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Dynamic Nature of Hydrological Similarity

O. Serova
Hydrological fuculty
Russian State
Hydrometeorological University
St. Petersburg, Russia
olgaserova1995@gmail.com

L. Timofeeva
Hydrological fuculty
Russian State
Hydrometeorological University
St. Petersburg, Russia
tilarisa@gmail.com

N. Reshin
Hydrological fuculty
Russian State
Hydrometeorological University
St. Petersburg, Russia
reshinn@yandex.ru

D. Abramov
St. Petersburg
State University
St. Petersburg, Russia
dmbrmv96@gmail.com

Abstract—Nowadays, there is a growing interest in understanding how water bodies and their catchments react to environment, landscape and climate change. Runoff change is an integral indicator of climate and landscape changes. Similar landscapes form a similar hydrological catchment response to precipitation.

The algorithm for identification of homogeneous groups of catchments (in terms of hydrometeorology) has been developed and tested. The 26 catchments studied are situated in the south-eastern part of the Baltic Sea Basin. Observational data from 1986 to 2016 were used for cluster analysis. Catchments clustering over three consecutive ten-year periods has shown some variability in the clusters content due to changes in the hydrological response of the study catchments. The results obtained were analyzed based on both hydrogrometeorological and landscape characteristics.

Keywords—clustering, landscape-hydrological similarity, runoff characteristics.

I. Introduction

Hydrological similarity is not constant, neither are the factors that determine it (stream flow, genesis, landscapes, forest, bog, lake coverage). Under the climate stationarity, the hydrological response can show the landscape changes occurring within catchments, which cannot be identified using the open accessible landscape information in Russia, since it was mainly obtained about 50 years ago and is out of date.

Reliable assessing landscape-hydrological changes over relatively short periods using averaged data is not possible. Therefore, to study intra-annual and inter-annual flow dynamics, daily runoff data for 1986-2015 were used for 26 river catchments in the geologically homogeneous south-eastern part of the Baltic Sea basin.

Creation of such a large database is extremely time and effort consuming. Thanks to modern technologies for processing large data series, it has become possible to carry out broad landscape-hydrological research effectively.

Initially, such studies were carried out in the United States in 2014 [1] and covered the entire country. Based on this experience, the authors have attempted to develop a methodology that would take into account the availability of hydrometeorological data in Russia. The basis of the method is the k-means cluster analysis. Using daily runoff data, four signatures for clustering were calculated. Clustering was carried out in STATISTICA. The ten-year time period was assumed to be long enough to capture climatic variability, but short enough to not be affected by climatic trends.

Clustering results have shown that the content of the three formed clusters does not remain constant, which may be an indicator of the dynamic nature of hydrological similarity.

II. Data and methods

A. Data

Daily runoff data from 1986 to 2007 were digitized from paper-based sources [2]. Since 2008, the data have been available on the website of the Automated Information System of Water Bodies State Monitoring [3]. Gaps in the data series are not more than 5%.

Annual precipitation amounts and average annual temperatures were obtained from the digital archive of the All-Russian Scientific Research Institute of Hydrometeorological Information [4]. Six weather stations were analyzed: Belogorka, Tikhvin, Staraya Russa, Velikiye Luki, Pushkinskiye Gory, Pskov. The analysis has shown the absence of significant trends in annual precipitation over the study period (Fig. 1). However, due to the increase in temperature, the wetness of the territory, estimated by the De-Marton index of aridity index (the ratio of the annual precipitation to the average annual temperature), decreases (Fig. 2).

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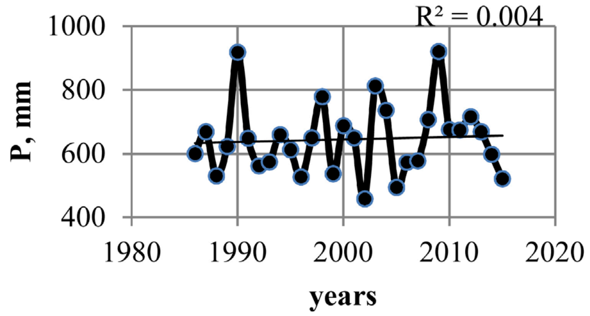

