Water bodies on the surface of the earth (reservoirs and lakes) and their influence on the long-term changes in the regulated rivers’ runoff. A comparative study

S G Dobrovolski*, M N Istomina, I P Lebedeva, O V Sokolova, I V Solomonova and T Yu Vyruchalkina

Water Problems Institute RAS, Gubkina 3, 119333, Moscow, Russia

sgdo@bk.ru*, vyruchi@list.ru, mari-istomina@yandex.ru, iplebed@gmail.com, _iren@mail.ru, o.l.g.a.s.o.k.o.l.o.v.a.1994@mail.ru

Abstract. Archives of data on the most important reservoirs and flowing lakes of the world, and on long-term changes in the flow of rivers regulated by them have been formed. The features of the parameters of artificially regulated rivers and lacustrine rivers and the dependence of these parameters on the characteristics of reservoirs and lakes were analysed. A phenomenon of «monotonous» and «intermittent» nonstationarity are described. The possible role of reservoirs and lakes in their formation has been assessed.

1. Introduction
The aim of this work was to study the influence of reservoirs and lakes of the world on the long-term variability of the runoff of regulated rivers. Studies of reservoirs, lakes and changes in river flow on a global scale are usually carried out separately [1, 2]. Conducting the present joint analysis on a global scale can reveal patterns that are poorly detectable at the regional level, taking into account the shortness of the runoff time series. In addition, as the studies of one of the authors show [1, 3], when analysing the runoff series of certain rivers, an alternation of segments was noted within the same runoff time series. For some of these segments the hypothesis of stationarity by mathematical expectation is satisfied, whereas for others it is not confirmed with a high degree of probability. An analysis of this effect and the possible role of reservoirs and lakes in its creation was also the goal of this work.

2. Materials and methods

2.1. Materials
The Global Reservoir and Dam Database (GRanD), presented in 2011 by a large international team, was taken as the initial information basis for studying the reservoir parameters [4]. Subsequently, for the first time, the specified database, supplemented and refined by a number of sources [5, 6], was combined with the database on long-term changes in the annual, maximum and minimum runoff, created earlier at the Laboratory of Global Hydrology of the Water Problems Institute Russian Academy of Sciences and discussed in detail in monographs [3, 4]. As a result, a «combined» computer database was created with various characteristics of reservoirs, as well as with variability
parameters of the runoff of rivers regulated by reservoirs. To date, it includes information on 388 reservoirs and their dams, associated with runoff series with the length of at least 20 years.

In accordance with the main purpose of creating reservoirs, they were divided into 8 groups. In this work, the analysis of the parameters of reservoirs and their impact on runoff was carried out for all reservoirs (in total), irrigation reservoirs (25% of total number) and hydropower reservoirs (40%).

An extremely uneven distribution of reservoirs around the world has been noted – in particular, irrigation reservoirs. The reservoirs are located within the boundaries of distinct areas reflecting both natural features and the degree of economic development of the territories. The spatial distribution of hydropower reservoirs looks more diffuse.

The database on flowing lakes contains characteristics of 249 lakes and data of long-term observations at 376 gauges on lake rivers. The main part of the summary table includes data on 142 parameters of the flow of regulated rivers and on the characteristics of the corresponding flowing lakes. The archives represent a set of annual, maximum and minimum runoff values with the duration of ≥20 years.

In accordance with the genetic classification of lake basins, the studied lakes were divided into three groups: those of glacial origin (moraine and moraine-tectonic) – 60.2%, of tectonic origin (including lakes formed by volcanic craters) – 9.7%, and others – 30.1%.

As well as reservoirs, lakes are distributed extremely unevenly around the world. They are grouped within distinct areas reflecting the natural features of the territories: North American area, North European, North Asian. In a number of regions, lakes occupy a significant part of the area and have a significant impact on the characteristics of river runoff [1, 3, 7, 8].

The data archives constructed for reservoirs and lakes, combined with the data on regulated rivers’ runoff, represent a hierarchical set of spreadsheets in the Statistica format. The use of a specialized algorithmic language of StatSoft company makes it possible to carry out analysis and modelling directly within the tables.

2.2. Methods
Information on fluctuations of the runoff parameters of the rivers regulated by reservoirs and lakes was analysed using a new system of statistical and stochastic estimates proposed by one of the authors [1, 3], in accordance with fundamental works on the theory of random functions [9, 10, 11, 12, 13]. The corresponding methods of analysis are based on a new economical method developed by one of the authors for obtaining pseudo-random Gaussian numbers by the method of mirror doubling of the generating algorithm.

