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The norm of long-term changes in the total water supply in river basins

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Abstract
Building upon the extensive empirical materials collated from 418 global river basins with the zonal pattern of discharge formation, it has been established that the normal long-term changes in the total moisture reserves differ significantly from zero values, due to the effect of detection, and are not indicative of persistent processes of soil depletion or saturation.

Keywords: hydrology, change in the total water supply, norm, water balance

Introduction
The annual water balance in a closed river drainage, under excluded azonal factors of discharge formation, is described by an equation [1]:

$$X = Q + E \pm \Delta U \,, \qquad (1)$$

where, X is precipitation; Q – runoff; E – evaporation; ΔU – change in the total water supply in the river basin. In terms of hydrology, the norm of changes in water reserves $\mathrm{M}[\Delta U]$ is considered to be equal to zero, under long-term averaging. This assumption allows for calculating and mapping the long-term evaporation rates and linking them with maps of precipitation and river runoff by the water balance [1]. The *E* maps, both for Russia [2] and the entire Earth [3], are constructed on this basis.
The assumption $\mathrm{M}[\Delta U]$ = 0 is based on an absolutely speculative postulation that in the long-term run ΔU values change their sign in various years and their sum tends towards zero. However, no conclusive evidence in favor of this hypothesis was ever provided, as well as there is no current evidence of the opposite.

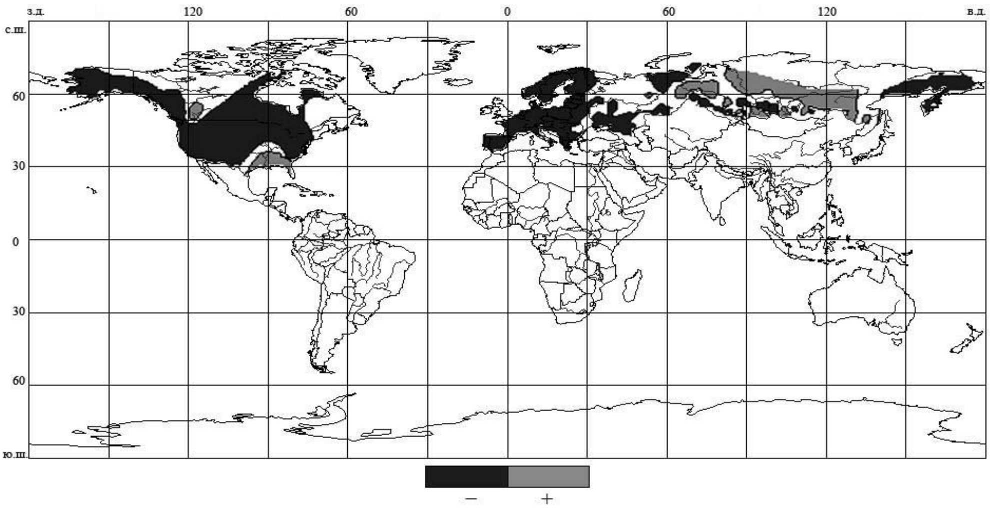
Materials and methods
To provide the empirical validation (or disproof) of this hypothesis, we refer to the well-known method (see, for instance, [1]) allowing us to evaluate the statistical significance of residual members in the balance equations $\sum_{i=1}^{n} x_i = 0$. If all members (in the primary view of a researcher) of the equation x_i are taken into account but a residual error ε_0 (residual term) appears, the error $\delta_0 = \sqrt{\sum_{i=1}^{n} \delta_i^2}$ (here, δ_i is the error of the *i*-th member of the sum) should be calculated. In case it does not exceed the value of the residual error, the latter is considered as «serious» and its physical origin should be discussed. Under the normal law of errors, it goes as follows: if $|\varepsilon_0| > \delta_0$, then ε_0 has 68.3 % confidence; if $|\varepsilon_0| > 2\delta_0$ – 95.4 %, and if $|\varepsilon_0| > 3\delta_0$ – 99.7 % (zones with statistically significant ε_0 values corresponding to $\mathrm{M}[\Delta U]$ are presented in the map below).
In our case, the role of such «residual» member is played by a normal value of $\pm \Delta U$ = $X - Q - E$. To make sure of its significance, evaporation should be evaluated independently of *X* and *Q*.

