channel" hydrodynamic system ($HDS_{f\text{-}ch}$) is dominant formative discharge and therefore the discharge of the conveying alleviation (Onischuk, 2002). These discharges usually stipulate the upper limit regarding the sustainable functioning of this system at the highest level of the structural changes (self-organization of $HDS_{f\text{-}ch}$ with demonstration of the course meandering in the absence of the strong restriction affect). Under the methodological approaches by V.V. Onischuk (2012), it is recommended to conceive the term of dominant formative discharge as the watercourse discharge (Q_{bf}), which is equivalent to the effect of integrated discharge for a long period of observations aimed at formation of the appropriate type of bed. In terms of such discharge, $HDS_{f\text{-}ch}$ is in dynamic equilibrium. Calculation of the dominant formative discharge is performed by the following equation (method by Ukrainian Hydrotechnics and Reclamation Research Institute – UkrNDIGiM) – Kyiv National University, 2002):

$$\frac{\omega_{bf}\left(h_{bf}^{0,666}\right)}{Q_{bf}}\sqrt{\frac{\Delta Z \pm \Delta\left(V_{bf}^2/2g\right)}{\Delta e}} - \frac{\varphi . R_{bf}^{0,166}}{(2g)^{0,5}\,(4\lg h_{bf}/D_{wa} + 4{,}25)} = 0, \tag{2}$$

where $\omega_{р\phi}$ – cross-sectional area of the watercourse subject to design discharge Q_{bf} ($Q_{bf} = h_{bf} \cdot B_{bf} \cdot V_{a.s}$, where B_{bf} – stream width on free surface at Q_{bf}, typically it is a width in the bed edges; h_{bf} – the average depth of the stream at Q_{bf}; V_{bf} – the average stream rate at Q_{bf} that meets the dynamic equilibrium $HDS_{f\text{-}ch}$; $\frac{\Delta Z}{\Delta e}$ –

hydraulic slope of the stream flow at quasi-uniform hydraulic regime at inspected site with the length of Δe in case of high floods with discharge of Q_{bf} ($\frac{\Delta Z}{\Delta e} = I \approx i$, where i - slope of the bed bottom at Q_{bf}); $\frac{\Delta(V_0^2/2g)}{\Delta e}$ – specific kinetic energy gradient at the inspected site at discharge Q_{bf}; φ – hydraulic resistance coefficient of channel forms, which ranges from 1 to 1.3, depending on the type of bed, $R_{bf} = (h_{bf} \cdot B) / \chi_{bf}$ – the most favorable hydraulic radius of a watercourse in terms of free manifestation of bed formation processes in case of high flood with discharge of Q_{bf}; g- acceleration of the gravity force; $D_{сер.зв}$ – average diameter of sediment particles for the surface layer of the bed bottom (self-spreading layer), which is equal to the weighted average absolute altitude of the bed bottom edge roughness – $D_{wa} \approx \Delta_{wa}$.

This equation is solved by the selection of the values for initial hydraulic and bed parameters with definition of $V_{bf} \approx V_{a.s}$ and use of design data of the hydromorphological relationship for correction $Q = f(h)$, $Q = f(V)$, $Q = f(\omega)$, $V = f(h)$.

It should be noted that the method of UkrNDIGiM – KNU enables to define the dominant formative discharge for both bankfull stage, and for dynamic equilibrium state $HDS_{f\text{-}ch}$. At the same time it is required to have reliable data of initial information concerning the hydromorphological parameters, including determining the appropriate roughness of the bed bottom. The roughness of the mountain river bed bottom which have a self-spreading layer shall be determined by the coarseness of sediments on the surface against the background of sediment mode in case of the dynamic equilibrium $HDS_{f\text{-}ch}$.

