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RESEARCH PAPER

Spatial and Temporal Changes in Hydrological Regionalization of Lowland Rivers

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Abstract

Regionalization of the riverine system is a challenging task not only for large-scale basins but also for catchments of regional relevance. Especially, there is a lack of studies related to the regionalization of lowland rivers. Therefore, this study aims to perform the regionalization of lowland rivers based on the example of Lithuanian rivers, using long data series and selected hydrological characteristics. The suggested classification scheme used the estimated proportional contribution of river feeding sources (rainfall, snowmelt, and groundwater) as well as hydrological indicators describing river runoff and its variability (specific annual runoff, coefficient of flow irregularity, and coefficient of variation). *K*-value clustering algorithms were applied for the hydrological regionalization of Lithuanian rivers. Three hydrological regions were determined: Western, Central and South-eastern. For the rivers of South-eastern region, the groundwater feeding was typical (55% of multiannual runoff). The rivers of Central region were mainly fed by surface sources—rain (47%) and snow (36%). The rivers of Western region were described as rain dependent (62%). These regionalization results were compared with the first hydrological classification established by Jablonskis and Janukėnienė (Change of Lithuanian river runoff. Science, Vilnius, 1978). Some catchments in Central region have changed their intra-annual and multiannual flow behaviour. Most of them tended to shift from snow-fed to rain-fed type. The uniqueness of the applied methodology is related to the proposed hydrological characteristics, which allow dividing the lowland rivers into regions. This opens the way to expand the proposed scheme of regionalization to neighbouring countries or regions where lowland rivers are prevalent.

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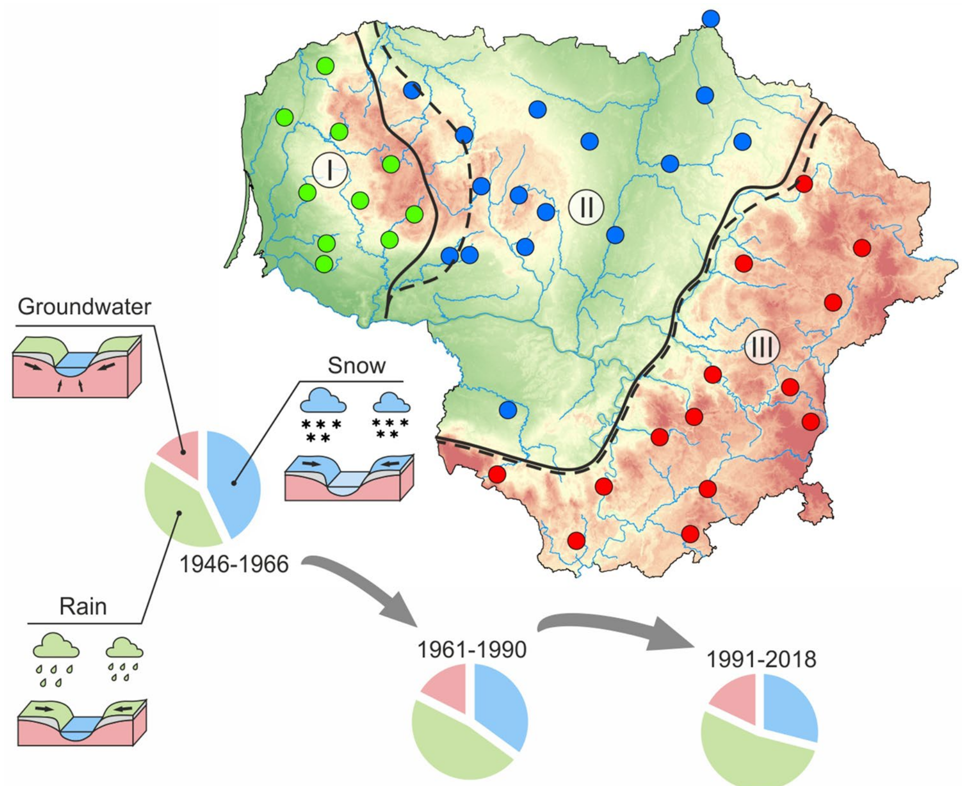
Graphical Abstract



Article Highlights

- The manuscript is dedicated to the research of spatial and temporal dynamics of hydrological regions formed by homogenous groups of lowland rivers.
- Based on long-term flow data series, a classification scheme was proposed to delineate homogeneous groups of Lithuanian river catchments with similar hydrological properties.
- The suggested scheme was based on the proportional contribution of river feeding sources (rainfall, snowmelt, and groundwater) and hydrological indices describing river runoff and its variability (specific annual runoff, coefficient of flow irregularity, and coefficient of variation).
- The summarized regionalization of lowland rivers was done applying multivariate clustering analysis using river feeding sources and hydrological indices as input data.

Keywords Lowland rivers · River feeding sources · Runoff indices · Hydrological regionalization · Multivariate clustering analysis

Introduction

People, by nature, tend to generalize and group various objects and phenomena. This helps to understand the complex surrounding environment. Classification of phenomena is a standard first step in scientific analysis and synthesis (McDonnell and Woods 2004). The main goal of hydrological classification is to reduce the complexity of water systems by grouping them into several categories (Sivakumar et al. 2015; Salami and Buehler 2020); it is the process of systematically arranging streams, rivers, or catchments into groups most similar to the characteristics of their flow regime (Olden et al. 2009).

Objective classification of catchments and the delineation of their homogeneous groups with the same hydrologic behaviour are the basis of regionalization procedures (Olden et al. 2009; Di Prinzio et al. 2011; Razavi and Coulibaly 2013; Toth 2013). Within identified homogenous regions, hydrological information may be transferred from gauged catchments to ungauged or poorly gauged sites. The ability to predict flow behaviour in ungauged catchments is relevant in many areas of hydrological research, water resource management, construction of hydrotechnical structures (such as bridges, dams, irrigation canals, etc.).

The differences between regionalisation techniques lie in the type of information that is transferred from gauged to ungauged watersheds, the transfer method and the watershed properties used to quantify similarity (Pagliero et al. 2019). There is no single method or approach that could be applied to regionalize catchments due to the tremendous variability in space, time, and process found in natural hydrological systems all around the globe (McDonnell and Woods 2004; Razavi and Coulibaly 2013; Guo et al. 2021). Diversity of catchment physico-geographical features and climate variability produces different performances for each method applied in different regions. Although scientific regionalization studies tend to focus on formalized regionalization methods, it is important to keep in mind that the quantity and quality of expert judgement included in any regionalization approach, whether in delineating regions, selecting catchment attributes or other avenues, play a crucial role in maximizing regionalization outcomes (Merz et al. 2006; Ley et al. 2011). Moreover, in some cases, data quality and origin might be even more critical than the classification technique applied (Peñas et al. 2016). According to Sivakumar et al. (2015), current approaches for the classification include regression-based methods, cluster analysis, principal component analysis, entropy-based methods, symbolic dynamic and nonlinear dynamic concepts, and other methods, such as data-driven, data-based mechanistic, and geostatistical.