Fig. 1. The long-term course of annual precipitation, Staraya Russa

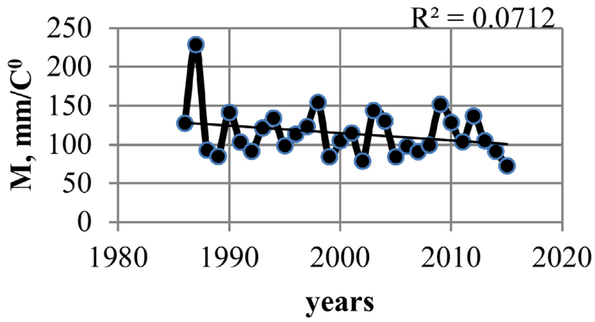

Fig. 2. The long-term course of the DeMarton index, Staraya Russa

Landscape characteristics were used for clustering results analysis: lake coverage (f_{lake}), bog coverage (f_{bog}), forest coverage (f_{forest}), average catchment height (h_{catch}), average catchment slope (I_{catch}). The values of these signatures were obtained from reference books [5].

Clustering signatures

Based on the daily runoff and precipitation observation data, for the three decade periods (1986–1995, 1996–2005, 2006–2015), four signatures were calculated for calendar years.

The complete list of signatures used in this study is the following:

1. Runoff ratio (R, [-]) – the ratio of the average runoff layer (mm) to the amount of precipitations (mm) over the catchment. It was calculated for each catchment for each ten-year period. To better considering the precipitation irregularity over the territory, hydrological posts were referred to the nearest meteorological station.

2. Slope of the Flow Duration Curve (S, [-]) – the slope between the 66% and the 33% flow exceedance percentiles, which is an indicator of streamflow variability [6]. A low value of this coefficient may indicate the prevalence of rain and / or underground feeding of rivers. The signature is defined as,

$$S = \frac{ln(Q33\%) \quad ln(Q66\%)}{(0.66 \quad 0.33)} \quad , \qquad (1)$$

where S – the slope of the flow duration curve, $Q_{33\%}$ – the 33rd streamflow percentile, $Q_{66\%}$ – the 66th streamflow percentile.

3. 10th percentile –10 % streamflow ($H_{10\%}$, [mm]), indicator of high flows.

4. 90th percentile – 90 % streamflow ($H_{90\%}$, [mm]), indicator of very low flows.

Thus, for each catchment, sets of the above signatures were designed for 30 years. To be used for clustering, each signature must provide independent information (Table 1).

TABLE I. Linear correlation values for four signatures used in this study, 1986-1995

	$H_{10\%}$	$H_{90\%}$	S	R
$H_{10\%}$	1	0.66	-0.09	-0.22
$H_{90\%}$	0.66	1	-0.52	0.03
S	-0.09	-0.52	1	-0.47
R	-0.22	0.03	-0.47	1

B. Clustering

K-means method is a cluster analysis method that allows *partition* n observations into k clusters, in which each observation belongs to the cluster with the nearest mean. The Euclidean distance is the proximity measure. The method has gained great popularity due to its simplicity, clarity of implementation, and rather high quality results [7].

After a preliminary generalized analysis of signatures, it was decided to allocate the catchments into three clusters. For each catchment, coefficients of their natural over-regulation were calculated. (Ω), but they were not used during clustering, due to their high correlation with other characteristics. The analysis and results interpretation were carried out taking into account the landscape characteristics of the catchments, based on the landscape-hydrological approach.

III. Results interpretation

As a result, the catchments in Cluster 1 are considered lowlands: their average height is 84 m (Table 2). They have low forest coverage (46%) and high bog coverage (10%). These catchments do not have sufficient natural over-regulation and it first decreases but then increases in the third period. Compared with the catchments in Cluster 3 (Table 4), the catchments in Cluster 1 have insignificant slopes and, as a result, lower runoff coefficients.

TABLE II. AVERAGE VALUES OF SIGNATURES AND LANDSCAPE CHARACTERISTICS, CLUSTER 1

Year	$H_{10\%}$, mm	$H_{90\%}$, mm	S	R	f_{lake}, %	f_{bog}, %	f_{forest}, %	h_{catch}, m	I_{catch}, ‰	Ω
1986-1995	6680	373	0.034	0.35	1.53	9.96	46.3	87	6.68	0.54
1996-2005	5970	343	0.039	0.34	0.79	10	46.2	80	5.8	0.48
2006-2015	4970	262	0.038	0.3	1.33	9.63	45	85	8.38	0.51
Mean	5873	326	0.037	0.33	1.22	9.86	45.8	84	6.95	0.51