In order to control the results of calculations obtained by formulas (1, 2) one can also use the Shezi-Manning equation in the following modification made by Onischuk V.V. (2014):

$$Q_{bf} = (2g)^{0,5} \lambda_з^{-0,5} h_{bf}^{1,5} B_{bf} I^{0,5}, \tag{3}$$

where $\lambda_з$ – the value of the total hydraulic resistance of the channel with the appropriate manifestation of bed formation process which must take into account primarily the impact of granular roughness of the bed bottom, resistance of the channel forms and response of the shores.

As a result, the comparative analysis of dominant formative discharge calculation by the formulas (2, 3), their overall slight differences is defined, indicating the morphological affinity of the methodological approaches (Onischuk, 2014). A similar comparison of the results of dominant formative discharge calculation by formulas (1 and 2) revealed significant differences (Obodovskyi et. al., 2012). Therefore, one of the fundamental tasks of this study is to establish certain relationship and interdependencies between these approaches in determining the mountain river dominant formative discharge.

3. Subject of study

The most flood dangerous basin of the Upper Tisa was taken for mentioned studies and included as a main-stream station on the Tisa river near the Vylok village (Figure 1), which is located in foothill area.

3.1. Methodical provisions for determining the mountain river dominant formative discharge

Monitoring stationary observations on the mountain rivers shall be in line with the course of bed formation natural processes. This means that one must have data of both average daily and fixed-term measurements of the water discharge and hydraulic slopes on river sections on at least the three rifts. These data enable to make more accurate course calculations, in particular, to determine the characteristics of “flow – course- floodplain” system. Until recently, it was impossible to use N.I. Makkaveev method (1955) for determining the mountain river dominant formative discharge to the full extent without such data. Only now, based on a comparative analysis of the series of observations of average daily and fixed-term measurements of high flood water discharge, especially given the bed formation cyclical development patterns, we managed to receive the transition coefficients for the respective river basins in the Carpathian region. The hydrological monitoring network for the rivers of the Upper Tisa basin was used for this purpose.