The standard guideline for drafting water balances [1] provides a comparative evaluation of the basic methods for determining evaporation from land surface. Moreover, semi-empirical calculations are preferable when building upon the mass-scale meteorological observations, in particular, by the widely accepted [1] method of A. P. Konstantinov. Following his recommendations [4], we can generate time series for annual evaporation by temperature *T* and air humidity *e* measured at hydrometeorological stations of the current network. The practical use of these recommendations is based on the nomogram in coordinates $E = f(T, e)$, as demonstrated in the article [4].

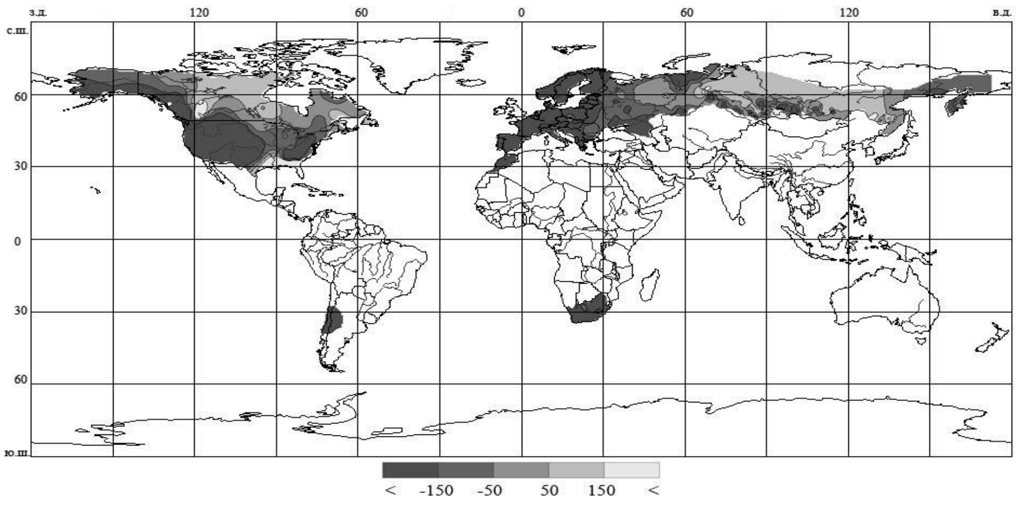
By applying this methodology, we have defined the $\mathrm{M}[\Delta U]$ values for 418 global river basins (of those, 252 in Russia), where the range of *T* and *e* changes remained within the valid limits of Konstantinov's nomogram (zones with the extreme values located in the North of Eastern Siberia, in Africa, Latin America, Southwest Asia, and Australia were excluded from evaluation). Information on hydrometeorological elements was retrieved from the Internet-resources (http://www.esrl.noaa.gov/psd/data.html; http://www.rivdis.sr.unh.edu). We have considered the watersheds of reasonably large rivers with a zonal pattern of the long-term runoff formation.

Fig. 1*a* presents a map of the geographical distribution of ± $\mathrm{M}[\Delta U]$ values corresponding to the 68.3 % confidence level, i.e., when $|\mathrm{M}[\Delta U]| > \delta_0$, under the error values of the norms in components of the water balance equation being 1.5 times greater than those accepted in hydrology: precipitation – 7.5 %, runoff – 7.5 %, evaporation – 22.5. With higher confidence probabilities (95.4 %; 99.7 %), these maps take a more mottled (patchy) form, due to the disappearing (become statistically insignificant) areas, where $|\mathrm{M}[\Delta U]| < 2\delta_0$ (at 95.4 %) and $|\mathrm{M}[\Delta U]| < 3\delta_0$ (99.7 %). The map in Fig. 1*b* is presented in $\mathrm{M}[\Delta U]$ gradations. White-colored areas on the map refer to the territories with lacking computations (for the above mentioned reasons) or to those where $\mathrm{M}[\Delta U]$ values can be considered (at a certain level of statistical significance) as almost zero (about 50 % of the whole territory). For instance, it is evident that Russia is characterized by the predominance of negative norms in the European part (with the Western moisture transport) and in the Eastern zone of the Pacific influence. The $|\mathrm{M}[\Delta U]|$ numerical values are generally below the long-term norms of other components in the water balance equation of river drainages but allow for mapping and identifying the geographical patterns, as reflected partly in Fig. 1.