The most popular is regionalisation based on regression of model parameters that are calibrated at gauged catchments and shifted to the ungauged catchments (Oudin et al. 2008; Pagliero et al. 2019). Grouping the similar catchments using various clustering methods is another broadly used technique (Li et al. 2018; Sharghi et al. 2018). Principal component analysis, being one of the simplest multivariable dimension reduction techniques, is also often applied on catchment attributes based on daily streamflow time series (Di Prinzio et al. 2011; Swain and Patra 2019). Each method has its advantages and limitations. This is why many attempts to classify river catchments and delineate their homogeneous groups are based on multiple techniques (Chiang et al. 2002; Oudin et al. 2010; Li et al. 2018; Swain and Patra 2019). In addition, like other research techniques, methods of hydrological regionalization are evolving; the old ones are being replaced by newer, more modern, more accurate ones. In recent decades, river flow regimes are getting highly affected by changing natural and anthropogenic factors. Over time, river catchments that previously belonged to one region may be assigned to different regions. A search of the literature revealed only one study aimed at refining improving and updating the old hydrological classification of homogenous catchments performed more than 40 years ago (Kondoh et al. 2004).

The first attempts to classify Lithuanian lowland river catchments into regions were made in the 1970s. The hydrological classification, mainly based on the origin of the flow, was established by Jablonskis and Janukėnienė (1978). This classification was developed according to discharge data of 1946–1966; the river catchments were assigned to three different hydrological regions based primarily on the origin of runoff formation and runoff indices. Recently, in hydrological studies, the following three distinct regions: western, central and south-eastern, are used (Gailiušis et al. 2001). Although a major part of Lithuanian territory falls into the one Nemunas river basin (46,626 km^2 out of a total 65,300 km^2), its catchments are actually highly variable. It has been well investigated that the hydrologic response of catchments in various areas of Lithuania is different, while the dissimilarities are projected to persist (Kriauciūniene et al. 2012; Šarauskienė et al. 2018). There are also studies that highlight a rising problem of extreme flow phenomena alterations in different regions (Meilutytė-Lukauskienė et al. 2017; Šarauskienė et al. 2020).

Changes in river flow regimes in different parts of the world over the past decades remain unprecedented. The understanding of these changes is of great importance not only for the scientific community but also for water resource managers and decision-makers. Most hydrological regionalization studies focus on large river catchments or areas with a wide range of climatic and geographical conditions and topography of a wide range of altitude. In contrast, few studies involve lowland river catchments with relatively similar physico-geographical conditions, but different flow regimes. The novelty of hydrological regionalization of the current study consists of involving to methodology not only runoff indices but also river feeding sources, that application not found in other studies. To date, hydrological regionalization has not been carried out in the Baltic region or neighbouring countries. Therefore, created methodology could be applied for mentioned region where lowland river catchments are dominant.

Considering all accomplished hydrological studies and being able to use a significantly larger database of flow observations, it is possible to analyse in more detail the relationship between river runoff and catchment physical geographical characteristics, as well as to assess river flow patterns in different regions of the country. This study aims to perform the regionalization of Lithuanian lowland rivers based on river feeding sources and selected runoff indices using long data series and applying various statistical methods and advanced computer technologies.

Study Area and Data

Lithuania is a relatively small country (65,300 km^2) located in the south-eastern part of the Baltic Sea region. Despite its size, Lithuania has more than 22,000 local and transboundary rivers and streams. All these rivers belong to the category of lowland rivers due to the low elevation (less than 300 m above sea level) of their catchments. However, such elevation, together with local climatic and physico-geographical conditions, determine the perceptible differences in the hydrological behaviour of Lithuanian rivers.

Forty water gauging stations (WGSs) representing hydrological patterns of Lithuanian rivers were selected for this study. These WGSs spatially cover the entire study area and are evenly distributed throughout Lithuania (Fig. 1). The WGS catchment areas varied from < 100 km^2 (3 WGSs) and 100–1000 km^2 (16 WGSs) up to 1000–6000 km^2 (17 WGSs) and > 10,000 km^2 (4 WGSs). The daily discharge data of the 40 selected WGSs were taken from the hydrological yearbooks of the Lithuanian Hydrometeorological Service (LHMS) of 1961–1990. For the subsequent period (1991–2018), only 23 WGSs (out of 40 selected) with continuous data series remained due to the closed gauging stations. To estimate the proportion of snow feeding in the annual hydrograph, snow data (snow thickness and snow density) from ten meteorological stations were used to evaluate the snow water equivalent before the spring flood. Such data were taken from the meteorological yearbooks of the LHMS for the period of 1961–2018. The Lithuanian Hydrometeorological Service under the Ministry of Environment is the official provider of verified data, and despite different periods or data series interruptions, the observations were performed according to uniform methodologies and are suitable for scientific research in Lithuania.

Methodology

In lowland rivers, the formation of runoff is mainly determined by the nature of the climate and some physico-geographical factors. The distribution of climatic factors in the area depends on atmospheric circulation processes and climatic zones. Meanwhile, most physico-geographical factors act as local-scale drivers. The importance of each component of both groups in the formation of river runoff is different. The climatic factor that directly shapes the runoff is precipitation (rainfall and snowfall/snowmelt). Physico-geographical factors are not directly involved as a primary source in the formation of river runoff. Still, they play a considerable role in runoff redistribution in rivers, both spatially and over the year. These two groups of factors have a significant impact on the type of river feeding, which directly affects the amount and distribution of river runoff. When performing hydrological regionalization of the Lithuanian river regime, we applied multivariate clustering for the period of 1961–1990 using ArcGIS software tools. The proportional (in percent) contribution of river feeding sources (rainfall, snowmelt, and groundwater) to annual runoff formation, as well as hydrological indices describing river runoff and its variability (specific runoff q, coefficient of flow irregularity d, and coefficient of variation C_v), were used as initial data for multivariate clustering analysis as it was done by Jablonskis and Janukėnienė (1978). Accordingly, the findings of this research (the