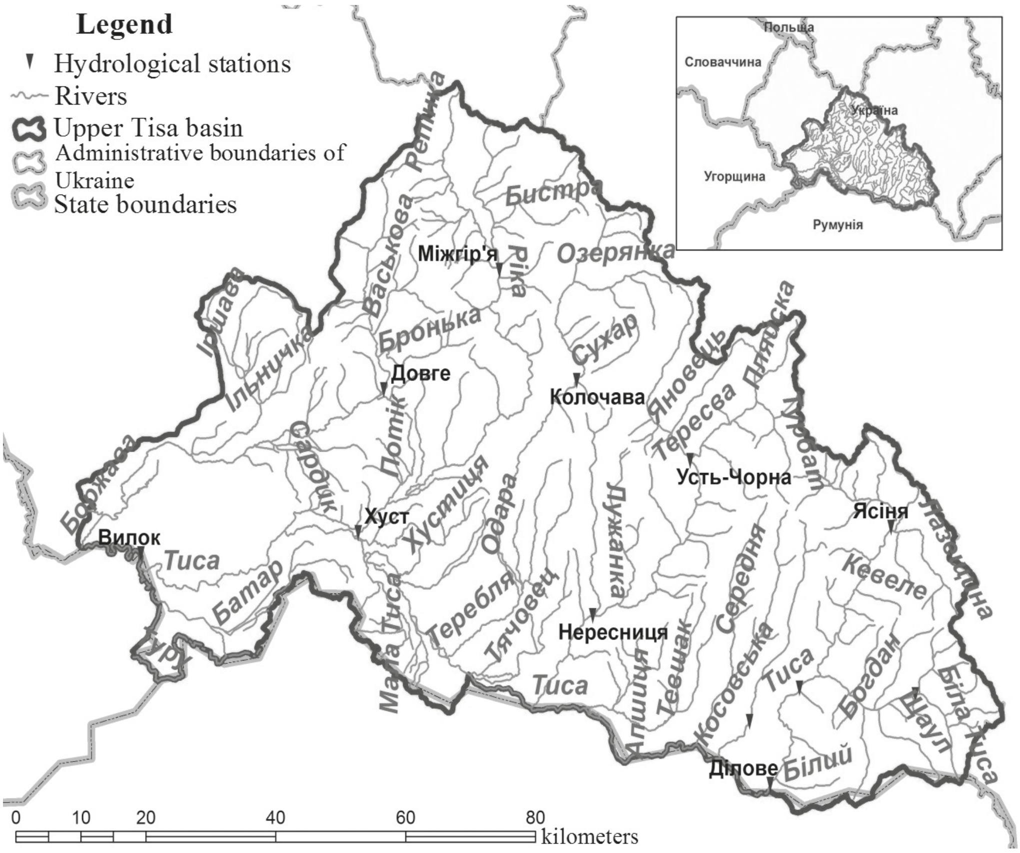


Figure 1. Schematic map of the Upper Tisa basin within Ukraine

3.2. Statement of the basic material

Based on the positions of open dynamic system regular cyclical development, including the course processes in the mountain rivers of the Carpathian region, given the current global climate change it is relevant to use the methodology for determining the dominant formative discharge according to N.I. Makkaveev (1955). In this context, comparison of the dominant formative discharge under this method is important for the various phases of water content (Table 1).

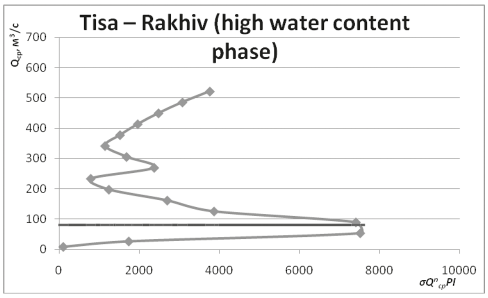
The value Q_{ui} observed within the channel edges is hardly changed for low and high water content phases, indicating the relative constancy of bed formation processes in the course of course filling. As for the upper intervals Q_{ui}, there is a significant difference in the water discharge for low and high water content phases, which reaches 30% or more. It should also be noted that in high water content phase the water discharge is less, and higher in the course of high water content phase (Table 1). Therefore, such discharge should be calculated taking into account high water content phases in fluctuations of the mountain river water content.

Table 1. Calculation of the dominant formative discharge under the method by N.I. Makkaveev for low and high water content phases in some hydrological stations of Upper Tisa rivers

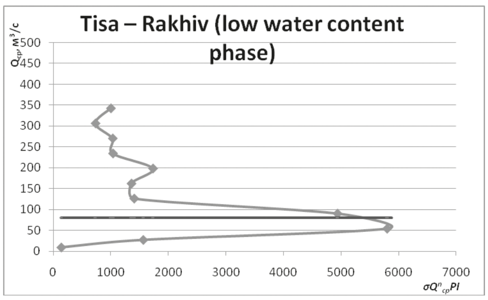
Hydrological station	Low water content phase				High water content phase			
	Upper interval Q_{ui}, $m^3 \cdot sec^{-1}$	P%	Within channel edges Q_{ui}, $m^3 \cdot sec^{-1}$	P%	Upper interval Q_{ui}, $m^3 \cdot sec^{-1}$	P%	Within channel edges Q_{ui}, $m^3 \cdot sec^{-1}$	P%
Chorna Tisa – Yasinya	30,4	0,21	18,3	1,6	70,0	0,06	14,2	8,4
Bila Tisa – Lugy	54,6	0,02	13,0	9,3	65,0	0,02	18,2	6,3
Tisa-Rakhiv	198	0,27	54,0	18,8	270	0,27	54,0	25,8
Kosivska- Kosivska Polyana	44,5	0,07	10,3	17,7	58,2	0,21	10,3	19,9
Tisa-Vylok	-	-	302	31,6	1910	0,55	302	33,8

For visual reference, the figure 2 demonstrates the diagrams of specific flow capacity for low and high water content phases for Tisa – Rakhiv hydrological station.