(*a*)



(*b*)



(c)

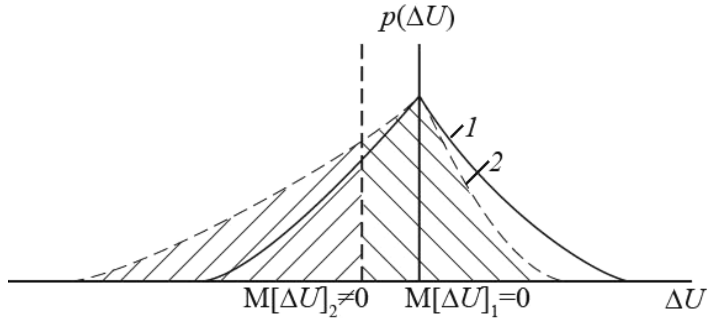


Fig 1: The distribution of statistically significant values of a multi-year rate of change in the total water supply in the river basin (black color M[Δ*U*] < 0, grey color M[Δ*U*] > 0 (*a*); distribution map, built in gradation values M[Δ*U*] (*b*), and illustration of the effect of the detection at nonzero correlation "external" (N') and "internal" (c') noise: *1* – at $G_{c'N'}$ = 0; *2* – at $G_{c'N'}$ ≠ 0 (*c*).

The Konstantinov's method (which leads to the obtained results) is not the only one to determine evaporation. Another method suggested by Academician M. I. Budyko [5, 6] (fractional standard error of 17 %) that synthesizes the two methods (Schreiber's and E. M. Oldekop's) is based on equations linking the annual totals of evaporation and precipitation. Dependence proposed by Budyko has the form:

$$E = \sqrt{E_0 \operatorname{th} \frac{X}{E_0} X[1-\exp(-E_0/X)]}, \qquad (2)$$

where, E_0 – is evaporation calculated as $R/\rho l$ (here *R* is the radiation balance; ρ and *l* – water density and specific heat of evaporation; the average annual values of *R* are mapped).

There is also the Turk's method [1] (and the identical method developed by V. S. Mezentsev [1, 7]) based on the formula

$$E = X\left[A + \left(\frac{X}{E_0}\right)^n\right]^{-1/n}, \qquad (3)$$

where, *A* is 0.9, on the average; *n* = 2, and E_0 is calculated by the relationship with the annual temperature.

Application of these methods when calculating the residual term in the water balance equation leads to a significant reduction of its statistical significance and this fact can be explained. Methods proposed by Budyko and Turk stem from the constraint equation derived from the balance relationship *Q* = *X* – *E* (i.e., assuming a priori that the long-term change in water supply is zero). It is further assumed that $dQ/dX = 1 - dE/dX = (E/E_0)^n$ (see p. 221 [1]) and both Schreiber–Oldekop and Turk–Mezentsev formulas are generated via formal transformations. If we write the balance equation with regard to the changes in water supply (±Δ*U*) *X* = *Q* + *E* ± Δ*U*, the value of ($X \mp \Delta U$) will appear in equations (2) and (3) (see formula 8.54, p. 221 of the guidelines [1]). The maps presented in this research article suggest that such entry format is valid for both the (intra-)annual interval(s) and the long-term period. However, formulas (2) and (3) "disallow" this. If the Konstantinov's method is created irrespective of the balance relationships and its temperature and humidity values refer to evaporation only, the constraint formulas (2) and (3) will actually evaluate the sum of $\overline{E} \pm \overline{\Delta U}$, rather than evaporation. This sum can be taken as evaporation only upon the assumption that $\pm\overline{\Delta U} = 0$.

