STREAMFLOW TRANSFORMATION UNDER PRESENT CONDITIONS

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ABSTRACT. An estimation of streamflow transformation in rivers of Belarus under present conditions influenced by natural fluctuations of flow and anthropogenic impacts, has been performed. On the whole, no sizeable changes in the annual streamflow have been found. At the time of spring floods, an average decrease in the maximum annual discharge in the territory of Belarus is 43%, while the increase in peak summer-autumn and winter yields are 27% and 36%, respectively.

KEY WORDS: streamflow, transformation, river, Polesie

1. INTRODUCTION

In general, the streamflow is formed under the influence of natural and climatic factors. However, lately anthropological impacts become increasingly important factors and in a number of situations are even comparable with natural processes of flow formation. The most powerful man-impacted factor, with a substantial influence on river ecosystems, is a large-scale agricultural reclamation started in the mid-60s of the last century (Lishtvan et. al. 1999; Kalinin and Volchek 2001). At that time, the southern part of Belarus (Byelorussian Polesie) suffered most from extensive drainage reclamation projects that could not but seriously affect the river discharge (Volchek 2004). Besides, there is a recorded significant effect of global warming (Leiserowitz 2006; IPCC, 2007; Dai 2013; Howe et. al. 2013). This effect will manifest itself in full within the next decade in the form of combined regional changes in river ecosystems — the very sensitive indicators of availability of both natural and human-caused factors (Jeton et. al. 1996; Cole et al. 1997; McMichael et al. 2008; Spence et. al. 2011).

With an indispensable volume of streamflow data on hand, as obtained from permanent stream-gauging stations over a considerable length of time — from 1940 to 2004 — and with the help of state-of-the-art geoinformation systems and technologies, it is now possible to obtain a quantitative assessment of river discharge fluctuations and to identify disturbances in the inner flow. For the sake of simplicity, \( \Delta M_{\text{clim}} \) can be determined by using standard deviation values for normal yield and its fluctuations. However, it calls for the study of peculiarities of its regime variations (seasonal and annual).

\[
M_{\text{nat}} = M_{\text{meas}} \pm \Delta M_{\text{aper}} \pm \Delta M_{\text{cl}} \pm \Delta M_{\text{anth}}, \tag{1}
\]

where \( M_{\text{nat}} \) is a would-be observed amount of stream flow under stationary process condition; \( M_{\text{meas}} \) is a measured (actual) value of discharge for the time period in question; \( \Delta M_{\text{aper}} \) are natural fluctuations of discharge due to apersonic climatic variations; \( \Delta M_{\text{cl}} \) represents changes in discharge induced by the effect of global warming; \( \Delta M_{\text{anth}} \) is a complex estimate of the effect of economic and other land-use activities on the bed and upon the river catchment area upstream.

The complexity of practical implementations of expression \( [1] \) arises from assessment errors and a relative uncertainty of its components.

Measured discharge may reflect visual errors in flow rates and section areas, these are the errors of discharge estimation of a momentary water flow. Besides, there are errors in computation of the volume of streamflow for the period under study; in other words, errors in estimation of stream fluctuations between measurements, as well as those due to a likely deformation of the river bed and flow rates profiles.

As a rule, value \( \Delta M_{\text{aper}} \) serves as a correction to the average discharge value for the period based on its annual normal structure of time-base series plots. An attempt to correlate the impact of these disturbances with particular changes in climatic factors and economic (or business) activity on the river watershed areas certainly offers potential for revealing concrete river courses and territories with altered hydrological regimes and explaining the cause of these transformations. In its turn, this will enable us to resolve issues of importance of drainage reclamation projects in changes in the hydrocity and comparability of their role with natural historical fluctuations of the elements of hydrologic budget. In the process, it is important to consider all types of streamflow discharge and, thus, to determine the origin of the above changes as a system (complex).

2. MATERIALS AND METHODS

The starting materials were the results of observational evidence on annual water discharges, spring-flood maxima, summer-autumn and winter flows based on data obtained from 164 control sections, available from the Department of Hydrometeorology under the Minprirody (Ministry of Nature Protection) of the Republic of Belarus, for the entire period of instrumental observations.

