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Current Tendencies of Change in the Streamflow of the Tributaries of the Middle Reach of the Dniester

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Abstract—We examine the theoretical and practical aspects of the current tendencies of change in the streamflow of the tributaries of the middle reach of the Dniester in conditions of an ever increasing deficit of water resources. The refined computed characteristics of the annual mean, minimum and maximum flow of the tributaries furnish insights into the current changes in hydraulicity of the rivers in the region under investigation.

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FORMULATION OF THE PROBLEM

Calculations of different characteristics of the streamflow (mean annual, maximum and minimum) are of significant theoretical and practical importance. It is known that the accuracy of determining the computed characteristics depends on the duration of the observing period. As regards the study territory of the Middle Dniester, their most thorough analysis as made by a unified technique is reported in [1] (for the time interval before 1962), and for separate tributaries in [2] (before 1980) has long not met the users' demands. A natural lengthening of the observational series required revision of SNiPa–83, and this was done in the Russian Federation in 2003 but never done hitherto in Ukraine, although such a task was set at the last Hydrological Congress of Ukraine held in Chernivtsi in 2011.

The objective of this paper is to refine the computed characteristics of the mean annual, maximum and minimum streamflow of the tributaries of the Middle Dniester as of 2008. We investigated the tributaries (from the Zolotaia Lipa river to the Derlo river) and the right tributaries (from the Tlumach river to the Sokirianki river) in a section of the Dniester more than 400 km long, within the boundaries of Ivano-Frankivsk, Ternopil, Chernivtsi, Khmel'nytskyi and Vinnytsia oblasts, approximately as far as the dam site of the Dniester Pumped Storage Power Station.

The current importance of this research is dictated by the increasingly stringent demands of modern society for the reliability of qualitative and quantitative characteristics of water resources which can only be refined on the basis of analyzing the natural (cyclic) and anthropogenic factors influencing the formation of river flow characteristics.

Many scientists were engaged on the study into the mean annual, maximum and minimum flow of the Dniester and its tributaries. Here, we confine our attention to the research efforts undertaken between the beginning of the 1980s and the present. More specifically, the mean annual flow of the rivers within the basin was investigated, with a different degree of detail, by Ya.A. Fomenko [2], V.I. Vishnevs'kii [3], M.V. Tsependa [4, 5], A.I. Shereshevskii and P.F. Vishnevskii [6], and O.V. Chunar'ov and I.M. Romas' [7]. Maximum flow was studied by P.M. Liutik [8], Ye.D. Gopchenko [9, 10], B.V. Kindiuk [11], M.M. Susidko and O.I. Luk'yanets[12], L.O. Gorbachova [13], and V.G. Yavkin and A.A. Mel'nik [14, 15]. Minimum flow within the basin is the least studied. Worthy of mention are the publications of K.A. Lysenko [16–18] as well as of M.V. Tsypenda [19, 20].

RESULTS AND DISCUSSION

It is most advantageous to carry out an analysis of the spatial distribution of the river flow for different phases of hydraulicity by using relevant maps. To construct them used observational data from 31 flow stations, including 21 main, currently operating stations, 4 stations that were closed at different times, and 6 stations located on neighboring territories. Maximum flow was determined from observational data at 26 stations, because the other 5 stations do not meet the adopted requirements.

The accuracy of determining the mean value of the series for the flow, according to [21, 22], is estimated from two indicators: the relative standard error δQ_0, the value of which for the mean flow must be within ± 5% for the mean flow, and within ± 10% for the maximum and minimum flow, as well as the error of the variation coefficient δC_V which, for this region, must not exceed 10–15%. Table 1 presents the values of these errors as

Table 1. Main hydrographic characteristics of moduli of mean annual flow in computed hydrometric sections