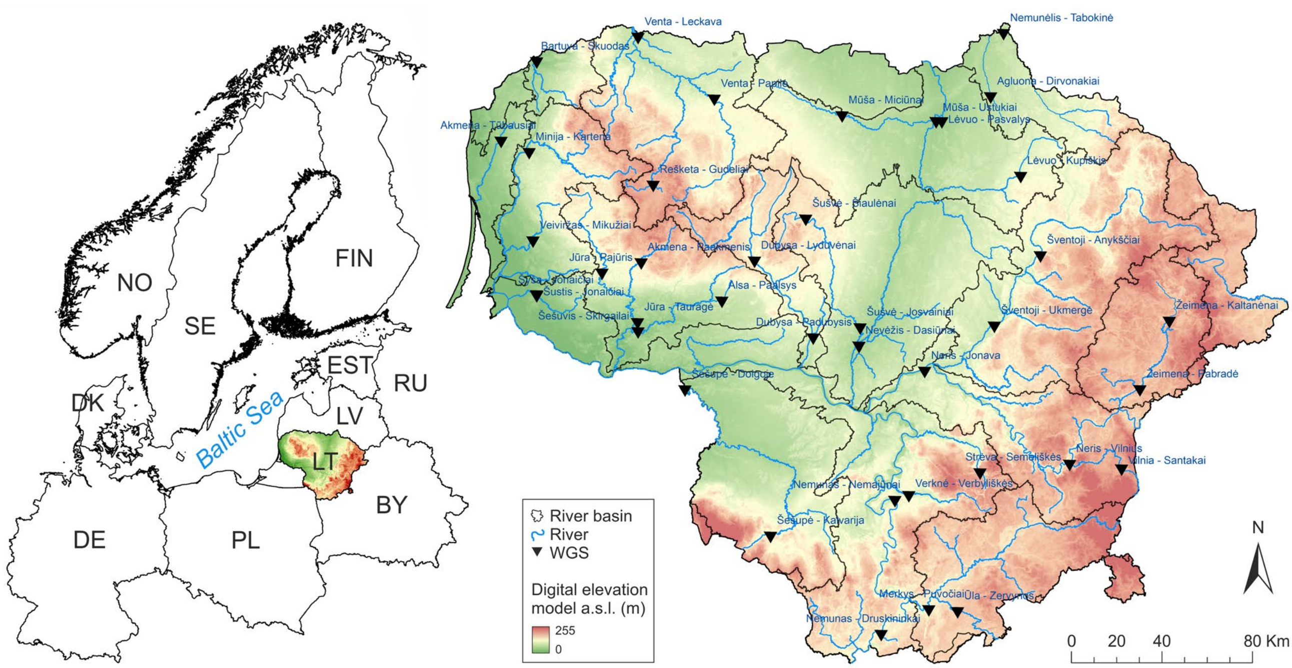


Fig. 1 Location of study area and selected WGSs

spatial changes in regionalization of 1961–1990 and temporal changes in river feeding sources of 1961–1990 and 1991–2018) were compared with the same parameters obtained by Jablonskis and Janukėnienė (1978) in the period of 1946–1966.

Estimation of River Feeding Sources

Contribution of different water sources to river runoff was estimated by separating annual runoff hydrographs into target feeding groups (Jablonskis and Janukėnienė 1978). Annual river runoff was divided into snow (snow melting during the spring flood), rain, and groundwater runoff. The daily discharge series of Lithuanian rivers were analysed in the period 1961–2018. Initially, the groundwater runoff part was estimated by calculating the minimum average discharge of 30 continuous lowest flow days for each year and then converting it into annual volume in cubic meters. The flood peak runoff of late winter or early spring was considered as snowmelt water. It was necessary to estimate the beginning and end of the spring flood each year and to remove part of the groundwater feeding to estimate only the volume of runoff generated by snow. In addition, the origin of snowmelt runoff was verified by the decadal data of snow water equivalent (*SWE*) before the flood, i.e., if the accumulated resources of *SWE* were small or non-existent, the spring flood runoff was attributed to rainfall runoff. Otherwise, it was considered as a feeding part generated by snow despite rainfall during the selected flood. The proportion of rainfall feeding was estimated from the volume of annual runoff by eliminating volumes of groundwater and snow feeding parts. In such a way, using annual hydrographs, the percentage of runoff components of different origins (% of total volume) of the studied rivers was calculated in each year. Such runoff fragmentation is approximate, as it does not consider various natural situations (e.g., when both snowmelt water and rainfall form spring floods). However, using a uniform methodology based on the origin of runoff, spatial patterns of river runoff formation can be identified.

From the obtained data, the average multiannual feeding part (%) of snow, rain, and groundwater for each river was determined for the selected periods (1991–1990 and 1991–2018). A specific dominant type of feeding components for each river was also identified. Snow supply was indicated by S, rain by R, and groundwater by G. If the type of feeding accounted for more than 50% of the total runoff, it was called predominant and marked in a capital letter. In this case, the capital letter of the dominant runoff feeding is followed by other two lowercase letters, arranged in descending order of their influence. If any source of runoff accounted for less than 10% of the total runoff, it was not included in the definition of a particular type of feeding. If the typical runoff feeding was less than 50%, then it was marked in a lowercase letter, and the feeding type was called mixed. For example, if $S=49\%$, $R=30\%$, $G=21\%$, then a typical feeding type of river is mixed with a snow component (s-rg).

The data of generalised feeding sources as a percentage were assigned to the central point of catchments represented by WGS. The Spline method of interpolation (in ArcGIS 10.5) was used to create maps of the distribution of the determined river feeding sources in the studied area for the period of 1961–1990. Based on these maps, spatial patterns of river feeding were estimated. A comparative analysis of river feeding sources for selected periods (1946–1966 (based on results of Jablonskis and Janukėnienė 1978), 1961–1990 and 1991–2018) was also performed. It aimed to assess the regularities of changes in these parameters over time and space.

Estimation of River Runoff Indices

River runoff indices such as specific annual runoff (q), coefficient of flow irregularity (d), and coefficient of variation (C_v) describing the amount and distribution of river runoff were chosen as parameters for hydrological regionalization.

One of these indices is the specific runoff, indicating the runoff per square kilometre of a river catchment. This index does not depend on the size of the river catchment, so it is possible to compare the amount of river runoff in the catchments of different areas.

The discharge of the gauged rivers Q (m^3/s) was converted into specific runoff (q, l/s·km^2) according to (Gailiušis et al. 2001):

$$q = \frac{Q \times 1000}{A},$$

where q is the specific runoff, l/s·km^2, Q is the annual discharge, m^3/s, A is the river catchment area at WGS, km^2.

The coefficient of flow irregularity (d) is used to estimate the distribution of discharge over the year. It describes the annual discharge allocation between the wet and dry seasons. The coefficient d is calculated as the deficit to average annual discharge Q that corresponds to the runoff surplus over the average annual discharge according to the formula:

$$d = \frac{\sum Q_p - \overline{Q} \cdot t_p}{365 \cdot \overline{Q}},$$

where ΣQ_p is the sum of discharges during time t_p when the discharge Q_p exceeds the average annual discharge Q. The magnitude of the coefficient of flow irregularity (discharge deficit to the average annual discharge rate) in numerical terms is equal to the magnitude of the excess discharge over the average annual discharge rate—b (Fig. 2).

The coefficient of variation (C_v) of the annual discharge data series is a parameter indicating the intensity of the change in these data with respect to the mean value. It is expressed as the ratio of the standard deviation to the mean discharge rate:

$$C_v = \frac{\sigma_Q}{\overline{Q}} = \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{Q_i}{\overline{Q}} - 1\right)^2}{n-1}}.$$

The determined values of q, d and C_v were mapped, and the regularities of river runoff indices in the study area were evaluated. The calculated indices were assigned to the centre of gravity of the catchments represented by corresponding WGS. The isoline maps of river runoff indices were created using the Spline interpolation method.