To correctly assess the amount of discharge, it is necessary to discriminate between human-affected and natural components on the basis of the following expression \([1]\):
Element $\Delta M_{\text{anth}}$ reflects a combined (multidirectional, compensating inclusive) influence of economic activities in the catchment area on the water yield. Due to limited utility of instrumental observations for water distribution and for a variety of other objective causes, the estimation of $\Delta M_{\text{anth}}$ is associated with considerable errors, the result of which represents the contribution of errors from all the components of the water distribution balance. Relation $\Delta M_{\text{anth}}/M_{\text{meas}}$ may serve as a simplified estimate of changes in the streamflow. If it is less than $1$ to $3\%$, then this quantity is inessential, with no loss in accuracy. Otherwise a detailed analysis of confidence for all the components is required, as well as the exclusion of $\Delta M_{\text{anth}}$ element by way of recovery of the discharge, using this element in this relation.

Based on the above, we have worked out a method for estimation of the anthropogenic component in discharge fluctuations founded on the analysis of the flow-field statistic structure. The essence of the method is to perceive the subtle differences between space and correlation functions (SCF) built up

$$\sigma_{\text{anth}} = (\sigma_{\text{nat}})^{0.5} - \left(\sigma_{\text{meas}}^2 + \sigma_{\text{anorr}} + \sigma_{\text{clit}}^2\right)^{0.5} = \sigma_{\Delta M} (R(0) - R(0)^*)^{0.5},$$

where $\sigma$ is the standard deviation of hydrological initial values; $R(0)$, $R(0)^*$, are extrapolated values of an empirical SCF implemented on discharge data before and after exposure to anthropogenic actions, respectively.

Significance of the value obtained, $\sigma_{\text{anth}}$, is assessed using well-known statistical criteria.

If it is established that $\sigma_{\text{anth}}$ is due not to random mistakes that depend on the length of series, then the quantity $\Delta M_{\text{anth}}$ characterizes anthropogenic component of the territory water flow. Identification of concrete water catchment areas susceptible to anthropogenic fluctuations is achieved by analyzing changes in pair correlative coefficients, and catchment areas with statistically different changes of these coefficients are revealed.

A priori, the motivation for solving task [1] has been substantiated by the analysis of uniformity of the initial hydrometrical data series, graphically and statistically. Further, the date of a radical change in the curve of time behaviour of discharge processes has been determined, causes and parameters of fluctuations in time of those anthropogenic factors that could give rise to them.

Variations in discharge caused by the economic activity, $\Delta M_{\text{econorm}}$, are determined from the following difference:

$$\Delta M_{\text{econorm}} = M_{\text{nat}} - M_{\text{meas}}.$$

Appraisal of man-influenced variations may be thought as credible, if their absolute values are well over the computational error:

$$|\Delta M_{\text{econorm}}| \geq \alpha_p \cdot \Delta M_{\text{econorm}},$$

where $\alpha_p$ is the confidence interval for computing errors, expressed in fractions of its root-mean-square value, is a function of the level of confidence, $p$.

Usually, when evaluating the confidence of computation, it is typical to set $p=0.95$, for which $\alpha_{0.95} \approx 2.0$.

Statistical computations were preceded by a special analysis of source information, to check the uniformity of data. On instances where violations were detected within the critical statistics limits, standard statistical methods were adopted in the computational procedure, namely:

- chronological charts of variations and integral difference curves were used to identify trends in fluctuations;
- the dynamics of time series was estimated with the help of linear and square-law trends.

on discharge time-based series for the periods of prior to and during the exposure to active man-induced disturbance (Volchek 1988).

The overall standard deviation of initial data can be objectively evaluated with the help of a reflectory empirical correlative function, of space $R(\rho)$ or time $R(\tau)$, using an extrapolated value, $R(0)$, corresponding to a null distance $\rho = 0$ or null shift in time $\tau = 0$.

When measuring hydrological quantities in very small time intervals or division steps ($\Delta \tau$, $\Delta \rho$), that are appreciably less than the period of oscillations of the type of «white noise» ($\Delta \tau^*$, $\Delta \rho^*$), that is, $\Delta \tau << \Delta \tau^*$ and $\Delta \rho << \Delta \rho^*$, the sampling or digitizing errors are close to zero.