Hydro-metric section No. on map	River – station	Drainage area (F), km^2	Absolute mark of minimum level in hydrometric section, m	Mean annual flow			Minimum mean monthly flow of 95% availability for warm period		
				modulus of flow M$_0$, L/(s/km^2)	δQ_0 act., %	δC_V act., %	modulus of minimum flow стока M$_{95}$%, L/(s/km^2)	δQ_0^E act., %	δC_V^E act., %
Hydrometric sections within the study region									
1	Zolotaia Lipa – Berezhany	690	264	5.96	3.7	9.3	1.74	4.8	9.5
2	Zolotaia Lipa – Zadarov	1390	209	6.24	3.8	10.0	2.81	3.9	10.1
3	Koropets – Podgaitsy	227	317	4.58	4.7	9.5	0.93	6.1	9.8
4	Koropets – Koropets	476	202	5.42	4.2	9.7	2.02	4.2	9.5
5	Stripa – Kaplintsy	411	326	4.21	4.7	9.5	0.95	5.5	9.7
6	Stripa – Buchach	1270	268	5.46	4.1	10.0	2.35	4.1	10.0
7	Seret – Bol’shaia Berezovitsa	939	295	5.85	3.4	10.6	2.00	4.1	10.7
8	Seret – Chertkov	3170	209	4.13	3.1	9.1	1.47	4.1	9.3
9	Gnezna – Plebanovka	1110	254	3.88	5.2	12.7	1.20	7.4	13.2
10	Nichlava – Strelkovtsy	584	179	3.12	5.6	10.4	0.74	6.8	10.8
11	Zbruch – Volochisk	712	271	4.48	4.6	10.3	0.87	5.7	10.6
12	Zbruch – Zaval’e	3130	136	4.10	4.6	12.1	1.56	5.4	12.2
13	Zhvanchik – Kugaevtsy	229	238	2.84	5.3	9.5	0.63	6.6	9.8
14	Zhvanchik – Lastovtsy	703	125	2.54	5.1	9.8	0.71	5.7	9.8
15	Smotrich – Kupin	799	230	3.82	4.2	9.0	0.96	4.9	9.2
16	Smotrich – Tsibulivka	1790	131	2.8	4.6	8.9	0.56	5.9	9.3
17	Muksha – Malaia Slobodka	302	148	2.95	6.0	10.5	0.46	8.7	11.5
18	Studenitsa – Golozubintsy	296	203	3.45	4.8	12.1	1.39	4.8	12.1
19	Ushitsa – Zyn’kov	525	196	4.27	6.0	9.6	1.35	4.2	9.1
20	Ushitsa – Timkov	1150	114	3.37	3.2	12.0	1.74	3.8	12.1
21	Ushitsa – Kryvchany	1370	89	2.95	6.3	12.3	0.98	4.9	12.0
22	Kalius – Novaia Ushitsa	259	166	3.09	2.9	9.6	0.69	5.0	10.0
23	Batog – Zamekhov	94.1	—	4.04	7.2	12.2	1.17	4.9	11.6
24	Liadova – Zherebilovka	652	129	2.67	4.7	11.3	0.46	7.0	11.9
25	Nemiia – Ozarintsy	359	150	2.59	4.6	14.2	0.50	6.7	14.7
Hydrometric sections contiguous to the study region									
26	Gnilaia Lipa – Rogatin	467	237	6.21	4.5	11.4	2.18	5.2	11.5
27	Gnilaia Lipa – Bol’shovtsy	848	215	5.08	3.8	9.2	1.60	4.5	9.4
28	Murafa – Kudievtsy	70	62	3.00	8.8	12.5	0.73	13.3	14.3
29	Murafa – Mironovka	2400	62	2.14	6.8	16.2	0.73	6.3	16.1
30	Markovka – Podlisovka	615	76	2.18	3.1	9.8	0.99	3.1	9.7
31	Kamenka – Kamenka	387	—	2.25	3.5	11.4	0.88	4.0	11.5

determined from actual observations in all computed hydrometric sections for the mean and minimum flow. It is apparent from the table that the error δQ_0 exceeds 5% in ten hydrometric sections, whereas the error of determining the variation coefficient of the mean flow, δC_V, shows an exceedance in one section only.

A calculation of the *normal runoff* must also take into consideration the representative period that includes an even number (two at least) of hydraulicity cycles. It is determined by using analog stations with the longest continuous observations ($n > 60$–70 years) by constructing an integral curve of deviations of single values of the flow from the mean value. The Chertkov station on the Seret river was used as such, where the period of continuous observations is 64 years. This hydrometric section was used as the analog for refining the computed period in the hydrometric sections where the values of $\delta Q_0 > 5\%$. The period 1949–2003 with the coefficient $K = 1.006$ can be used as representative for the Chertkov hydrometric section; during that period the mean flow actually corresponded to normal. Its value (13.4 m^3/s) is recommended as a computed value for adjusting to a long-term period the mean values of the observational series in the hydrometric sections where the error δQ_0 is larger than 5%.