TABLE III. AVERAGE VALUES OF SIGNATURES AND LANDSCAPE CHARACTERISTICS, CLUSTER 2

Year	$H_{10\%}$, mm	$H_{90\%}$, mm	S	R	f_{lake}, %	f_{bog}, %	f_{forest}, %	h_{catch}, m	I_{catch}, ‰	Ω
1986-1995	9139	235	0.043	0.47	1	3	41.3	104	4.5	0.49
1996-2005	5095	503	0.027	0.32	3.13	4.83	45.6	123	14.2	0.6
2006-2015	7395	1770	0.015	0.56	2.12	7.37	67.2	158	23.1	0.73
Mean	7210	836	0.028	0.45	2.08	5.07	51.4	128	13.9	0.61

TABLE IV. AVERAGE VALUES OF SIGNATURES AND LANDSCAPE CHARACTERISTICS, CLUSTER 3

Year	$H_{10\%}$, mm	$H_{90\%}$, mm	S	R	f_{lake}, %	f_{bog}, %	f_{forest}, %	h_{catch}, m	I_{catch}, ‰	Ω
1986-1995	7996	1437	0.017	0.5	2.11	8.55	65.5	149	19.2	0.68
1996-2005	7039	1502	0.017	0.48	1.62	9.56	66.7	147	19.2	0.65
2006-2015	6767	800	0.024	0.41	1.85	7.35	59.8	138	9.6	0.61
Mean	7267	1246	0.019	0.46	1.86	8.49	64.0	145	16.00	0.65

Cluster 2 has turned out to be quite unstable, its characteristics vary from period to period by more than 10% (Table 3). As a result, its content is constantly changing. In the third period, this cluster is formed by small catchments with high natural over-regulation (Ω = 0.73), and therefore, the values of the coefficient S, which characterizes the variability of the flow, are minimal (0.015).

Cluster 3 includes quite elevated catchments, the average height is 145 m (Table 4). They have high forest coverage (64%) and relatively high bog (8%) and lakes (2%) coverage. Consequently, the coefficient of natural over- regulation is higher than in other clusters. However, it decreases with time.

TABLE V. CATCHMENTS CHANGING CLUSTERS

Number in the database	River	1986-1995	1995-2005	2006-2015
17	Velikaya	3	2	3
25	Uza	1	2	1
26	Plyussa	1	2	1
11	Bol'shoy Tuder	2	1	3
19	Sorot'	1	1	3
13	Perekhoda	2	1	1
23	Cherekha	2	1	1
10	Lovat'	1	2	1
15	Luga	1	2	1
21	Kudeb	1	2	1
18	Alolya	3	3	2
22	Zchelcha	3	3	2

According to the results of clustering over three periods, 14 catchments stayed in the same cluster, but 12 catchments shifted between clusters (Table 5). Several rivers formed stable groups in which they moved from cluster to cluster.

Catchments Uza and Plyussa could shift from cluster 1 into cluster 2 in the second period due to the fact that the high flow and coefficient S significantly reduced. Therefore, the rivers were included in the cluster with smaller average values of these characteristics (second period: cluster 1 $H_{10\%}$ – 5970 mm, S – 0.039, cluster 2 $H_{10\%}$ – 5095 mm, S – 0.027).

Catchment Bol'shoy Tuder is the most unstable. The shift from cluster to cluster is mainly due to changes in the high flow. In the first period, the river is in cluster 2, which is characterized by the maximum average value of the high flow (9139 mm). In the second period, the river goes into cluster 1, since its high flow (6972 mm) is approximately equal to the average value for the cluster (6680 mm).

High and low flows of the Perekhoda and Cherekha rivers are quite changeable. Their shift from cluster 2 to cluster 1 in the second period is probably due to a decrease in the high flow. Besides, cluster 1 in the second and third periods has minimum low flows among the three clusters.

Catchment Lovat' goes from cluster 1 to cluster 2 and then back, possibly due to the variability of average characteristics in cluster 2. In the second period, the characteristics of the cluster ($H_{10\%}$ – 5095 mm and $H_{90\%}$ – 503 mm) and the catchment ($H_{10\%}$ – 4581 mm and $H_{90\%}$ – 585 mm) turned out to be closest.

Catchment Velikaya goes from cluster 1 to cluster 2 in the second period, possibly due to a decrease in high flow. In the third period, the catchment returns to cluster 3, since its low flow becomes close to the corresponding value in this cluster (800 mm).

Catchments Alolya and Zchelcha could go into cluster 2 in the third period, because the average value of the low flow in cluster 3 has changed significantly (800 mm) compared with the second cluster (1770 mm).