Theoretical rationale of the findings

The question naturally arises – what is the nature of this phenomenon, the nonzero norm of long-term changes in the total water supply in river basins? As demonstrated in the research articles [8, 9], the fractal dimension of the annual long-term runoff series in the temperate zone often lies within the range of 2 – 3, i.e., all three phase variables included in the right part of the formula (1) contribute to the runoff formation and the model of evolution of probability density $p(Q, E, \Delta U)$ does not necessarily imply that $\mathrm{M}[\Delta U]$ = 0. This can be shown just on the example of a stochastic equation for only one of the phase variables ΔU:

$$d(\Delta U) = \{[-(\mathrm{M}[c] + c')\operatorname{sgn}(\Delta U) + \mathrm{M}[N] + N']/\tau_{\Delta U}\}dt, \qquad (4)$$

where, $N = X - Q - E$; *c* is a parameter that characterizes the saturation rate (or water loss) of the river basin; $\tau_{\Delta U}$ – the relaxation rate of the basin capacity; $\mathbf{sgn}(\Delta U)$ – sign function; $\mathrm{M}[N]$, $\mathrm{M}[c]$ – expectations; N' and c' – white noise with $G_{c'}$, $G_{N'}$ intensities and interrelated intensity $G_{c'N'}$ (henceforth we assume $\tau_{\Delta U} = 1$ without sacrificing the generality of conclusions).

The equation of similar structural type describes a relay servo system that was studied comprehensively and in different versions by Academician V. S. Pugachev and his research fellows (see, for example, [10]). Building on their findings, we will demonstrate the possible occurrence of nonzero value for the long-term averaged ΔU. Let $\mathrm{M}[N]$ = 0, against the non-zero noise intensity

($G_{N'} \neq 0,\ G_{c'} \neq 0,\ G_{c'N'} \neq 0$).

By performing a standard transition procedure from the stochastic differential equation (in our case, (4)) to the statistically equivalent Fokker–Planck–Kolmogorov equation, we obtain the stationary probability density expression:

$$p(\Delta U) = k \exp\left\{ -\frac{2\mathrm{M}[c]|\Delta U|}{G_{c'} - 2G_{c'N'}\mathrm{sgn}\Delta U + G_{N'}} + \frac{G_{c'N'}\mathrm{sgn}\Delta U}{G_{c'} + G_{N'}} \right\}, \quad (5)$$

where, k is a normalizing factor per unit of the integral of probability density.

If $G_{c'N'} = 0$, the $p(\Delta U)$ distribution is symmetric. When $G_{c'N'} \neq 0$, it gets skewed; the sign of asymmetry depends on either positive or negative correlation of additive (N') and multiplicative (c') noises. The emergence of $\mathrm{M}[\Delta U]_2 \neq 0$ at zero expectation of the input $\mathrm{M}[N]$ effect (but with an interaction of the «external» N' and «internal» c' noises) is called the effect of detection (Fig. 1c).

Synthesis and discussion of results

Fig. 2 presents a typical example of chronological course of hydrometeorological elements and their histograms. Analysis of similar figures drawn for 252 river basins in Russia provides certain generalizations: 1) histograms of water supply change can be bimodal, while the norm is always single; 2) evaporation histograms often have negative skewness, as compared with consumption histograms; 3) approximately 25–30 % of graphs of water supply change are placed entirely either in the negative or in the positive areas.

The first case can be explained by hysteresis effects and is partly addressed in the article [11]. The negative skew in evaporation series is due to the same detection effect; however this phenomenon has not yet been studied comprehensively in physiography (the same as with the runoff series). The most intriguing situation is presented by the third generalization. Given that the value of $\pm\Delta U$ is a time-dependant derivative of the water supply volume, location of a chronological graph $\Delta U(t)$ in the same area, e.g., in the negative, does not indicate the process of water supply depletion. According to the differential calculus, the derivative of a function with zero average value does not necessarily have an average of zero. This thesis is visualized in Fig. 3.