The computed value of the normal runoff for the Markovka river at the village of Podlisovka was refined by using the integral curve of the flow for the 56-year-long period of continuous observations in this hydrometric section. The observational data from the currently inactive Zamekhov, Plebanovka and Kryvchany stations were adjusted to a long-term period by analogy with the flow of the Liadova river at the village of Zherebilovka ($r = 0.81$), the Seret river at the city of Chertkov ($r = 0.89$), and Ushitsa at the village of Zin'kov ($r = 0.82$). The values of the normal runoff in the Kudievtsy and Mironovka hydrometric sections are thought of as being insufficiently justified.

The values of the long-term normal runoff as determined in this manner for 31 computed hydrometric sections are provided in Table 1 (column 5). These data were used to construct the distribution map of the mean flow across the territory of the Middle Dniester basin (Fig. 1), permitting determination of the normal runoff of any tributary in its mouth or at the station at which observations are made.

Minimum flow of the rivers within the basin under investigation is formed during the winter and autumn-winter periods. It is known that values of the minimum flow are necessary for calculating the discharges of waste waters into rivers, assessing the sanitary state and self-purification of the water in them, and assessing the possibility of withdrawing the water from the channels. For dealing this and other problems, it is important to know the value of the mean monthly (30-day-long) as well as the mean daily discharge of water for a warm and cold season and for a year. Determination of the length of a warm period depends on the onset of stable ice phenomena; therefore, it can last from May to December. A cold period lasts from December (and,

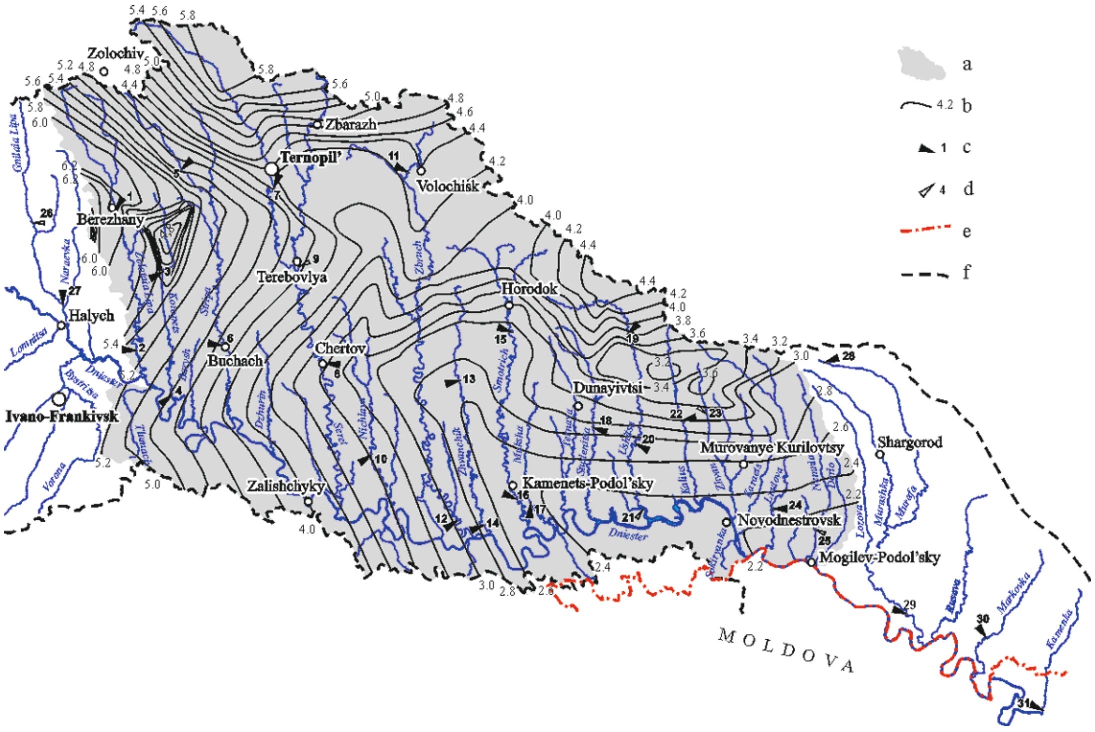

Fig. 1. Distribution of river normal runoff within the Middle Dniester basin.
1–31 – here and in Figs. 2 and 4, see Table 1. a – Middle Dniester basin; b – isolines of values of normal runoff (L/s·km^2); c – active observation station; d – inactive observation station. Boundaries: e – State border, f – drainage basin of the Dniester.

sometimes, from November) to February (March). It must be taken into consideration that no freeze-up (formation of a solid stable ice cover) occurs on the rivers of the basin in some years.