Regionalization According to Multivariate Clustering

ArcGIS software was used to identify clusters and their regional affiliation applying multivariate clustering analysis. Natural clusters were produced based on the attributes of selected objects in shape file format by Spatial Statistics toolbox. Data on feeding sources (rain, snow, and groundwater), d, C_v, and q were used as input data. The instrument used tries to find the best combinations when all the parameters are as similar as possible within the cluster, and as different as possible between the separate clusters. In this study, clusters were created using the K-means algorithm. The K-means is the simplest partitional algorithm. This algorithm divides data points into clusters with the minimal squared error between the cluster's points and the empirical mean of a cluster. This type of error can be defined as (Jain 2010):

$$J(C_k) = \sum_{x_i \in C_k} \|x_i - \mu_k\|^2,$$

where $X = \{x_i\}$, $i = 1,\ldots,n$ is the set of n d-dimensional points clustered into a set of K clusters, $C = \{C_k, k = 1, \ldots, K\}$, μ_k is the mean of cluster C_k. The main idea of the K-means algorithm is to minimize the sum of the squared error in all clusters:

$$J(C) = \sum_{k=1}^{K} \sum_{x_i \in C_k} \|x_i - \mu_k\|^2.$$

The K-means algorithm has three main steps (Jain and Dubes 1988): (i) select an initial partition with K clusters; (ii) generate a new partition by assigning each pattern to its nearest cluster center; (iii) calculate new cluster centers; repeat steps ii and iii until cluster membership stabilizes.

To start the calculation, the K-means algorithm requires the following parameters: number of clusters K, cluster initialization, and distance metrics (Jain 2010). Using ArcGIS software, the central points of each cluster were defined automatically. In addition, different numbers of clusters were tested according to the initial parameters; in our case, three clusters showed the best fit results. After running the tool, the K-means algorithm identifies the central points around which clusters are created. The first point is selected randomly. The weighting of other points continues in favour of the objects farthest from the existing set of seed features.

Results

Pairwise Correlations Between Selected Rivers

At the initial step of the river catchment similarity analysis, the natural synchronicity between the annual discharge data of 40 selected water gauging stations (WGS) was investigated. The pairwise correlations between all WGSs were calculated. The comparison combined data series from 1961 to 1990. The total number of tested relationships reached 780; the estimated correlation coefficients varied from 0.23 to 0.99. Due to the very wide dispersion, it was decided

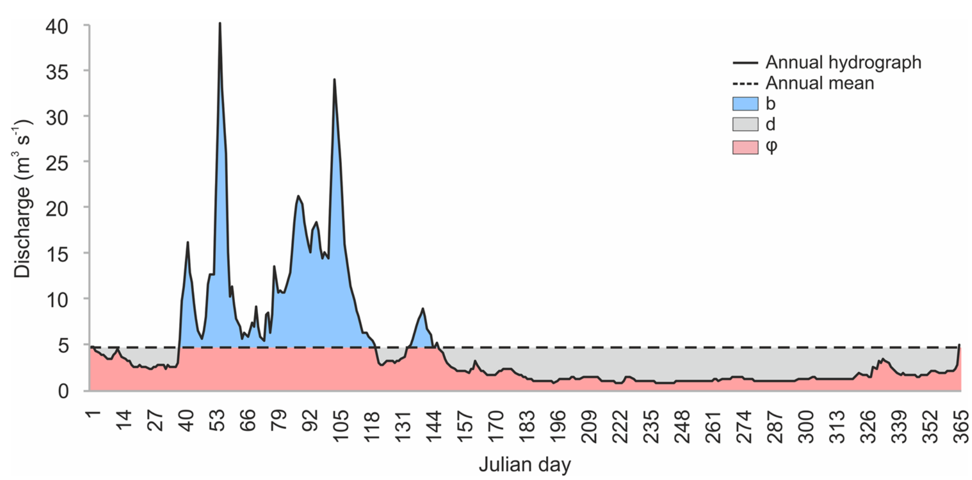


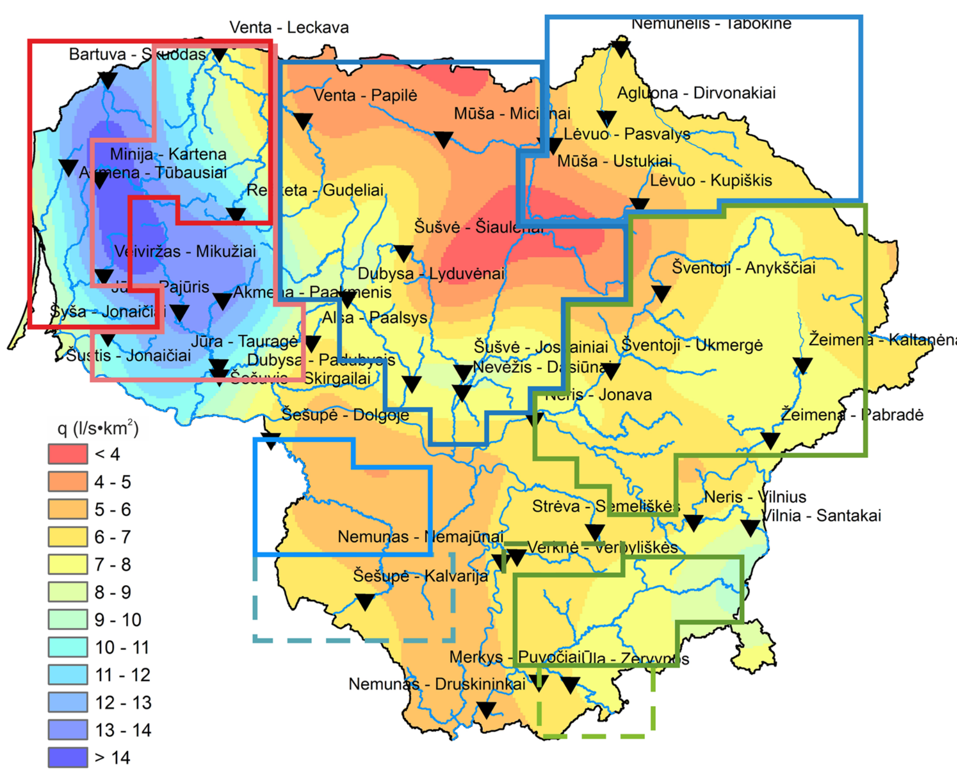
Fig. 2 Allocation of river runoff per year (coefficient of flow irregularity $d = b = 1 - \varphi$)

to divide all the obtained relationships into quartiles and consider only those that had the strongest correlations, i.e., from the fourth quartile (the coefficients of correlation from 0.81 up to 0.99). These interrelated rivers with the strongest pairwise correlation were grouped (Fig. 3). In addition, the interrelated areas were indicated by the same colour. A total of five areas were detected where relationships combined four and more WGSs. These areas covered the western, northern and eastern parts of Lithuania. In the western part, two areas overlapped, resulting in four WGSs, which fell into two areas with synchronous annual discharge. The other three large areas were located in central-north, north-east and east of Lithuania. The central-north and north-east parts were also interrelated and covered a significant part of the study area. Whereas, two additional areas in south-west and south-east were determined as a local feature with weak links to the other rivers. The rivers of these two small areas had only individual synchronicity with neighbouring catchments. From a hydrological point of view, all patterns of annual discharge synchronicity were evenly distributed throughout the study area and closely coincided with the map of the specific runoff (Fig. 3). The synchronous areas of western Lithuania covered the region of the highest values of specific runoff, which fluctuated from 8 up to 14 l/s/km^2. The south-west, central-north and north-east parts of Lithuania combined the related areas, where most of the territory was characterized by a small specific runoff (6 l/s/km^2 and less). The remaining part (south-east and east areas) coincided with a relatively evenly distributed specific runoff, which varied from only 6 to 8 l/s/km^2. Such analysis proved the presence of interrelations between the annual discharge series from different WGSs. However, some relationships showed similar patterns in different regions, and it is difficult to state something from just one variable and qualitative analysis. Therefore, more variables and quantitative analysis have been included to assess a clearer picture of regionalization in further steps of this research.