A new modification of the Akaike method for estimating the orders of stochastic (autoregressive) models for describing long-term changes in river flow is proposed. This modification eliminates the shortage of existing methods: the strong dependence of estimates on the length of time series.

To study the problem of the degree of stationarity / non-stationarity of the runoff series, «indices of stationarity» with respect to mean value ($I_{SM}$), variance ($I_{SS}$), autocorrelation ($I_{SR}$) were proposed [1, 3]:

$$I_{SM} = \frac{M_{SAM}^2 - M_{SAM}^1}{\sigma(M_{SAM}^{MC} - M_{SAM}^{1})}$$

where $M_{SAM}^2 - M_{SAM}^1$ is the difference between the sample means of the second and first parts of the runoff series, calculated by conventional formulas; $\sigma(M_{SAM}^{MC} - M_{SAM}^{1})$ is the standard deviation of the analogous difference evaluated by Monte-Carlo procedure for a stationary series with appropriate length and time correlation and approximated by an analytical expression. Note that for the purpose of estimating the degree of stationarity/non-stationarity, initial time series were recalculated into the series of the sample values of the Gaussian random numbers (using a new algorithm described in [1]).

The 5% probability of the $I_{SM}$ ($I_{SS}$, $I_{SR}$) indexes’ absolute values exceeding 1.96 level is taken as a measure of the stationarity/non-stationarity of the time series or its segment. If a series contains at
3. Results and discussion

3.1. Statistical analysis of quantitative parameters of reservoirs and lakes

Following main parameters of the reservoirs are considered: the area of the reservoir; average depth; reservoir volume; average water discharge through the dam; water exchange coefficient, WEC (or «degree of runoff regulation », DOR) (table 1). (Note that WEC=1/DOR). Calculations have shown that when studying the «reservoir-river» system, the most informative is the WEC, calculated as the quotient of dividing the average annual water discharge through the dam by the reservoir volume. Probability densities (probability functions) of all the main parameters of both main types of reservoirs according to their purpose in the first approximation are satisfactorily described by the geometric distribution [14]. The indicated type of distribution, therefore, is a kind of universal for describing the characteristics of reservoirs and their dams.

Following main quantitative parameters of flowing lakes are analysed as well: lake surface area, average and maximum depths, lake volume; coastline length; water exchange factor [15] (table 1). When studying the parameters of the lakes and constructing the corresponding graphs, the approximation method was used [2]. The analysis showed that the probability functions of the main quantitative characteristics of flowing lakes, as well as for reservoirs, in the first approximation are satisfactorily described by a geometric distribution.

| Groups of lakes by origin: | Glacial | Tectonic | Other | All |
|---------------------------|---------|----------|-------|-----|
| Area, km²                | 1980    | 2311     | 1476  | 1855 |
| Mean depth, m            | 26.4    | 78.4     | 38.6  | 35.3 |
| Volume, km³              | 144.9   | 1499.0   | 429.6 | 299.6 |
| Water exchange coefficient, % | 13.0 | 1.9 | 23.6 | 14.4 |
| Drainage area, km²       | 74694   | 50710    | 20338 | 56663 |

| Purpose of reservoirs:    | Irrigation | Hydropower | All |
|---------------------------|-------------|------------|-----|
| Area, km²                 | 130         | 963        | 323 |
| Mean depth, m             | 66.1        | 73.0       | 60.0 |
| Volume, km³               | 2.7         | 11.8       | 5.7 |
| Water exchange coefficient, % | 156.1 | 66.2 | 100.9 |
| Drainage area, km²        | 103233      | 154135     | 106307 |

From table 1 it follows that in terms of most parameters, lakes of tectonic origin significantly exceed other groups. The greatest value of the WEC corresponds to the glacial lakes of the world; tectonic reservoirs are characterized by the greatest depths and volumes, which is due to their origin.

In terms of most parameters, the hydropower reservoirs, on average, significantly exceed the reservoirs for irrigation purposes. The average depth and degree of regulation, for both, are approximately of the same order of magnitude.