Analysis of the values of the minimum mean monthly flow obtained for a warm period showed that its value may well be underestimated because of the unclear boundaries of its determination; therefore, it would be more appropriate to use for practical purposes the notion of ecological flow of the river ensuring a normal functioning of its ecosystem at the growing period and also corresponding to the category of minimum flow. Since there are currently a unified methodological approaches to its determination and generally accepted terminology are lacking to date, use is made of flow names, such as sanitary, ecologically sufficient, environmental-protective, allowable, reserved, residual, etc. In different States, the value of ecological flow is determined as the minimum daily discharge of water of 95–97% availability, the minimum monthly flow for a low-water period of 95% availability, 75–80% of the monthly minima of 95% availability, etc. In the recommendations of the State Water Resources Agency of Ukraine, the long-term (minimum for a year) mean monthly discharge of water of 95% availability as sanitary [5].

We suggest that the notion of "sanitary flow" and "ecological flow" should be distinguished. The importance of the latter is higher than that of the former, which permits a larger amount of water to be reserved precisely during a warm period when its consumption is increased due to the anthropogenic and natural withdrawal of the flow. Ecological flow implies the long-term minimum discharge of water of 95% availability for six months: from May to October, i.e. for the growing period when the demand for water increases substantially from many users and when the sanitary-hygienic conditions of the water ecosystems are impaired.

By introducing this parameter, it will be possible to increase the minimum discharge of water, determine the limit below which water should not be withdrawn or waste waters discharged into the river. The assured values of the ecological flow were inferred by the technique similar to the method of determining the mean annual flow. For all the stations for each year we selected the smallest mean monthly discharge of water for the growing period (from May to October). The resulting series were processed by statistical methods using the StokStat software, and their standard parameters Q_0^E and C_V^E, as well as the errors of their determination (see Table 1, columns 9 and 10). The computed values of the ecological flow of 95% availability were obtained by using the theoretical curves of availability (see Table 1, column 8). These values were used to construct (by the method similar to the technique of compiling the schematic map for the mean flow) the schematic map of the distribution of the minimum mean monthly flow across the territory (Fig. 2). The schematic map displays the territorial

