Spatiotemporal Trends in Changes in the River Water Contents in the Sakha Republic (Yakutia)

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Abstract. Studies of long-term fluctuations of the river flow are of interest with regard to causal relationships and associations between the climate changes and water regimen of the rivers. It is important to minimize the negative effects associated with fluctuations in the river flow based on long-term predictions of the water contents. Long-term and very long-term predictions of the water contents require understanding of the nature of the long-term changes in the water contents of the rivers. Investigation of the spatial trends in changes in the river water contents is important. It was established that there was an increasing straight-line trend of change in water content for the majority of the rivers on the territory of the Republic of Sakha (Yakutia) during the period from 1964 till 2015. Mapping of the slope factor of the linear trends allowed to determine the main regularities of the spatial breakdown of the type of perennial change in river flows. Besides, smoothing of the time series of the river flow by the method of 20‒year sliding linear trend in a span of twenty years allowed to establish the types of perennial change in water content for each water body with further zoning.

1. Introduction

Specific negative consequences of fluctuations of the water contents of the rivers include disruption of normal river transport and other economic and industrial activities associated with the use of aqueous resources. Overfilling of the rivers can cause dangerous (or even disastrous) flooding that cannot be efficiently prevented even with the use of modern technology [1]. Northern regions have low population density; however, river basins of the Northern regions are “typical subjects of human environmental activities. Most likely, this will continue in the future” [2]. Thus, it is important to minimize the negative effects associated with fluctuations in the river flow based on long-term predictions of the water contents. The hydrological regime investigated in the region was studied in the works [3-9]. The water content of almost all rivers in Yakutia has increased in the last 30 years (approximately), thus confirming general assumptions based on predictive models of climate changes; however, in most cases, such changes were the result of reaching the high-water stage of established
long-term cycles [10]. When working on the study, the authors relied on the works of scientists who studied water content in other regions of the world [11-16].

Investigation of the spatial trends in changes in the river water contents is important; one of the avenues for this type of studies involves hydrological zoning and specific territorial zoning based on synchronous fluctuations of the flow. The zoning is involved in “the solutions of the numerous scientific and practical hydrological problems associated with complex use of water resources in planning and design of the large energy- and water industry-related systems” [2].

This study attempts to identify certain trends in perennial changes in the water contents and to determine the regions of synchronous (inphase) fluctuations of the trends in Yakutia, one of the largest regions of Russian Federation (figure 1).

Figure 1. Schematic map of distribution of the slopes of the linear trends characterizing an increase in the water contents of the rivers in the Sakha Republic (Yakutia).
Synchronous fluctuations of the river flow in Yakutia have been studied previously. One of the most recent investigations by M.V. Bolgov and E.A. Korobkina was performed in the context of a study of synchronous fluctuations of the river flow in Siberia and Far East [17]. However, a substantial volume of additional data has accumulated after the publication thus yielding a larger dataset that may enable certain generalizations and should enhance the reliability of statistical evaluation.

Moreover, the present study attempts to formulate a zoning classification based on synchronous fluctuations of the trends in changes in the water contents that is not based on synchronous fluctuations of the river water contents.

The present study analyses long-term flow fluctuations by detecting a linear trend with preliminary smoothing of the values via a moving average.

Trend analysis is frequently criticized in scientific publications because specific types of trend depend on selection of the initial and final points and duration of the observation period. However, these or similar drawbacks are characteristic for essentially any method of analysis of temporal sequences of the hydrological parameters.

2. Materials and methods
The data on annual flow were obtained from 18 hydrological outposts of the observation network of the Office of Hydrometeorology and Environmental Monitoring of Yakutia. The following data were not considered: (a) observation outposts within the middle and lower regions of the largest transregional rivers, Lena and Aldan, because the flow of these rivers does not correspond to zonal specifics and represents huge watersheds; the changes in the water flow of these two river represent a complex interference of changes in the flow of the tributaries located over a huge distances away from the regions of the observation; (b) observation outposts on small rivers and waterways because random and specific local factors influence the flow. The study shows the change in the slope of the water surface and the rate of increase and decrease of the water level at the analyzed hydrometric stations [18]. The results of the flow observations from 1964 to 2015 were used in the calculations. This timeframe corresponds to the beginning of the observations in the following outposts: Anabar River (Saskylakh village), Olenyok River (7.5 km to the south of the junction with Buur River), and Alazy River (Argakhtakh village). We decided to include these observations aiming to perform the complete analysis of the spatial trends in the water contents of Yakutia rivers. Thus, all observation outposts have the same data set size thus enabling their direct comparison. A small number of cases of missing data for some years were restored by linear regression imputations based on the results obtained at the adjacent outposts or in similar rivers. Annual data on the mean annual water flow within the observation period of the study were reformatted as the modular flow coefficients and the values were smoothed using a 5-year moving average; the normalized arrays were used to calculate the linear trends. Preliminary smoothing was performed in order to exclude the effects of the random factors. Moving average interval of 5 years is usually used as a first choice for smoothing of the temporal flow arrays. The protocol yields satisfactory results of territorial generalization of the trends in changes in the flow (see below) and thus, no additional averaging intervals were tested.