Distribution Patterns of River Feeding Sources and Runoff Indices

Spatial distribution maps were generated based on extracted river feeding sources (rain, snow and groundwater) and estimated river runoff indices (coefficient of flow irregularity and coefficient of variation) (Fig. 4). All feeding sources were expressed as the average percentage of multiannual runoff. Rain was the most dominant feeding type in the western part of Lithuania, where the share of runoff generated by rain exceeded 60%. Whereas in the southern, south-eastern and eastern parts of Lithuania, this feeding source accounted for only 10–30% of multiannual runoff. The magnitude of the snow feeding part in the study area was more evenly distributed (20–40% on average). Only in the south-eastern area, a small (10–20%) snow feeding part was detected. In the case of groundwater feeding, two clearly expressed areas were determined. One of them was located in the

Fig. 3 Pairwise correlations and specific runoff distribution



south-eastern part of the country, where the runoff part from groundwater exceeded 60%. The other areas covered west and central-north Lithuania. In the latter area, only 10–20% (or even less) of river runoff came from groundwater.

The coefficient of flow irregularity (*d*) acquired similar spatial distribution patterns as the rain feeding. The highest (from 0.41 and more) *d* values were in western and central-northern parts of Lithuania. Also, the two areas (in central-north) with the values of *d* higher than 0.50 coincided with the territories of the greatest share of snow feeding. On the other hand, the area with the smallest *d* values (lower than 0.20) matched up the zone of strongest groundwater feeding part. Quite similar regularities were found for the coefficient of variation as in the case of *d*. The catchments fed by surface runoff (e.g., rain and snow) had a higher runoff variability during the year and in multiannual scale. Whereas, in the catchments with the greatest share of the groundwater component, the runoff was more evenly distributed over time.

Regionalization of Lowland Rivers Using Multivariate Clustering Analysis

To determine homogenous regions based on the hydrological features of selected WGS catchments, a multivariate clustering analysis was used, including six different input parameters, which described the hydrological behaviour of selected river catchments in 1961–1990. These parameters consisted of the estimated percentage of feeding sources (snow, rain and groundwater), coefficient of flow irregularity, coefficient of variation, and specific runoff. Multivariate clustering analysis was chosen as a tool to provide a generalised quantitative view of the combined regularities of all previously analysed parameters in the centres of selected WGS catchments (Fig. 5). The results showed three clearly expressed clusters that were closely interrelated according to the selected input parameters.

The variation of the produced clusters across the standardized values of the selected parameters is displayed in Fig. 6. The first cluster was described by a weak snow and rain feeding but a strong groundwater component, low intra-annual and multiannual variability of river runoff as well as close to the average multiannual specific runoff. The rivers of the second cluster were strongly supplied with snow and moderately with rain. Whereas groundwater feeding was very weak, and due to the lack of its compensation mechanism, the values of *d* and C_v coefficients were very high. However, the specific runoff of the second cluster rivers was the lowest. The third cluster was characterised as a cluster where snow feeding part variated near the average and the rain feeding was the highest from all the analysed rivers. The values of the average specific runoff were the highest as well. Whereas, the groundwater feeding was the weakest, resulting