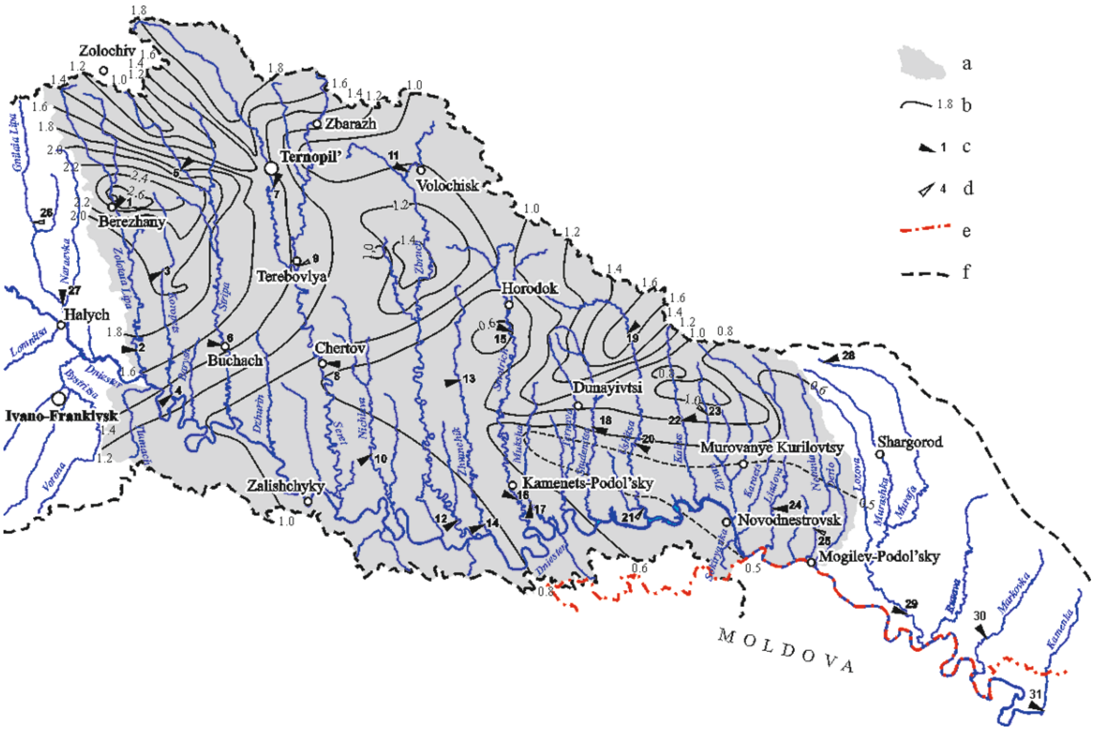

Fig. 2. Distribution of minimum mean monthly flow for a growing period within the Middle Dniester basin, $M_{95\%}$.
a – Middle Dniester basin; b – isolines of values of minimum flow, L/(s·km^2); c – active observation station; d – inactive observation station. Boundaries: e – State border, f – drainage basin of the Dniester.

distribution of the mean flow and highlights the areas of increased and decreased runoff in depth, which suggests a decrease in the minimum flow along a southeastern direction (see Fig. 2).

The distribution maps of the minimum flow are not necessarily accurate; therefore, to determine the minimum flow in the mouths of the rivers also used the analogy method where the modulus of flow in the river mouth is taken according to data from the nearest flow-gauging station. A dependence of this modulus in each hydrometric section on the incision depth of the channel ($M_{95\%} = f(H_{inc})$) and on the basin's area (M_{95}% $= f(F)$) is plotted in Fig. 3.

Analysis of the relation $M_{95\%} = f(H_{inc})$ shows that the points corresponding to the river basin numbers are grouped together within the four straight lines: I, II, III and IV, with incision depths of 320–200, 280–200, 180–100 and 160–60 m abs. elev., respectively (see Fig. 3, a). The correlation ratio $M_{95\%} = f(H_{inc})$ of these segments is estimated by the correlation coefficient $r = –0.77$; $r = –0.61$; $r = –0.72$ and $r = –0,82$, respectively, which made it possible to find their analytical expressions (except for curve II, where the value of $r < 0.70$) and determine the values of the minimum mean monthly flow for the growing period in the mouth of each tributary.

The correlation $M_{95\%} = f(F, \text{km}^2)$ is represented by dependencies I, II and III with the correlation coefficients of 0.81, 0.84 and 0.73, respectively; they permit their analytical expressions to be obtained and the computed values of the minimum flow determined in the mouths of all tributaries (see Fig. 3, b).

On the basis of analyzing the data obtained by different methods, it is possible to recommend, as the computed values, the values of the ecological flow as determined from the map (see Fig. 2), because they coincide or lie in the range between the largest and the smallest values inferred by other methods. The values of the ecological flow in the mouths of all tributaries are listed in Table 2 (column 8).

The tributaries of the Middle Dniester under investigation flow across a lowland territory; therefore, their maxima are formed both from snowmelt and storm rainfalls. Analysis of the series of the *maximum flow* showed that the long-term period shows more frequently (by a factor of 1.5–3) snow maxima; they prevail also in absolute values (only in six hydrometric sections are the rain maxima higher). Unlike the Carpathian mountain rivers where the maximum water discharge of rainfall and mixed floods (caused by rainfall and snowmelt) is formed and there is a need to discriminate between maxima of a different genesis (rainfall and snow-rainfall), the largest short-term discharge of snowmelt or rain waters was used as the maximum flow for a year.

The availability of the annual maximum discharge of water from 25 hydrometric stations for the observing period until 2008 inclusive made it possible to determine the computed maximum discharge of water with 1–2% exceedance probability as the most demanded when designing bridges, protection embankments, etc. To accomplish this, the observational series, obtained for the maximum flow, were ranked and subjected to a statistical processing by three methods: the moments method, the maximum likelihood method, and G.A. Alexeev's grapho-analytical method by using the StokStat software. The best match of the empirical and theoretical curves occurs when the second method is used. Analysis of the series showed that the values of the relative standard error of the variation coefficient C_V are within the allowable range (Table 3, column 5).