The trends were identified by the least square method; the slopes of the linear trends were used as the main parameter for assessment of the changes in the water contents. Significance of the trends was determined by the Fisher’s and Student’s tests. Initial temporal arrays were divided into two arrays based on the number of the elements (24); each of these subarrays was treated as a separate dataset with normal distribution. Presence of a trend was established based on a hypothesis that the means of two normally distributed datasets are equal. If a trend is present, the means of the subarrays should be significantly different. Fisher’s test was used to determine the differences in the variances between two subarrays. Then, if the variances are equal, two-tailed Student’s homoscedastic t-test was used to compare the means (12 cases) and if the variances are not equal, two-tailed Student’s heteroscedastic t-test was used to compare the means (6 cases). Comparison of the calculated t-test values with the critical values indicates whether the trends are statistically significant; in 14 cases out of 18, the calculated t-test values exceeded the critical values at 5% significance level.
Moreover, significance of the trends was verified with the phase frequency Wallis-Moore test. The test can discriminate the dynamic arrays with trends from the random sequences. The trend is present if the calculated values of the test exceed the critical values at 5% significance level (all tested cases).

Additionally, we have evaluated statistical significance of the slopes of the linear trends $a_1$ using Student’s $t$-test; in this case, the ratio of the $a_1$ parameter to the standard error of estimation of $a_1$ was used. If calculated values of the ratio exceed the tabulated values, the slope values are considered statistically significant. The slopes of the linear trends were statistically significant because the calculated values exceeded the critical $t$-test values (2.013 at df=46 and $\alpha=0.05$) in 14 cases out of 18 total cases. In addition to the evaluation of the general trends in changes in the water contents within the observation period, we have analyzed the changes in the trends in the water contents. The moving 20-year linear trend window was used according to recommendations of A.A. Lyubashin et al. [19]. According to the description of the method, the length of the temporal window should be approximately one third of the length of the analyzed temporal sequences and should ideally be sufficiently long to permit evaluation of the global climate factors, e.g., 11-year periods of solar activity. Temporal window of 20 years was used to partially meet both requirements; unfortunately, the length cannot be increased due to relatively short duration of the observation period.

3. Discussion of results
During the observation period, an increasing linear trend was observed in all water bodies of the Sakha Republic (Yakutia) indicating that the average water contents tend to increase. The mean linear trend slope of the total sequence array was 0.006. The slope varied from 0.001 (Uchur River, Maya River) to 0.016 (Alazeya River, Chara River). The slope values indicate that the river water contents in Yakutia have been increased during the observation period by an average of 28.2%; minimal increase was 4.7% and maximal increase was 75.2%. Mapping of the linear trend slopes of an increase in the water contents revealed certain trends in the territorial distribution of the intensity of the increase (figure 1). The territory covered by the study included two core regions characterized by the most pronounced increase in the water contents within the observation period: the most northeastern zone including the Alazeya River basin and the southwestern zone including the Chara River basin. Intensity of an increase in the water contents of these water bodies was assessed based on the linear trend slope and the intensity reached 0.016. A decreased in the slope of the trend was detected at a certain distance away from these core regions. The directions of the decrease were to the west, southwest, and south from the northeastern core and to the north, northeast, and east from the southwestern core. Thus, a decrease in the intensity of an increase in the water contents involved longitudinal and latitudinal directions towards the central part of Yakutia. Linear trend slopes in the regions directly adjacent to the river basin cores varied from 0.011 to 0.013 (Adycha River to the northeast; Nyuya River to the southwest). The slope values varied from 0.001 to 0.005 in the case of the rivers of the southwestern parts of the Sakha Republic (Anabar, Olenyok, and Markha) and the rivers of the southern and southeastern parts (Olekma, Timpton, Uchur, and Maya).

Such area-specific pattern of an increase in the water contents is in general agreement with the spatial distribution of the linear trend slopes of the changes in the long-term precipitation as reported for the 1976-2016 period according to an estimate of the Institute of Global Climate and Ecology or Russian Meteorological Agency and Russian Academy of Sciences [20]. Significant increase in the slope of the linear trend of the water contents was more pronounced in certain specific water bodies than in other bodies apparently due to a number of high water years (including several super high water years) starting from the end of 1990s. During that period, water contents of these specific rivers occasionally dropped down to the normal levels while in the majority of the years, the water levels reached 1.5-2.5 times their long-term average levels.