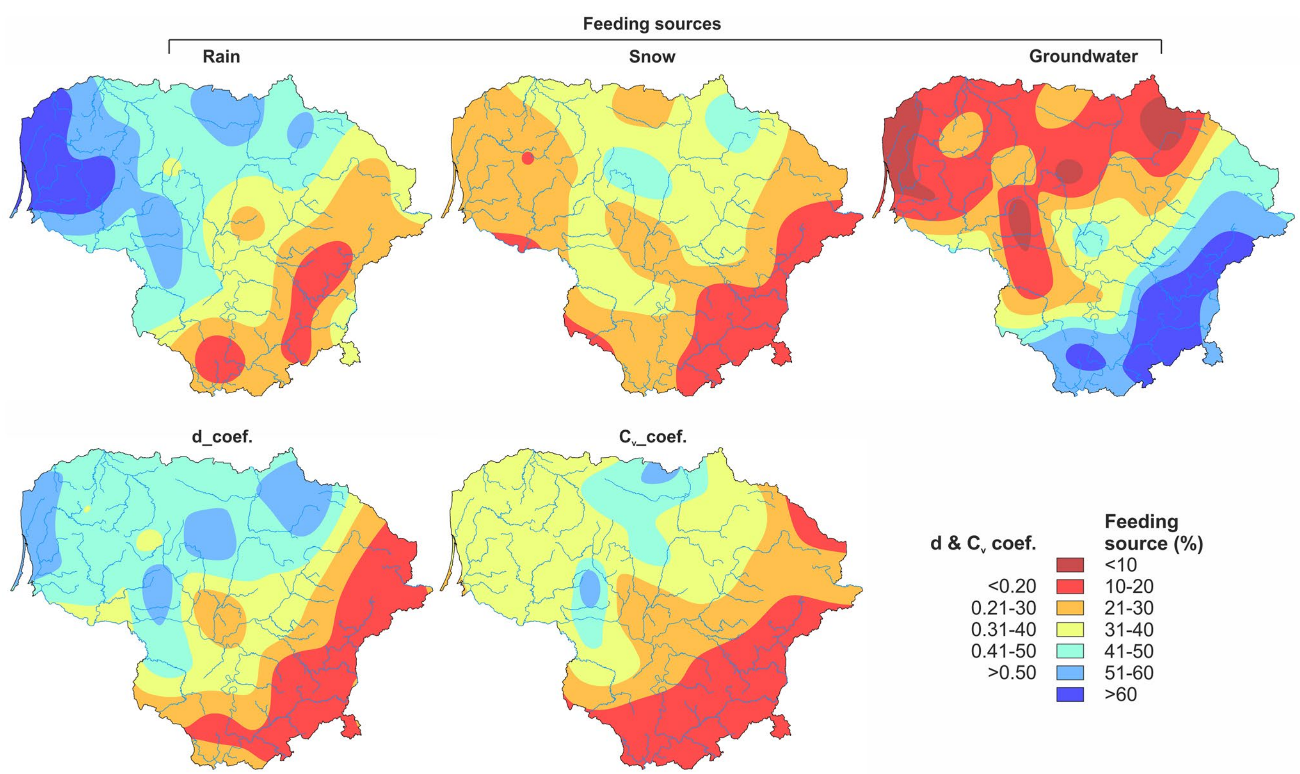


Fig. 4 Feeding sources, *d* and C_v coefficients for the period of 1961–1990

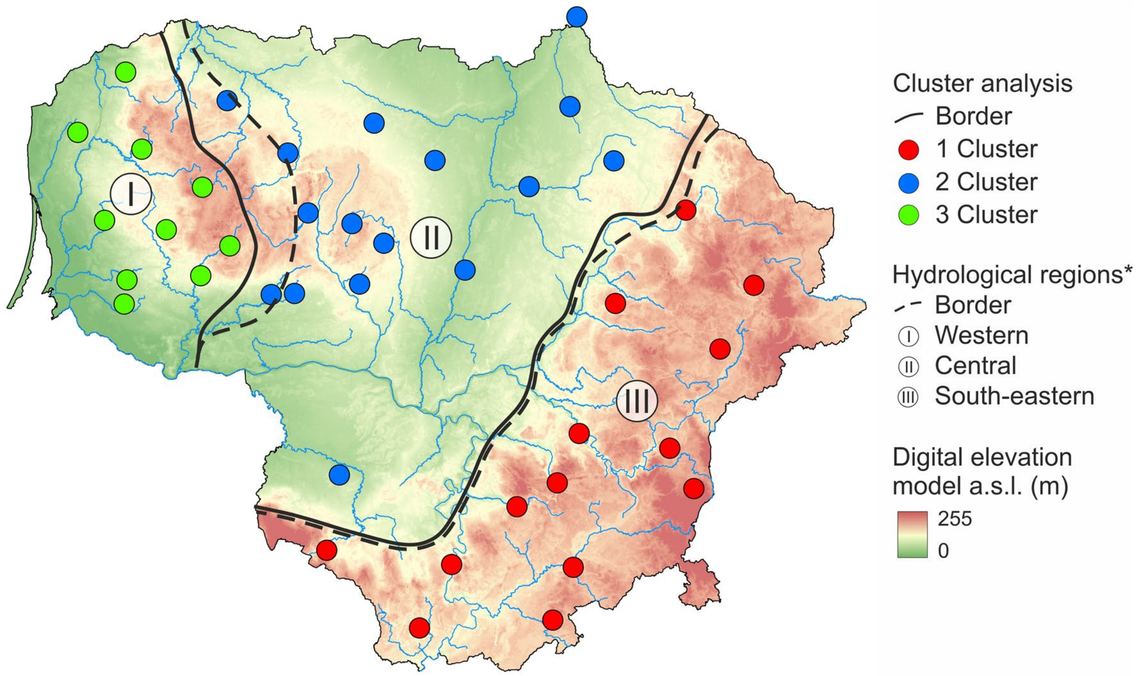


Fig. 5 Results of multivariate clustering analysis (according to determined feeding sources, *d*, C_v and *q*) and their comparison with the hydrological regions (Jablonskis and Janukėnienė 1978)

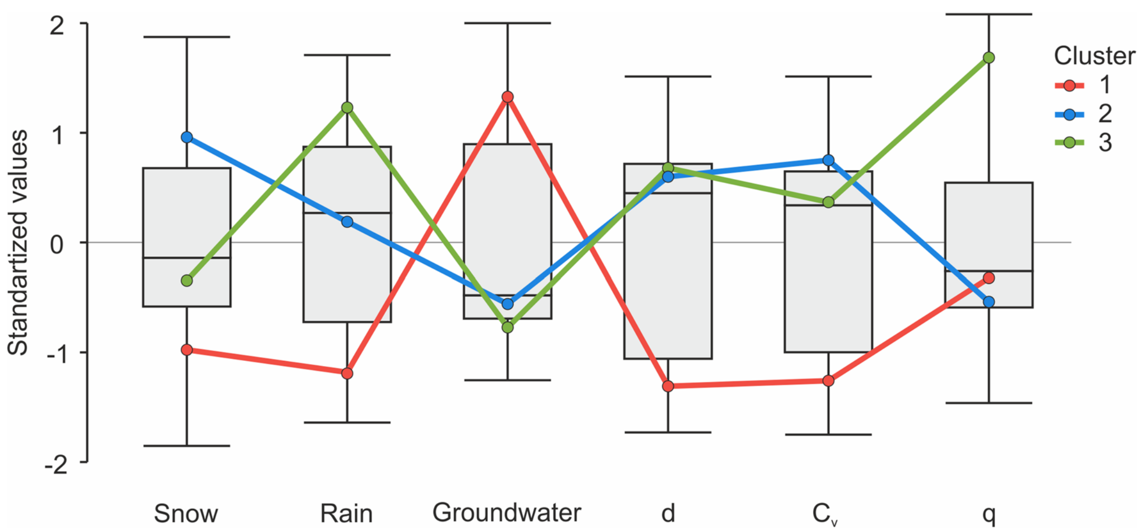


Fig. 6 Distribution of different clusters according to the weights of selected parameters

in considerable intra-annual and multi-annual variability of runoff as in the case of the second cluster.

The defined clusters were assigned their regularities in absolute numbers according to the selected feeding sources and river runoff indices (Fig. 7). All averages and constants were calculated for the period of 1961–1990 using data from 40 selected water gauging stations. For the rivers of the first cluster, the groundwater feeding was typical and accounted for an average of 55% of multiannual runoff. Whereas, snow and rain constituted 20% and 25%, respectively. The rivers of the second cluster were mainly fed by surface sources: rain on average composed 47% of total runoff, while snow 36%. The share of groundwater feeding was only 17%. The rivers of the third cluster were described as rain dependent, because 62% of their multiannual runoff were generated from rainfall. Accordingly, other feeding sources (snow—24% and groundwater—14%) accounted for a smaller part of total runoff. River runoff indices also had meaningful distribution patterns between the clusters. Specific runoff (q) was found to be the most pronounced, especially in the rivers of the third cluster. There, q values fluctuated on average between 13.0 and 14.3 l/s per km^2. Whereas in the other clusters, the average q values were estimated to be 6.9 (I cluster) and 6.3 l/s per km^2 (II cluster). The coefficient of flow irregularity was the lowest (0.21) in the rivers of the first cluster, while in the rivers of the second and third clusters, the coefficient was the highest and reached 0.47. Quite similar regularities were found with the coefficient of variation, only the amplitude of this coefficient (0.33–0.52) was the highest in the rivers of the second cluster.

Discussion—Could Regionalization Change due to Different Period of Evaluation?

Climate, geology, topography, soils, and vegetation help determine both the water supply and the pathways by which precipitation comes to the channel (Poff et al. 1997). The diversity of river flow regimes and regional distribution patterns are the result of the interaction between all these natural factors as well as anthropogenic activities. As global warming shifts precipitation patterns, the whole world faces the challenges in predicting the dynamics of water resources to support sustainable societal development in a changing environment (Montanari et al. 2013).