Comparison of the parameters of lakes and reservoirs in table 1 shows that in terms of surface area, volume of water and, partially, of average depth, lakes are many times larger than reservoirs. The catchment areas are comparable. However, the WEC of reservoirs is several times higher than the corresponding indicator of lakes.

3.2. Impact of reservoirs and lakes on the parameters of long-term fluctuations in the runoff of rivers regulated by them

The features and patterns of long-term changes in the regulated rivers’ runoff were analysed using the methods proposed and listed above. Table 2 presents the results of calculating the average values of long-term runoff fluctuations’ parameters: rivers regulated by irrigation reservoirs, hydropower reservoirs, as well as all in total, by lakes (glacial, tectonic) and unregulated non-lake rivers. Four parameters are presented: coefficient of variation – $C_V$; asymmetry coefficient – $C_S$; the value of the
correlation of the runoff of neighboring years – \( r_i \); the average generalized order of autoregression \( M \), which is equal to one at \( M > 1 \). Hydropower reservoirs reduce the range of long-term fluctuations in the annual runoff (\( C_V \)). At the same time, irrigation reservoirs, on average, significantly increase the long-term variability of the annual runoff values. Similar patterns are inherent in the influence of reservoirs of two types on the \( C_S \) of the annual runoff. However, hydroelectric reservoirs fail to significantly reduce the degree of variability of long-term fluctuations of maximum and minimum (monthly) runoff, and irrigation reservoirs greatly increase \( C_V \) and \( C_S \).

Regarding the structure of long-term fluctuations in the regulated rivers’ runoff, the influence of reservoirs of two main types in relation to the series of both annual and maximum and minimum discharges is unambiguous: in all cases, the construction of reservoirs increases the average correlation of the runoff of neighbouring years and increases the average order of stochastic (autoregressive) models. The consequence of this is an increase in the «correlation time» (and errors in estimates of the mathematical expectation of the runoff), an increase in the differentiation of the corresponding graphs of the spectral density of the runoff oscillations, etc.

### Table 2. Mean parameters of long-term runoff variations by lake and reservoirs regulated rivers.

| Runoff types | Parameter | a       | b       | c       | d       | e       | f       |
|--------------|-----------|---------|---------|---------|---------|---------|---------|
| Annual       | \( C_V \) | 0.29    | 0.60    | 0.40    | 0.37    | 0.27    | 0.27    |
|              | \( C_S \) | 0.40    | 1.13    | 0.67    | 0.62    | 0.31    | 0.40    |
|              | \( r_i \) | 0.23    | 0.30    | 0.26    | 0.15    | 0.67    | 0.85    |
|              | \( M \)   | 0.70    | 0.90    | 0.78    | 0.53    | 0.57    | 0.75    |
|              | \( C_V \) | 0.41    | 0.67    | 0.50    | 0.47    | 0.33    | 0.33    |
|              | \( C_S \) | 0.92    | 1.28    | 1.06    | 0.84    | 0.15    | 0.23    |
| Maximal      | \( r_i \) | 0.20    | 0.20    | 0.20    | 0.04    | 0.39    | 0.55    |
|              | \( M \)   | 0.79    | 0.80    | 0.80    | 0.45    | 0.38    | 0.40    |
|              | \( C_V \) | 0.43    | 0.95    | 0.61    | 0.47    | 0.35    | 0.37    |
|              | \( C_S \) | 0.59    | 1.62    | 1.03    | 0.76    | 0.38    | 0.40    |
| Minimal      | \( r_i \) | 0.40    | 0.42    | 0.40    | 0.30    | 0.92    | 0.91    |
|              | \( M \)   | 1.17    | 1.27    | 1.21    | 0.85    | 0.71    | 0.70    |

a – rivers regulated by hydropower reservoirs;
b – rivers regulated by irrigation reservoir;
c – all rivers regulated by reservoirs;
d – non-lake unregulated rivers, in the feeding of which the role of mountain glaciers is absent or insignificant;
e – rivers regulated by glacial lakes;
f – rivers regulated by tectonic lakes.

The differences in the coefficient of variation between the values of river runoff regulated by glacial and tectonic lakes are small. At the same time, the correlation between the annual and maximum runoff of the neighbouring years for «tectonic» rivers by \( \sim 0.1 \) (a significant value for this parameter) exceeds the analogous value for rivers flowing from lakes of glacial origin. This is due to the much larger volume of tectonic lakes. This also explains the fundamental difference between the average orders of the autoregressive models of the maximum runoff: 0.39 and 0.55, respectively. In other words, if the white noise model prevails in the description of long-term changes in the maximum flow of rivers flowing from glacial lakes, then the corresponding model for «tectonic» rivers is closer to the Markov-type model. For the series of annual and minimum runoff of both types of lake rivers, the model of a simple Markov chain – the first-order autoregression process – prevails.