The double smoothing method (moving average and moving trend) used in the current study enables to estimate synchronous (or asynchronous) changes in the water contents in various rivers. Visual analysis of the plots of the long-term dynamics of the slopes of the moving 20-year trends revealed several types of the dynamics (figure 2).
Each dynamic type is specific for certain water bodies located within a certain geographical region thus enabling the zoning of the whole Yakutia based on the changes in the water content trends:

- Region I (figure 2a); northwestern part of the Sakha Republic (Yakutia) including the basins of Olenyok, Anabar, and Markha Rivers, upstream of Vilyui River and northern part of the watershed area of the Vilyui Dam Reservoir;
- Region II (figure 2b); southwestern part of the Sakha Republic (Yakutia) including southern part of the watershed of the Vilyui Dam Reservoir and the Nyuya River basin;
- Region III (figure 2c); south of Yakutia including the upstream regions of the Aldan and Amga Rivers and the basins of the Chara, Timpton, and Uchur Rivers; Region IV (figure 2d); north and a part of northeast of the Sakha Republic (Yakutia) including the basins of Yana and Alazeya Rivers; Region V (figure 2e); northeast of the Sakha Republic (Yakutia) including the basin of Kolyma River and the upstream region of Indigirka River.

The basins of Olekma and Maya Rivers cannot be assigned to any of these regions based on their changes in the water content trends and should not be considered as separate classification groups because of the geography of their basins since the majority of the basins is outside of the administrative borders of the Sakha Republic (Yakutia).

It should be noted that the classified regions with similar changes in the trends in the water contents essentially coincide with the regions of synchronous flow fluctuations, as described in a previous study of M.V. Bolgov and E.A. Korobkina, established based on the hydrometeorological characteristics and zone classification by the cluster analysis. There are a number of differences: Region III includes the water subjects as described for region 19 according to [17] and additionally includes the basin of Uchur River; Region IV is similar to region 22 according to [17] and additionally includes the basin of Alazeya River. Interestingly, the regional borders expand in the longitudinal direction in both cases. Moreover, we have identified Region I as a separate entity that was absent.
from [17] apparently due to insufficient number of observations at the time of that previous study in certain outposts in northwestern Yakutia. Synchronous flow fluctuations and homogenous changes in the water content trends are different characteristics; however, they both reflect the same natural process visible on the temporal graph as the temporal synchronous fluctuations in the water contents.

The graphs of the changes in the trends of the water contents reveal certain general features of the changes.

In Region I (figure 2a), a single wave of changes in the water content trends was observed during the investigated period that includes essentially complete phases of rises and falls of the water contents. Starting from the beginning of the observation period, the water contents were continuously increased and this increase accelerated up to 1995–1996; then, intensity of an increase in the water contents began to slow down and starting from 2000s and up until the present time, the water contents of the regional rivers have been consistently decreasing. The variations in the slope of the moving linear trend fluctuations during the observation period are quite noticeable (from -0.030 to +0.030).

In Region II (figure 2b), an increase in the water contents has slowed down at the start of the observation period and was followed by a decrease is the water contents from 1993–1997 which was in turn followed by a variable increase in the water contents from 1995 up until the present time. At the end of the observation period, an increase in the water contents becomes significantly weaker and approaches zero. The slope changes in the moving linear trends vary from -0.005 to +0.030.

In Region III (figure 2c), essentially complete oscillation period includes two phases, a negative phase and a positive phase. Negative phase lasted from the start of the observation period to the end of 1990s and the positive phase started from the end of 1990s and continues to the present. Direction of the plot suggests that a negative phase in the water level trend fluctuations is likely to happen in the next several years. Slopes of the moving linear trends in various rivers of Region III varied from -0.02 to 0.02.

In Region IV (figure 2d), changes in the trends in the water contents include three stages; start of the observation period coincided with a transition from a decrease in the water contents to a growth that continued for the whole period of observation with variable intensity. The slope fluctuations of the moving linear trends are considerably variable.

Graph of the changes in the slope of the moving linear trends in Region V (figure 2e) is essentially similar to that in Region II; it should be noted that the rivers of these two regions were not combined into a single region only because of considerable distance between these regions.

4. Conclusion
1. During the observation period from 1964 to 2015, the water contents tend to increase in the rivers of the Sakha Republic (Yakutia). Average increase in the water contents was 28.3%. This trend had a heterogeneous zoning distribution. Two cores of the most substantial water content increase can be identified within Yakutia including the Alazea River basin in the northeast and the Chara River basin in the southwest (slope of linear trend was 0.016; water content increase was 75.2%). Intensity of the water content increase was lowered in the longitudinal and latitudinal directions away from these cores towards the central part of Yakutia (slopes of the linear trends varied from 0.001 to 0.003; increase in the water contents varied from 4.7% to 14.1%).

2. Five regions of the homogenous changes in the water content trends were identified; these regions have significant overlap with the region of synchronous fluctuations of the water flow established based on the characteristic classification of the hydrometeorological zones by cluster analysis [17]. Thus, zoning of the homogenous fluctuations of the flow in Yakutia [17] is sufficiently accurate and is confirmed by an independent method of analysis. Zoning suggested in [17] is supplemented with an additional region that includes the river basins of the northwestern Yakutia.

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