On the basis that different types of errors are independent, the dispersion of total error is equal to the sum of dispersions of these errors. The Root-mean-square error induced by human factors is defined by the following expression:

$$\Delta \sigma_{\text{anth}} = \Delta \sigma_{\text{nat}} - \Delta \sigma_{\text{meas}} + \Delta \sigma_{\text{anorr}} + \Delta \sigma_{\text{clit}}.$$

Table 1. Rivers-Sections with Essentially Disturbed Inner Structure of Historical Series

<table>
<thead>
<tr>
<th>Type of discharge</th>
<th>River–Section</th>
<th>Discharge fluctuations (formula 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual</strong></td>
<td>riv. Kopayuvka – village</td>
<td>-0.61</td>
</tr>
<tr>
<td></td>
<td>Chersk</td>
<td>-0.57</td>
</tr>
<tr>
<td></td>
<td>riv. Vit – vil.</td>
<td>-0.20</td>
</tr>
<tr>
<td></td>
<td>Borisovschina</td>
<td>-0.20</td>
</tr>
<tr>
<td><strong>Maximum spring flood</strong></td>
<td>riv. Viliya – vil. Vilejka</td>
<td>-1.03</td>
</tr>
<tr>
<td></td>
<td>riv. Bobrik – control section Parokhonsk</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>riv. Vit – vil.</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Borisovschina</td>
<td>0.20</td>
</tr>
<tr>
<td><strong>Minimum</strong></td>
<td>riv. Zhabinka – vil. M.</td>
<td>1.42</td>
</tr>
</tbody>
</table>
It is appropriate here to note the curve riv. Vit’ – village Borisovschina, the discharge series of which for all types of discharge demonstrated the most thorough transformation. First and foremost, it can be linked to variations in the water catchment area. The disturbed structure of the spring-flood maximum discharge curve at riv. Viliya – village Vilejka can be explained by a partial accumulation of the flow in water storages basins and its further transfer to the Vilejsko-Minskaya Water System. The rest of rivers presented in this Table are also classified under a category of small watercourses and, as it is known, this kind of streams are most susceptible to man-induced activities.

![Fig. 1. Chronological charts of, and trends in, discharges for rivers with the most disturbed inner structure of time-series: a – annuals; b – spring-flood maxima; c – summer-autumn low-water minima; d – winter low-water minima.](image1)

Values $k_i$ computed with the formula (5) have been gridded (Figs. 2 to 5) using catchment-area coordinates of the river–sections under observation.

![Fig. 2. Spatial structure of fluctuations in annual mean discharges for rivers in Belarus](image2)
An analysis of spatial structure for annual discharge fluctuations (Fig. 2) indicates that no variations of annual discharge have practically taken place in the north and central parts of Belarus, less exposed to ameliorative hazards. In the northwest part the discharge of water has insignificantly decreased during the period from 1966 to 2004. Whereas in the south and southwest parts an increase of the annual discharge for the period of 1966 to 2004, as compared to the situation prior to 1965. To summarize, fluctuations in the annual discharge are insignificant – an average value of the fluctuation coefficient was 2.7%, i.e. within the discharge measurement error limits. At the same time, these fluctuations were found more pronounced – the mean value of fluctuation coefficient was equal to 0.201, suggesting a 20-percent increase in the annual discharge. Hence, the large-scale amelioration projects contributed to the increase in annual discharge on small rivers of Byelorussian Polesie through a partial draw-
down of secular storage in earth surface horizons and redistribution of component ratios in the hydrologic budget.

The mean value of the discharge-change coefficient for spring flood maxima was down to -0.425, the same coefficient for summer-autumn low-waters equals to 0.271, and for winter discharge minima amounts to 0.356. In other words, in average, a 43-percent decrease in maximum spring-flood discharges, 27-percent increase in minimum summer-autumn low-waters, and 36-percent increase in minimum winter low-water season are registered in Belarus.

Studies of maximum spring floods, minimum summer-autumn and minimum winter discharges of Belarus rivers form a basis for formulation of the following infringements of the inner structure of time series:

– a decrease in maximum water flow after 1965 (up to 25–40%) over the entire territory of Belarus (Fig. 3);

– a substantial (up to 50–80%) increase in minimum discharges during the summer-autumn low-water period for the south and southwest parts of Belarus during the 1966-to-2004 period, as compared to the period before 1965, inclusive, while the stated above variations are not so drastic (10–30%) (Fig. 4);
minimum winter yields increased in the aggregate by 20–40 percent, a compared to the prior-to-1965 period, let us mention in passing that maximum of these variations is specific for Byelorussian Polessie (60–80%) (Fig. 5):

This increase in winter low-water season is an aftereffect of prolonged thaws which became more frequent recently and are characterized by intensive thawing of snow and replenishment of ground water stocks. As a result, the spring flood discharges decrease, while the summer-autumn low-waters increase.