To assess the homogeneity of the empirical distributions and the stationarity of the main

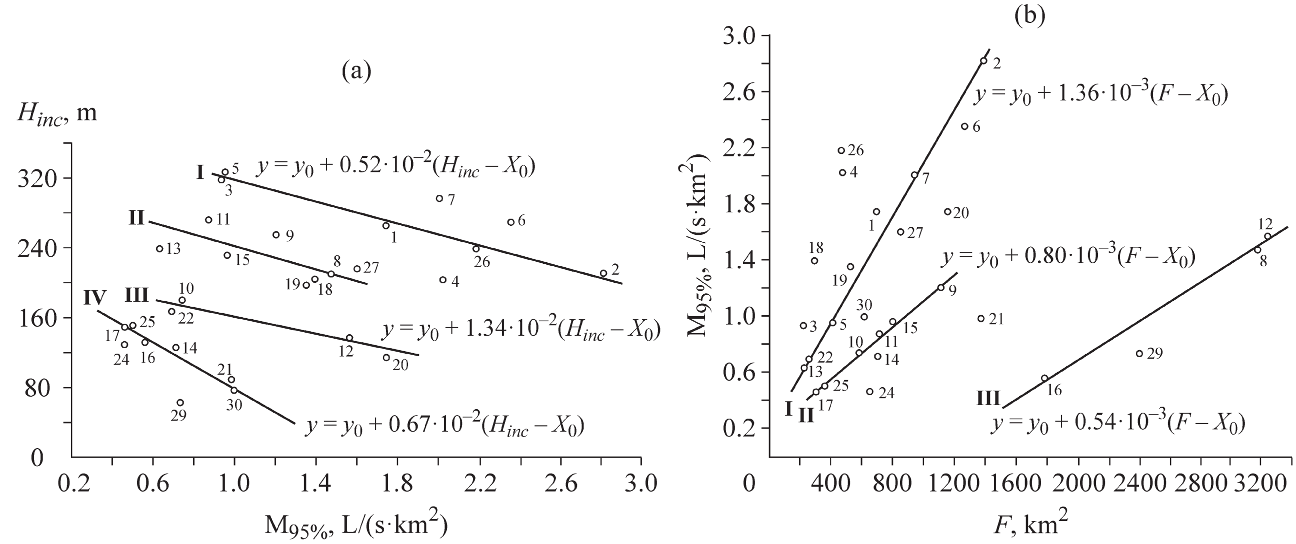

Fig. 3. Relationship of moduli of mean monthly flow for a growing period of 95% availability in computed hydrometric sections with incision depths of the river channel (a) and the drainage area (b).

Table 2. Ecological flow of the rivers within the Middle Dniester basin

River basin	Incision depth of river mouth, m abs.	Modulus of minimum mean monthly flow of 95% availability for warm period (L/(s/km^2)) as determined				Modulus used in calculation, L/(s· km^2)
		by analogy method	from map	from incision depth, H_{inc}	from drainage area, F	
Zolotaia Lipa	193	2.81	2.60	2.27	2.54	2.60
Tlumach	193	—	1.26	1.59	0.92	1.26
Koropets	182	2.02	2.01	2.33	1.27	2.01
Barysh	178	—	1.44	2.35	0.83	1.44
Stripa	159	2.35	2.10	2.45	2.63	2.10
Dzhurin	153.5	—	0.98	1.98	0.99	0.98
Seret	138	1.47	1.42	2.13	1.76	1.42
Nichlava	124	0.74	0.78	1.51	0.96	0.78
Zbruch	112.5	1.56	1.50	1.66	1.48	1.50
Zhvanchik	111	0.70	0.65	0.73	0.87	0.65
Smotrich	97.7	0.56	0.59	0.82	0.62	0.59
Muksha	95.3	0.46	0.46	0.84	0.52	0.46
Ternava	90.0	—	0.59	0.87	0.58	0.59
Studenitsa	85.0	1.39	0.88	0.91	1.23	0.88
Ushitsa	79.5	1.74	1.40	0.95	1.39	1.40
Kalius	70.0	0.69	0.90	1.01	1.11	0.90
Zhvan	66.0	—	0.70	1.04	0.71	0.70
Karaets	62.5	—	0.48	1.06	0.43	0.48
Liadova	61.5	0.46	0.70	1.07	0.86	0.70
Nemnia	58.5	0.50	0.50	1.09	0.59	0.50
Derlo	58.0	—	0.48	1.09	0.44	0.48