Although there are many studies on alterations in the hydrological regime due to climate change, in reviewing the literature, only a few studies were found on the dynamics of regionalization of river runoff over time. The closest

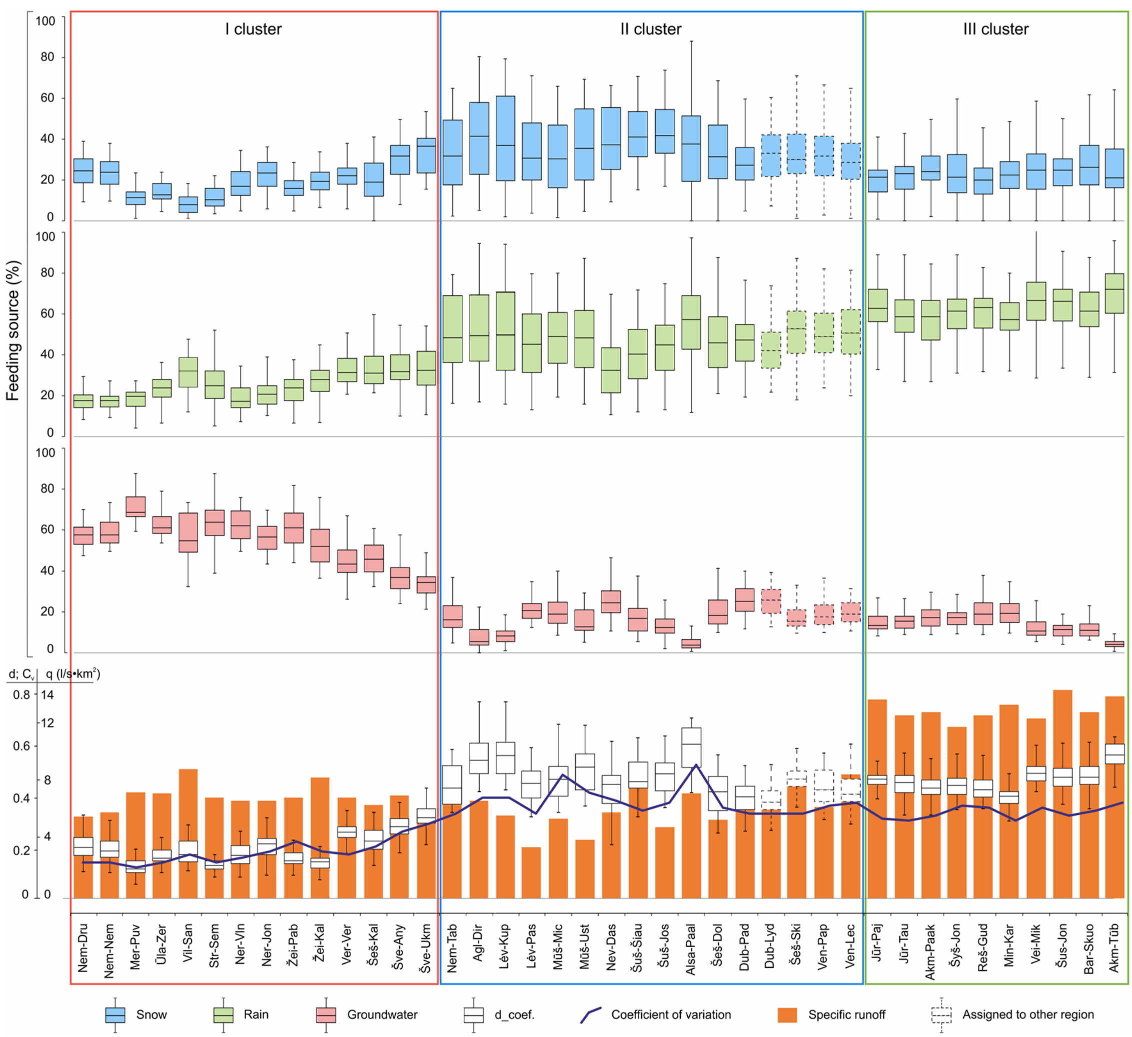


Fig. 7 Distribution of feeding sources and river runoff indices in determined clusters

in the context is a study (Sawicz et al. 2014) in which 314 catchments across the contiguous US were classified into 12 distinct clusters for 4 subsequent decades. This analysis allowed to assess the movement of the catchments between clusters over time and, therefore, to find out whether their hydrologic similarity/dissimilarity had changed.

The present study focused on regional changes in the hydrological regime of lowland rivers in Lithuania from the middle of the twentieth century to 2018. A previous study by Jablonskis and Janukėnienė (1978) assessed the regional variability of Lithuanian river runoff in 1946–1966 and proposed a first classification scheme for the delineation of homogeneous groups of catchments having a very similar hydrological behaviour. In the present study, an attempt to develop a new hydrological regionalization based on a much larger amount of available flow data (until 2018) and new research tools is presented.

To assess catchment similarity or dissimilarity, a variety of hydrological information should be considered (Toth 2013). Table 1 summarizes the comparison of the annual contribution of different water sources to river runoff over three different periods (1946–1966, 1961–1990, and 1991–2018). The values of two runoff indices: coefficient of flow irregularity (d) and coefficient of variation (C_v) as well as their changes were also calculated and presented for 1961–1990 and 1991–2018. Identification of the dominant runoff generation processes is essential for assessing the impacts of climate and land-use changes on the hydrological response of a catchment (Gonzales et al. 2009). Hydrograph separation remains a valuable tool in regional hydrological assessments (Curtis et al. 2020). Throughout all the years of observations (1946–2018), the rivers assigned to the South-eastern hydrological region showed patterns consistent with the dominant groundwater feeding, while the runoff of rivers from the Western hydrological region was mainly generated by rain. The feeding types of the rivers from these two regions remained the same when comparing the data for all three periods (Table 1). The exception was the rivers from the Central hydrological region, as most of them did not have a clear dominant feeding source and besides, there was a tendency over time to shift from snow-fed to rain-fed type (Table 1). The identified alterations indicate that the rivers in the Central region were the most sensitive to changes in natural and possibly anthropogenic forces during the analysed time. In the catchments of this region, due to rising winter temperatures, a vast amount of precipitation fell as rain, not snow as before.

The comparison showed a decrease in the values of the coefficient of flow irregularity (d) in the last period (1991–2018) compared to 1961–1990, although the smallest d remained typical for the rivers of the South-eastern region indicating a relatively stable runoff throughout different seasons of the year (intra-annual variation). The diminished coefficients of flow irregularity might indicate the response of river flow to warmer winters with a high share of liquid precipitation, i.e., floods decrease, flow gets more even throughout the year with respect to the dry and wet seasons. The comparison revealed different trends in the year-to-year variability of discharge (coefficient of variation). The river runoff in the South-eastern region that typically has the smallest coefficient of variation (C_v) exhibited a slightly higher variability with respect to time; on the contrary, in the remaining regions, river runoff variability decreased. The most significant decline of C_v values comparing the periods of 1961–1990 and 1991–2018 was estimated in the river gauges downstream hydropower plants (HPPs) installed during the last period. This proves that the operation of HPPs disrupts the natural variability of the river flow regime.