To estimate the influence of large-scale amelioration projects on the hydrological regime of Byelorussian Polessie, an analysis of changes in SCFs has been completed for the following periods: from the starting point of observations until 1966, i.e. the time of the onset of large-scale land-reclamation and development projects, and since 1966 to date implemented on data from 26 measuring sections established on rivers with catchment areas from 67 to 2560 km². Computations have been carried out for the three specific-type dis-charges: maximum spring floods (SF), minimum summer-autumn (S) and annual water debits (A) (Fig. 6).
Instances with disclosed statistically distinguishable changes in correlation coefficients indicate the exposure to human-initiated activity. Thus, the comparison of SCFs for the period free from ameliorative effects, \( R(0)_A = 0.774; R(0)_A = 0.687; R(0)_A = 0.853 \), with SCFs like \( R(0)_S = 0.734; R(0)_S = 0.351; R(0)_S = 0.742 \) for the period of building large-scale land-reclamation structures indicates the presence of statistically discernible distinctions between them \( \Delta R(0)_S = 0.040; \Delta R(0)_S = 0.326; \Delta R(0)_S = 0.111 \).

These distinctions are most substantial for the minimum discharge (47.5%); it can be associated with variations in the general water content in rivers, the extent of catchment area, the size of drained marshes and water-logged land areas, as well as the density drainage channel network and the degree of channelization. Polessie is characterized by the predominance of peat bogs of shallow density drainage channel network and the degree of channelization. Hence, a substantial increase in the minimum discharge (approximately by 50 percent) has been noted in this area for the 1966-to-2004 period as compared with the period since the time of commencement of observations and till 1966.

At the early stage of land reclamation projects changes in discharge maxima took an ambiguous route. The water catchment areas where the uniformity of maximum rate of flow and runoff patterns had been infringed demonstrated an increase and decrease alike. This is the consequence of amelioration activity in the catchment areas leading to the establishment of an intricate set of various conditions. The latter have appreciable multidirectional effects on the formation of maximum discharge in rivers during spring floods. A pronounced increase in the storage capacity of areas reclaimed by draining in the catchment area results in loss of melt waters and a decrease in maximum discharge intensity, while an artificial expansion of gauging station density coupled with river regulation favours the formation of augmented discharge maxima. In the context of simultaneous combined action of both factors, the pattern, as well the scale of maximum discharge variations is actually a function of the factor whose effect is more severe.

Following the establishment of equilibrium condition, a certain decrease in the maximum discharge is noted (approximately by 25%), also, it is more “organized” both, in time and in space, as opposed to processes with an increase in the minimum discharge. Hence, an insignificant decrease in the correlation coefficient \( R(0)_S = 5.2 \% \).

Maximum changes of the yearly streamflow has been registered at the water catchment areas located within flat lowlands, as well as on those with wide water-logged flood plains. The higher the degree of swampiness of the catchment, the greater fluctuations of the yearly runoff subsequent to amelioration. As a rule, it also increases with the added portion of drained swamps and waterlogged-land patches. As the results of our study for the territory of Byelorussian Polessie imply, the yearly runoff augmented approximately by 20% for the period from 1966 to 2004, as compared with the period prior and including 1965. At the same time the parameter \( R(0)_A \) came to 13%.

**Fig. 6.** The space-correlation function of the mean annual (a), springtime flood (b), and minimum summer-autumn low-water (c) total streamflow for rivers in Byelorussian Polessie.

**REFERENCES**


**4. CONCLUSION**

Thus, the main causes of river flow transformation in Belarus are environmental repercussions due to the global climate changes on the backgrounds of man-made effects in the form of the large-scale reclamation projects in Byelorussian Polessie. The influence of the anthropogenic component (for example, amelioration) on different types of flow should be examined individually, on a case by case basis. Changes in flows demonstrate a varied character, with a certain “intra-annual” transformation of river hydrological regime in Belarus. The observed reduction of maximum spring-flood discharge is made up by an essential increase in minimum discharges during both winter and summer-autumn low-water seasons. In other words, global climatic changes have led to the flow change within the hydrological year, while the yearly normal runoff has not practically changed in quantity, with the exception of the Byelorussian Polessie territory which differs from other regions of Belarus by the conditions of flow formation and man-impacted loads.

Further still, it is not so much the drainage (of marshes), as incompetent servicing and improper operation of the drainage systems and incorrect water usage and economic practices on the territories of water catchment areas that impair the inner structure of flow formation and lead to those quantitative changes of water discharge that have been recorded during this study.