Table 3. Characteristics of maximum flow in computed hydrometric sections

Hydro-metric section No. on map	River – station	$C_{\text{V max}}$	δC_{V}	$M_{1\%}$, m^3/(s/km^2)	Reduction factor, n	M_{200} of 1% availability
	Hydrometric sections within the study region					
1	Zolotaia Lipa – Berezhany	1.06	12.99	0.17	0.49	0.32
2	Zolotaia Lipa – Zadarov	0.58	11.27	0.07	0.51	0.21
3	Koropets – Podgaitsy	0.78	11.53	0.21	0.46	0.23
4	Koropets – Koropets	0.60	10.77	0.16	0.48	0.25
5	Stripa – Kaplintsy	0.98	12.49	0.39	0.48	0.55
6	Stripa – Buchach	0.87	12.66	0.17	0.51	0.45
7	Seret – Bol’shaia Berezovitsa	0.49	11.37	0.07	0.50	0.15
8	Seret – Chertkov	0.74	9.52	0.10	0.54	0.46
9	Gnezna – Plebanovka	0.76	15.07	0.18	0.51	0.44
10	Nichlava – Strelkovtsy	1.02	13.67	0.14	0.49	0.25
11	Zbruch – Volochisk	0.94	13.34	0.22	0.49	0.42
12	Zbruch – Zaval’e	0.84	13.36	0.10	0.54	0.44
13	Zhvanchik – Kugaevtsy	1.06	12.54	0.25	0.46	0.27
14	Zhvanchik – Lastovtsy	1.00	12.86	0.14	0.49	0.27
15	Smotrich – Kupin	0.98	11.86	0.28	0.50	0.56
16	Smotrich – Tsibulivka	0.94	11.14	0.17	0.52	0.55
17	Muksha – Malaia Slobodka	1.31	15.60	0.28	0.47	0.35
19	Ushitsa – Zin’kov	1.31	15.10	0.64	0.49	1.03
20	Ushitsa – Timkov	0.69	15.11	0.13	0.51	0.31
22	Kalius – Novaia Ushitsa	1.31	15.47	0.58	0.47	0.66
24	Liadova – Zherebilovka	1.25	16.71	0.29	0.49	0.53
25	Nemnia – Ozarintsy	0.80	17.48	0.22	0.48	0.29
	Hydrometric sections contiguous to the study region					
26	Gnilaia Lipa – Rogatin	0.47	12.05	0.13	0.49	0.20
27	Gnilaia Lipa – Bol’shovtsy	0.45	9.61	0.08	0.50	0.16
28	Murafa – Kudievtsy	1.06	15.10	0.42	0.44	0.26
30	Markovka – Podlesovka	1.49	16.66	0.26	0.49	0.46

parameters of the time series for identifying the values sharply differing from the general set, use was made of the Grubbs–Smirnov and Dixon criteria. The 5% significance level was specified, which, according to mathematical statistics theory, implies assuming the zeroth hypothesis of homogeneity with 95% probability [23]. As a result, this hypothesis is assumed in all cases. Our investigations, along with other studies [9, 12, 13], demonstrate that the period 1980–2008 showed a disturbance to the stationarity of the hydrological series, and the period after the 1980s shows signs of a trend of different signs, i.e. an increase or a decrease in the maximum discharge in regions of low probabilities. By using the triparametric gamma-distribution at any value of the ratio C_S/C_V in smoothing and extrapolating the empirical distribution curves, it was possible to find the parameters of the analytical distribution curves $\bar{Q}_{max}$, C_V and C_S/C_V by the trial-and-error method for all of the computed hydrometric sections. Table 3 presents the main parameters of the theoretical curves taken into account. Since the modulus of maximum flow undergoes a reduction across the drainage area, the resulting moduli of maximum flow with 1% exceedance probability were adjusted to the area of 200 km² by the formula [21]:

$$M_{200} = M/(200/F)^n,$$

where M is the maximum modulus with 1% exceedance probability, M_{200} is the same modulus adjusted to the area of 200 km², and n is the reduction index of the modulus of maximum flow of water.

The data in Table 3 (column 8) were used to construct the schematic map of isolines (Fig. 4) making it possible to detail the distribution of the maximum flow in the region. The map was employed to identify specific areas of increase in the maximum flow, such as within the Ushitsa basin. The largest value of the index M_{200} of 1% availability is 1.03 m³/(s/km²) in the Zin'kov hydrometric section on the Ushitsa, and the smallest value corresponds to the upper reaches of the Zolotaia Lipa, Koropets, Seret and Murafa, 0.21–0.26 m³/(s/km²).