Using the materials of long-term observations, including for hydrological stations on Upper Tisa rivers (within Ukraine), according to the morphological parameters the dominant formative discharges were calculated by the formula (2) UkrNDIGiM – KNU, which are listed in the table 2. Analysis of Qbf calculations demonstrated that their quantitative indicators are higher than Qui, and occur in case of submerged floodplain. At the same time, the flow capacity is close to the maximum values (Obodovskyi *et al.*, 2012).



a)



b)

Figure 2. Diagrams of the functional relationship for determination of the dominant formative discharge for Tisa-Rakhiv hydrological post: a) – high water content phase; b) low water content phase; red line – water outflow to the floodplain.

With the purpose of more complete comparative analysis, table 3 demonstrates the estimated values of dominant formative discharge calculated under the method of UkrNDIGiM – KNU and M.I. Makkaveyev for eleven operating hydrological stations on Upper Tisa rivers (within Ukraine) and the ration of such discharges is defined.

As shown in the table 3, the results of dominant formative discharge calculation significantly differ. This is caused by the fact that the calculation by method of UkrNDIGiM – KNU was conducted using the design parameters which met the hydromorphological indices in the course of fixed-term water discharge passage.

Therefore, under such technique the values of the dominant formative discharge Qbf are significantly higher even than the upper intervals Qui calculated under the method by M.I. Makkaveyev. As for the latter technique (Table 3), the values of the dominant formative discharge are slightly lower since the average daily water consumption is used for their calculation.

Data on Q_{ui} and Q_{bf} for larger number of rivers in the Upper Tisa basin, including the Borzhava river, are added to five operating hydrological stations (Table 1) in order to establish a more reliable relationship between

Table 2. The values of the main morphometric characteristics and dominant formative discharge by the methods of Ukrainian Hydrotechnics and Reclamation Research Institute (UkrNDIGiM) – KNU according to the data of the hydrological stations on Upper Tisa basin rivers (after Onyschuk, 2012)

No.	Hydrological station	B_{bw}, m	h_{av}, m	I_o	$D_{wa.}$, mm	$d_{wa.}$, mm	$S_{0} = (d25/d75)^{0,5}$	Q_{bf}, $m^3 \cdot sec^{-1}$
1	Black Tisa – Yasinya urban settlement	28	2,0	0,006	144	70	0,59	140
2	Bila Tisa – Lugy village	18	2,0	0,007	188	80	0,56	140
3	Tisa – Rakhiv city	21	2,6	0,0085	230	115	0,60	430
4	Tisa – Dilove urban settlement	53	2,5	0,007	190	110	0,55	589
5	Kosivska – Kosivska Polyana village	20	1,3	0,008	250	100	0,59	75
6	Teresva – Ust Chorna urban settlement	48	2,0	0,0126	220	165	0,35	368
7	Teresva – Neresnytsia urban settlement	86	2,3	0,005	200	100	0,40	600
8	Tereblya – Kolochava village	46	1,7	0,008	370	185	0,33	280
9	Rika –Mizhgirya urban settlement	50	2,2	0,011	200	95	0,35	403
10	Rika – Hust city	100	2,2	0,005	90	50	0,40	670
11	Borzhava – Dovge village	50	2,2	0,013	150	60	0,28	290

Table 3. Design values of the dominant formative discharge for Upper Tisa rivers (within Ukraine)