The above-described changes in cluster affiliation are shown in Figures 3-5.

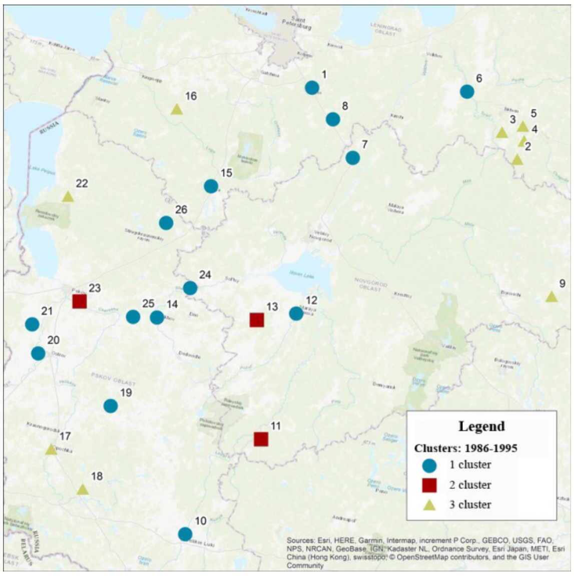

Fig. 3. Geographical location of clusters, 1986-1995.

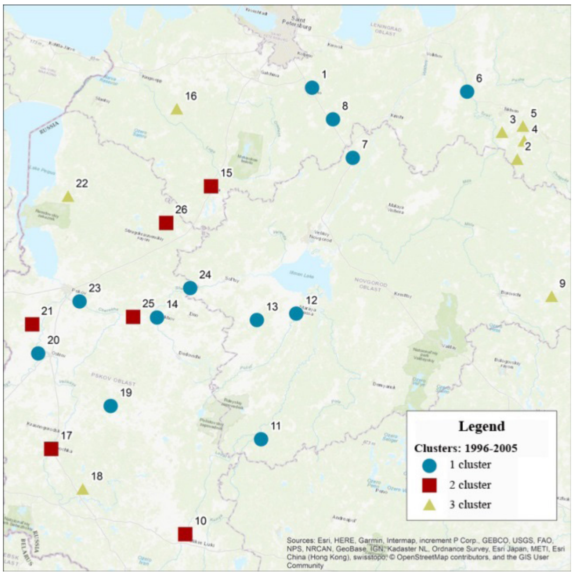

Fig. 4. Geographical location of clusters, 1996-2005.

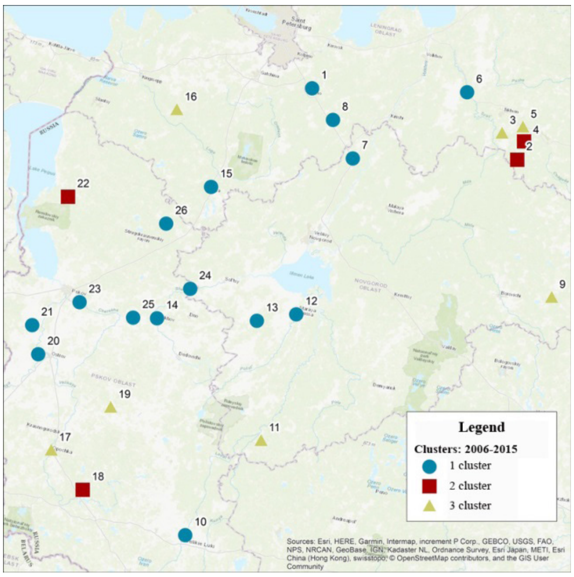

Fig. 5. Geographical location of clusters, 2006-2015.

Conclusions

The authors consider their first attempt to assess the dynamics of hydrological similarity using the clustering method to be quite successful. Catchments clustering can be a valuable tool for understanding hydrological changes, as it allows to compare them with the physical and climatic characteristics.

The observed temporal variability of the catchments behavior was interpreted on the basis of landscape-hydrological analysis. In conditions of a decrease in the wetness of the study area, a decrease in the flow during the study period is observed, what is proved by the previously completed study [8]. Natural over-regulation of most catchments decreases towards the second period and increases in the third one. This may be due to changes in the genesis of runoff and landscape conditions, related to a decrease in the area's wettness.

Nowadays, it is not possible to assess large-scale genetic changes in runoff and landscapes reliably; therefore, the relevance of the proposed approach is obvious.

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