(*a*) (*b*)

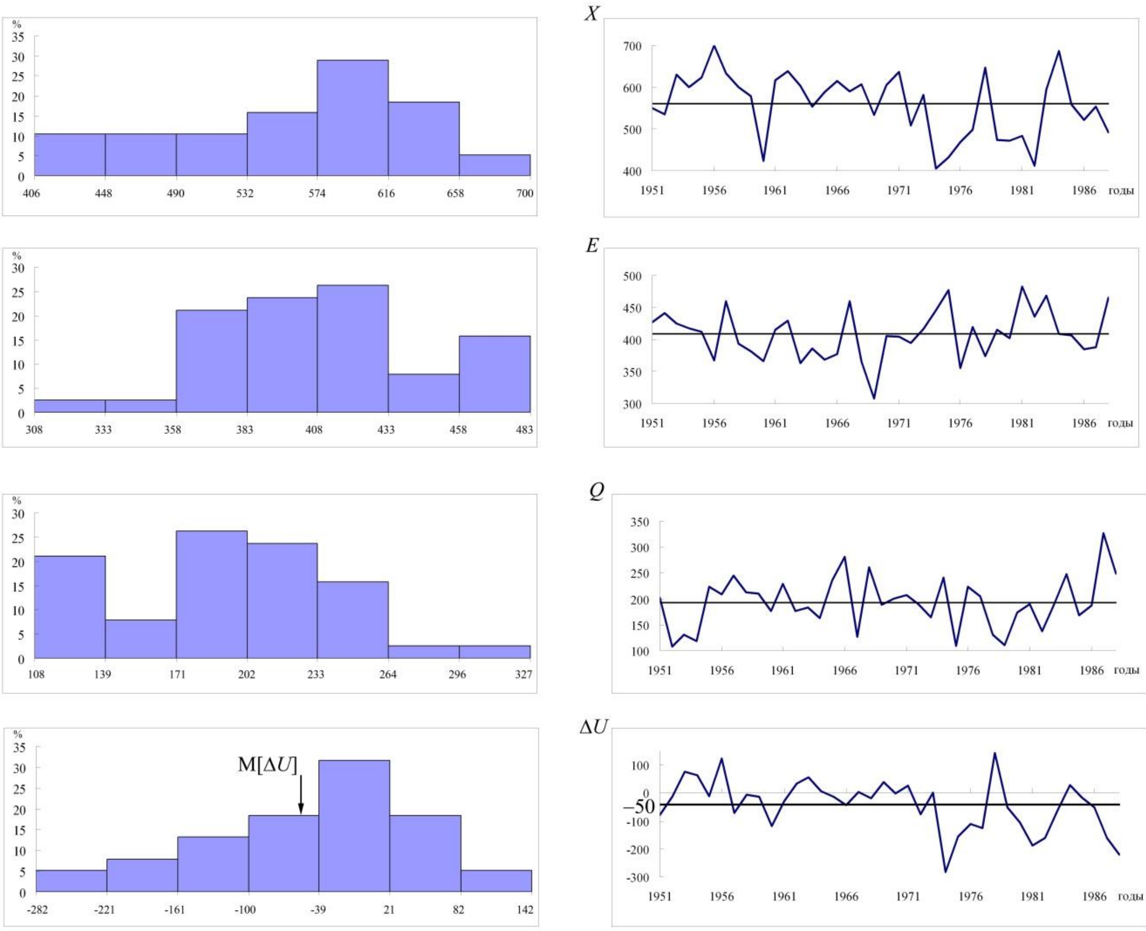


Fig 2: Histograms (*a*) and chronological course hydrometeorological elements in mm (*b*) (river Cheptsa – station Polom).