No.	Hydrological station	Dominant formative discharge, m^3/s					Q_{bf}/Q_{ui}, %
		Method by (UkrNDIGiM) – KNU, Q_{bf}	Method by Makkaveyev M.I. (high water phase)				
			Upper interval Q_{ui}	P%	Within course Q_{ui}	P%	
1	Chorna Tisa – Yasinya	140	70,0	0,06	14,2	8,4	200
2	Bila Tisa – Lugy	140	65,0	0,02	18,2	6,3	215
3	Tisa – Rakhiv	430	270	0,27	54,0	25,8	159
4	Tisa – Dilove	589	406	0,1	46,0	30,3	206
5	Kosivska – Kosivska Polyana	75	58,2	0,21	10,3	19,9	129
6	Teresva– Ust Chorna urban settlement	368	200	0,14	68	3,52	184
7	Teresva – Neresnytsia	600	389	0,06	122	3,78	155
8	Tereblya – Kolochava	280	149	0,06	95	0,58	188
9	Rika –Mizhgirya urban settlement	403	276	0,1	100	1,32	146
10	Rika – Hust	670	510	0,12	286	0,45	132
11	Borzhava – Dovge	290	163	0,12	85,0	0,79	178

Average value Q_{bf}/Q_{ui}, 178%

specified water discharge. In total, the calculations were made for 11 hydrological stations (Figure 3).

Figure 3 depicts the close relationship between the abovementioned water discharge which is set by the approximation ratio of 0.92. This suggests the possibility of using the appropriate coefficients for transition from dominant formative discharge defined by Makkaveev N.I. technique to the relevant discharge

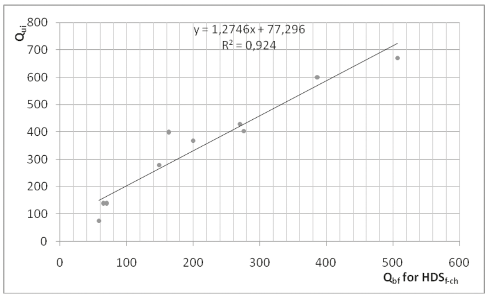


Figure 3. The diagram of relationship between the Q_{ui} under M.I. Makkaveyev technique and Q_{bf} calculated by the method of UkrNDIGiM – KNU (Q_{bf} for $HDS_{f\text{-}ch}$) for some rivers of Upper Tisa

defied by the method of UkrNDIGiM – KNU for the rivers of this basin (Table 3). In this context, the averaged evaluation of the Q_{bf} /Q_{ui} ratio demonstrated the value of 1.78 (or 178%) (Table 3). And given quite close relationship between such discharges (Figure 3) one can attest the authenticity of transition from one technique to another.

It should also be noted that the Tisa river -in the cross section of the hydrological station Vylok already has quite a large catchment area. Here it has some features typical for already plain river, wherein the processes of flood and high water travel are quite "stretched". This stipulates slight difference of the maximum fixed-term and average daily discharge (Q_{bf} / Q_{ui} = 10%).

As for the ratio of fixed-term and average daily discharge for Upper Tisa basin rivers, depending on the altitude of their location and catchment area there is some differentiation in its quantitative indicators. It should be noted that all observational stations were selected in

Table 4. Comparative evaluation of the fixed-term and average daily water discharge for Upper Tisa rivers in percents (%)

No.	Hydrological station	Comparative evaluation of the fixed-term and average daily water discharge in % for the whole period of the observations		
		Q_{aver}	Q_{max}	Q_{min}
1	Chorna Tisa – Yasinya	182	329	106
2	Chorna Tisa – Bilyn	175	311	109
3	Bila Tisa – Lugy	175	619	100
4	Bila Tisa – Roztoky	163	403	105
5	Tisa-Rakhiv	160	337	103
6	Tisa-Dilove	161	316	107
7	Kosivska-Kosivska Polyana	169	466	101
8	Shopurka-Kobyletska Polyana	160	263	103
9	Borzhava-Dovge	170	275	123
10	Teresva-Ust Chorna	153	256	101
11	Rika – Verkhniy Bystryi	170	358	111
12	Rika –Mizhgirya	178	278	110
13	Golyatynka – Maydan	242	521	126
14	Pylypets-Pylypets	277	525	141
15	Studetyi – Nyzhniy Studenyi	214	463	106
16	Mokranka-Ruska Mokra	141	198	105
17	Tereblya – Kolochava	151	245	102
	Average values	178	362	109

Furthermore, it appears that the tightness of relationship between mentioned discharges are quite significant as shown in Figure 4 (a, b, c). Therefore the set transition ratios from the average daily to fixed-term discharge are statistically justified.

order to assess such ratio. This made it possible to detail the indicated evaluation. For mid-mountain rivers it was found that for transition of average daily to fixed-term discharge one can use the ratio of 1.8 (or 180%), and for lowland rivers such transition provides for the ratio of 1.6 (or 160%) (Table 4). Alternatively, for small streams that flow in the area of medium-altitude mountains, such figure can reach 2.0 (or 200%) and higher.