CONCLUSIONS

The research reported in this paper showed that between 1962 [1] and 2000 [5] the normal runoff in the region increased (depending on the hydrometric station) by 5.1–50%, which was caused by cyclic fluctuations of the flow, a lengthening of the series, the more justified selection of analog rivers, and by the possible influence of agricultural practices in the drainage areas. By 2008, a change in the normal runoff, compared to 2000, was ± 3.4% at all observation stations, which is below the accuracy of its calculation, and only at three hydrometric sections did it increase from 11.7 to 35.6% for the reasons mentioned above. A change in the minimum mean monthly flow during

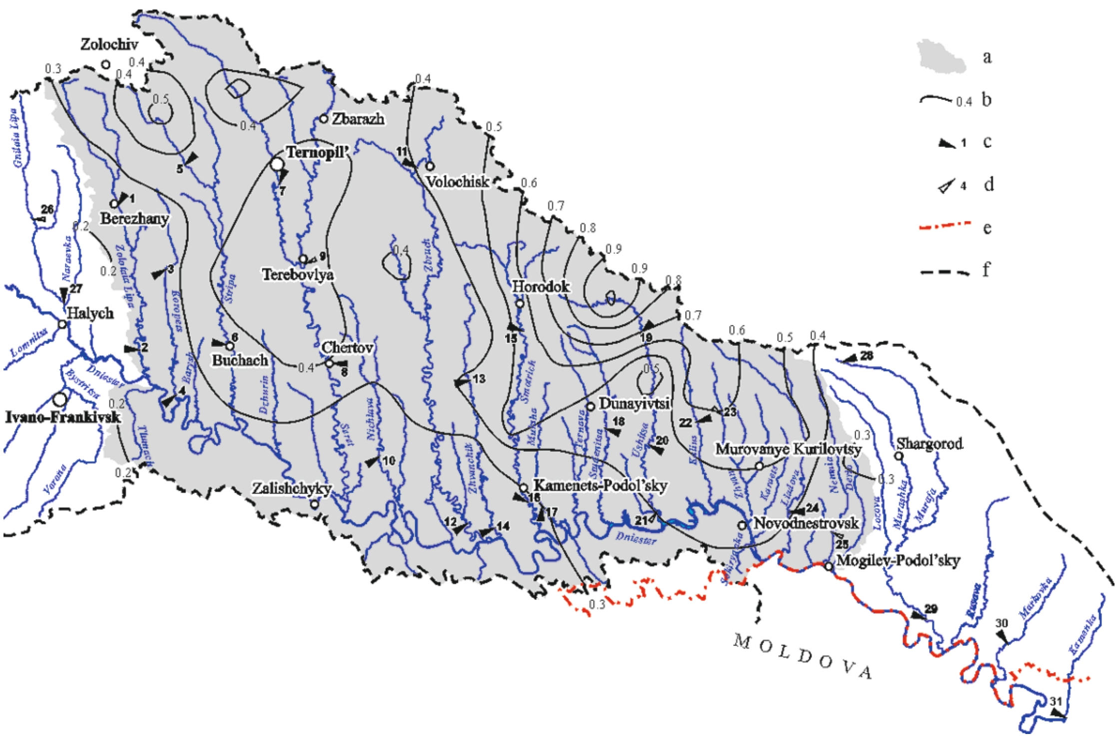

Fig. 4. Moduli of maximum flow within the basins of the tributaries of the Middle Dniester with 1% exceedance probability as referred to the area of 200 km².
a – middle Dniester basin; b – isolines of values of maximum flow, m³/(s·km²); c – active observation station; d – inactive observation station. Boundaries: e – State border, f – drainage basin of the Dniester.

a growing period remained within ± 5% at most of the stations, and only at three of them did it vary from +10.1 to +24.1%.

A lengthening (compared to previous research [1, 8, 21]) of the observational series, and analysis of the 2008 disastrous rainfall-induced flood suggest an increase in the modulus of maximum flow with 1% exceedance probability. The distribution maps of 1% moduli of maximum flow, adjusted to the area of 200 km^2, and of the variation coefficients of the maximum flow show that the areas of increase in these characteristics on the study territory remain and that the new estimates of the variation coefficients are smaller and the estimates of the maximum moduli of flow are larger [1, 8, 21].

The refined computed characteristics of the mean annual, minimum and maximum flow of the tributaries of the Middle Dniester offer a means of gaining an integral insight into the current changes in hydraulicity of the rivers in the region. The findings reported in this paper can serve as a basis for predictive assessments in the interests of rational utilization and protection of water resources, and improvement in the state of the region's river ecosystems.

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