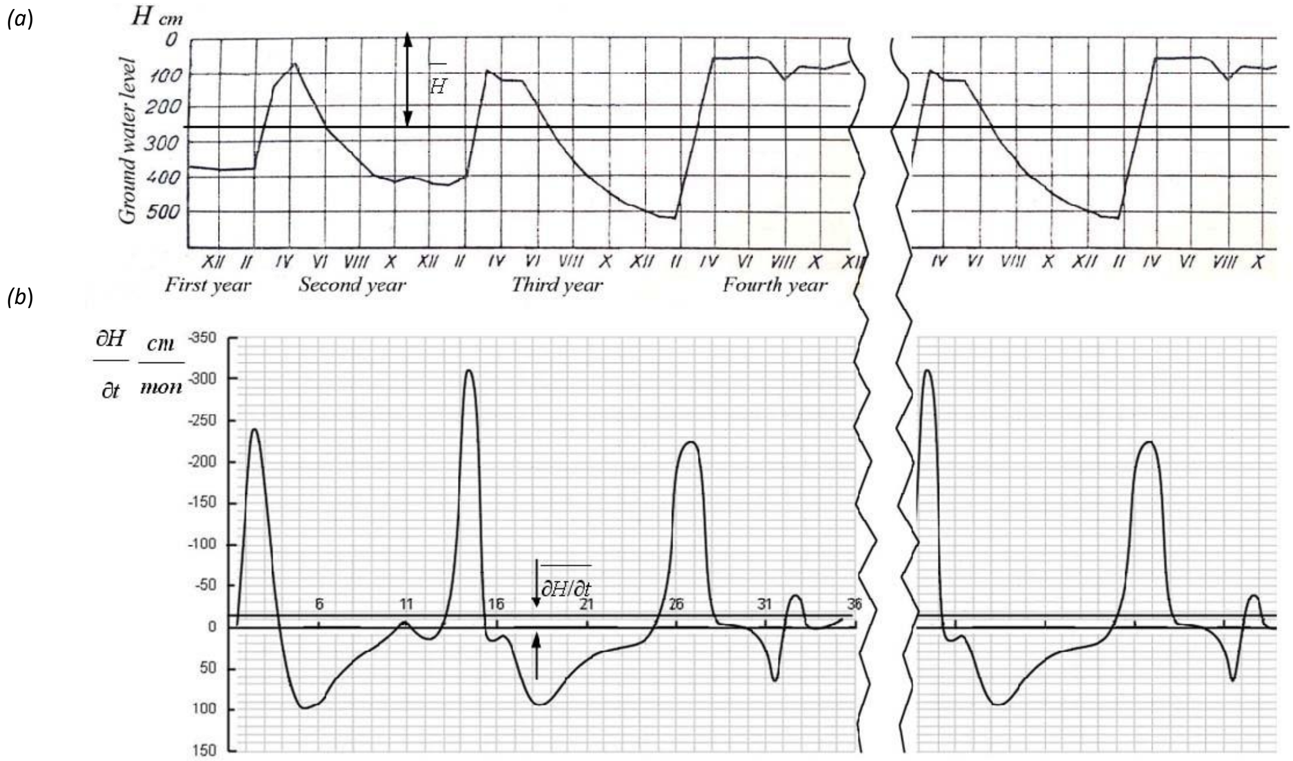


Fig 3: The occurrence of the nonzero average value of the derivative ($\overline{\partial H / \partial t}$) of function, not having a long-term trend (*H*) (fig. *a* according to [12]).

The groundwater level *H* characterizes the major component of the total water supply in a river basin *W*, i.e., *W* = *f*(*H*). Its long-term average value $\overline{H}$ can remain constant (no trends towards aridization/humidification, Fig. 3*a*) and the long-term average value of its time-dependent derivative ($\overline{\partial H / \partial t}$) is not zero (Fig. 3*b*). Note that $\partial H / \partial t \sim \partial W / \partial t \sim \Delta U$. According to Fig. 1, the sign of $\mathrm{M}[\Delta U]$ is determined by geographical conditions in the respective location of river basins. Positive values are observed mainly in the regions with permafrost formations (Siberia), whereas the negative – in the regions with regular moderate freezing of the earth's crust (Europe, part of North America), with a relatively significant thickness of the active layer participating in the water exchange processes (see map in Fig. 107, pp. 282, 283 in the guidelines [13]).

Conclusions

Thus, a previously unknown phenomenon – a nonzero norm of long-term changes in the total water supply in the soil of river basins – has been discovered by our studies. This phenomenon implies that under nonzero interaction the intensity of moisture inflow (outflow) into/out of a watershed and saturation (emptying) of soil, a non-zero value of the average annual values of water supply changes occurs, as determined by a systematic shift of the average value respective to the mode of probability density distribution of water supplies [14].

One of the obvious applications of the discovered phenomenon is the adjustment of maps of the long-term average evaporation in the areas, where the norm of water supply change is significantly different from zero.

Acknowledgments

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