However, if one uses percentages of the average daily and fixed-term water discharge and transfer the average daily water discharge used in the method by M.I. Makkaveyev into fixed-term, the difference between the indicators of two methods (Table 3) does not exceed 10%. Relevant factors for such discharge were introduced for transition from the average daily to fixed-term discharge.

It seems obvious from the tables 3 and 4 that both the ratio between the fixed-term and average daily water discharge and the ratio of Q_{bf}/Q_{ui} value for eleven hydrological stations on upper part of the Tisa basin on average reach 178% or transition ratio coefficient of 1.78. It is recommended to use such coefficient for adjustment of the more universal, in our view, technique by N.I. Makkaveev, for its reliable regional application in order to determine the dominant formative discharge in the mountain rivers.

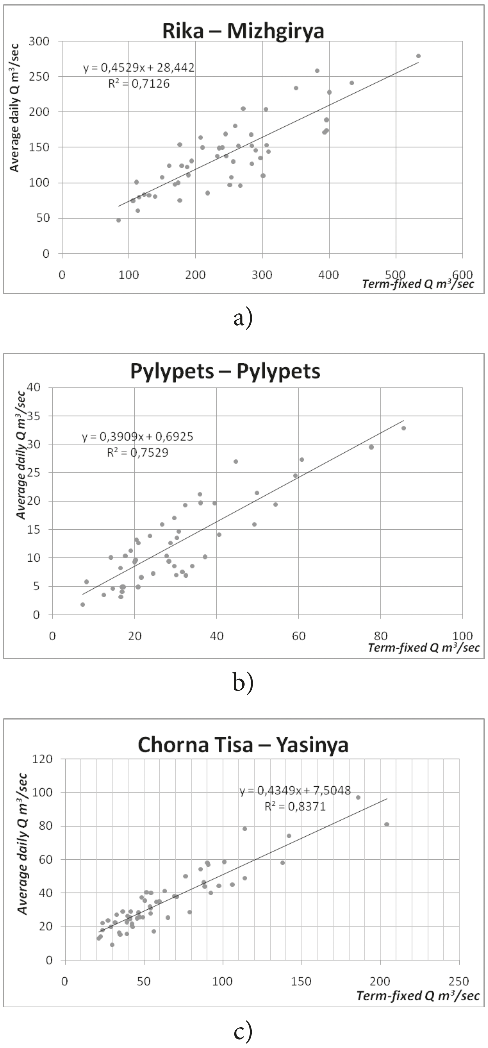


Figure 4. The diagrams of relationship between the maximum average daily and fixed-term discharges: a) – for Rika – Mizhgirya river; b) – for Pylypets – Pylypets river; c) – for Chorna Tisa – Yasinya river

4. Conclusions

In view of the above material the following generalization can be made. Technique by N.I. Makkaveev for definition of the specific structural levels of bed formation process self-organization for both lowland and mountain rivers can be used in the future in a wider format. To complete its use for the mountain rivers it is especially recommended to apply the value of the regional transition coefficient which determines the difference between the average daily and fixed-term discharge of the water runoff. The average level of the bed formation hierarchy (average extreme point on the course flow capacity curve) under the method by M.I. Makkaveyev with due regard to the transition coefficient accurately characterizes the state of the dynamic equilibrium of $HDS_{f\text{-}ch}$ determined by the method of UkrNDIGiM – KNU.

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