### 3.3. On stationarity of long-term fluctuations of rivers regulated by reservoirs. The phenomenon of «intermittent nonstationarity»

The estimation of the degree of stationarity of the considered runoff series was calculated by the method mentioned above and given in detail in [1]. The calculation results showed that reservoirs
significantly (approximately 2 times) increase the percentage of nonstationary segments in the annual and maximum runoff series compared to the percentage of nonstationary segments in the runoff series of non-lake unregulated rivers, and also noticeably – by 42% – increase the percentage of nonstationary segments in the minimum runoff, bringing it to almost up to 1/4.

It is of interest how the parameters of the reservoirs themselves (first of all, the main parameter - the water exchange rate) affect the degree of non-stationarity of «monotonous» type in the runoff (a general increase or decrease in average runoff values covering the entire series of observations). The studies carried out indicate that an increase in the reservoirs’ DOR significantly increases the degree of non-stationarity in terms of the average values of the annual flow, to a lesser extent the maximum flow, and practically does not affect the degree of non-stationarity of the minimum runoff. With respect to the degree of non-stationarity in terms of standards and autocorrelation, a completely different pattern is observed. The corresponding $I_{SS}$ and $I_{SA}$ indices, which are close to single («stationary») values, variate insignificantly with changes in the degree of runoff regulation by reservoirs.

Similar calculations for lakes show that regulation by lakes significantly (approximately 3 times) increases the percentage of nonstationary segments in the annual and maximum runoff series compared to the percentage of nonstationary changes in the runoff of unregulated rivers, and also significantly increases the percentage of nonstationary series in the minimum runoff [15]. It is noteworthy that nonstationarity of different signs can be characteristic for the same series. In addition, the decrease in the value of the main parameter of lakes – the water exchange coefficient – significantly increases the degree of non-stationarity of long-term changes in the runoff of rivers regulated by them. The number of runoff series of lacustrine rivers, which are characterized by the alternation of segments of realizations of stationary random processes and nonstationary processes, significantly exceeds appropriate percentage in the series of unregulated rivers.

Thus, one of the most interesting results obtained was the discovery in the series of long-term changes in the annual, maximum and minimum runoff of rivers regulated by reservoirs and lakes, a new phenomenon, which we call «intermittent nonstationarity» of the runoff. The indicated phenomenon consists in the fact that within the variations in the runoff of these types of rivers, the segments of realizations of stationary random functions (with temporal scales corresponding to tens of years) can alternate with segments of realizations of nonstationary processes with different signs. Calculations have shown that the phenomenon of «intermittent nonstationarity» is most typical for the minimum runoff of regulated rivers.

It is noted that the phenomena of «monotonous» and «intermittent» nonstationarity are more common in the runoff of regulated rivers as compared to the runoff of unregulated rivers [14]. Apparently, the effect under consideration is generally associated with the presence of such large capacities of moisture as lakes, reservoirs, and underground horizons on the path of water flows.

**Conclusion**

1. The probability density of all the main parameters of reservoirs and flowing lakes in the world in the first approximation is satisfactorily described using a geometric distribution.

2. The effect of regulation of river runoff by reservoirs and lakes is reflected in the overall increase in the correlation of the runoff of neighbouring years (both annual, maximum, and minimum runoff) and in an increase in the order of the corresponding autoregressive models. Irrigation reservoirs and all reservoirs (in total), on average, increase the coefficients of variation and asymmetry of runoff. At the same time, a positive relationship is observed between the above parameters of the runoff variations and the «degree of regulation» by the reservoirs. Almost all analysed parameters of lake rivers’ runoff increase with an increase in the values of the water exchange factor.

3. Long-term changes in river runoff, regulated by reservoirs and lakes, are characterized by a significant number of series containing statically significant negative and positive trends of both «monotonous» and «intermittent» types. It is possible that the effect under consideration is generally
associated with the presence, within the river basins, of such large capacities of moisture as lakes, reservoirs, and underground layers.

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