In addition to GIS-based maps generated by interpolation, to compare changes in the hydrological regime, the outputs of clustering were investigated. Cluster analysis is considered as one of the popular statistical methods for combining catchments into groups (Ley et al., 2011). The employed multivariate clustering technique identified three clusters of similar catchments (the solid line in Fig. 5) that showed the best fit results based on the selected attributes. The produced structures had similar patterns as the regions identified long ago (the dotted line in Fig. 5). The catchments of the first cluster occupied the southern and eastern parts of Lithuania, and the border with the neighbouring cluster was similar to the boundary of the hydrological regions described by Jablonskis and Janukėnienė (1978). Whereas, the second cluster (central part of the country) together with the third cluster (western part) formed a changed location of the border between them comparing with the boundary of the hydrological regions delineated in 1978. The border moved slightly westward since a more detailed analysis with more catchments was done in this research. The comparison of the defined contiguous regions of catchments having similar hydrological behaviour showed that different multivariate analysis techniques produced quite similar results both in the past and present. This may mean that the physico-geographical features of the catchments have not changed much over time. However, a slightly shifted boundary was established between the western and central regions. According to the new approach, a group of catchments located on the leeward side of the eastern slopes of the Samogitian Uplands shifted from the western to the central region.

Different behaviours of these catchments were detected and presented in Fig. 7, and was also analysed based on the comparison presented in Table 1. Changes in the hydrological regime (feeding sources) of the catchments newly assigned to the central region might be a hydrological response to a changing climate. The above-mentioned study (Sawicz et al. 2014) found that climatic characteristics had the primary control on catchment behaviour

Table 1 Changes of river feeding type and runoff indices in three periods

No.	WGS abbreviation	Feeding type 1946-1966*	Feeding type 1961-1990	Feeding type 1991-2018	d_1 1961-1990	d_2 1991-2018	d_2-d_1	C_{v1} 1961-1990	C_{v2} 1991-2018	C_{v2}- C_{v1}
				South-eastern hydrological region**						
1.	Nem-Dru	-	G-sr	G-sr	0.21	0.18	-0.03	0.14	0.16	0.02
2.	Nem-Nem	-	G-sr	G-sr	0.20	0.17	-0.03	0.14	0.15	0.02
3.	Mer-Puv	G-rs	G-rs	G-rs	0.14	0.12	-0.02	0.12	0.14	0.02
4.	Ūla-Zer	-	G-rs	G-rs	0.18	0.15	-0.03	0.14	0.17	0.03
5.	Vil-San	G-rs	G-rs	-	0.19	-	-	0.17	-	-
6.	Str-Sem	-	G-rs	G-rs	0.14	0.13	-0.01	0.14	0.18	0.04
7.	Ner-Vln	-	G-rs	G-rs	0.18	0.15	-0.03	0.16	0.19	0.03
8.	Ner-Jon	-	G-sr	G-rs	0.21	0.18	-0.03	0.18	0.21	0.04
9.	Žei-Pab	-	G-rs	G-rs	0.15	0.15	0.00	0.18	0.19	0.01
10.	Žei-Kal	-	G-rs	-	0.17	-	-	0.22	-	-
11.	Ver-Ver	-	g-rs	g-rs	0.27	0.24	-0.03	0.17	0.24	0.07
12.	Šeš-Kal	-	g-rs	-	0.24	-	-	0.20	-	-
13.	Šve-Any	-	g-rs	g-rs	0.29	0.25	-0.04	0.26	0.27	0.01
14.	Šve-Ukm	g-sr	g-rs	g-rs	0.32	0.26	-0.06	0.29	0.25	-0.04
				Central hydrological region**						
15.	Nem-Tab	s-rg	r-sg	r-sg	0.45	0.41	-0.04	0.33	0.32	-0.01
16.	Agl-Dir	-	r-sg	-	0.56	-	-	0.39	-	-
17.	Lėv-Kup	-	r-sg	-	0.56	-	-	0.39	-	-
18.	Lėv-Pas	s-rg	r-sg	-	0.45	-	-	0.33	-	-
19.	Mūš-Mic	S-rg	r-sg	-	0.48	-	-	0.48	-	-
20.	Mūš-Ust	-	r-sg	r-sg	0.51	0.45	-0.06	0.41	0.30	-0.11
21.	Nev-Das	-	s-rg	-	0.44	-	-	0.38	-	-
22.	Šuš-Šiau	-	sr-g	r-sg	0.48	0.47	-0.01	0.34	0.33	-0.01
23.	Šuš-Jos	s-rg	sr-g	R-sg	0.49	0.48	-0.01	0.37	0.34	-0.03
24.	Alsa-Paal	-	R-s	-	0.59	-	-	0.52	-	-
25.	Šeš-Dol	sr-g	r-sg	-	0.42	-	-	0.35	-	-
26.	Dub-Pad	sr-g	r-sg	-	0.40	-	-	0.33	-	-
27.	Dub-Lyd	-	r-sg	r-sg	0.39	0.36	-0.03	0.33	0.26	-0.06
28.	Šeš-Ski	r-sg	R-sg	R-sg	0.48	0.44	-0.04	0.33	0.30	-0.03
29.	Ven-Pap	r-sg	r-sg	r-sg	0.44	0.41	-0.03	0.36	0.27	-0.09
30.	Ven-Lec	-	r-sg	r-sg	0.42	0.40	-0.02	0.37	0.28	-0.09
				Western hydrological region**						
31.	Jūr-Paj	R-sg	R-sg	-	0.47	-	-	0.31	-	-
32.	Jūr-Tau	R-sg	R-sg	R-sg	0.46	0.42	-0.04	0.30	0.29	-0.01
33.	Akm-Paak	-	R-sg	R-sg	0.44	0.41	-0.03	0.32	0.26	-0.06
34.	Šyš-Jon	-	R-sg	-	0.45	-	-	0.36	-	-
35.	Reš-Gud	R-sg	R-sg	-	0.45	-	-	0.35	-	-
36.	Min-Kar	R-gs	R-sg	R-sg	0.41	0.41	0.00	0.30	0.27	-0.03
37.	Vei-Mik	R-sg	R-sg	-	0.50	-	-	0.32	-	-
38.	Šus-Jon	-	R-sg	-	0.48	-	-	0.35	-	-
39.	Bar-Skuo	-	R-sg	R-sg	0.49	0.45	-0.04	0.34	0.26	-0.08
40.	Akm-Tūb	R-s	R-s	-	0.56	-	-	0.37	-	-

*Jablonskis and Janukėnienė (1978)

**Regionalization according to multivariate clustering analysis

Table 1 (continued)

Feeding type: Orange—Groundwater dominant, Light orange——Groundwater predominant, Blue—Snow dominant, Light blue—Snow predominant, Green—Rain dominant, Light green—Rain predominant. d and Cv coefficients: Shades of red—negative deviation, Shades of green—positive deviation

when comparing catchments on a decade scale. This study revealed that catchment classification could be a valuable tool for understanding hydrological changes if it allows linking hydrologic behaviour to physical and climatic characteristics; it can be used to characterize temporal and spatial changes in similarity and dissimilarity between catchments, and to provide an overall indicator of the sensitivity of catchments to changes. By embedding local (place-based) in-depth studies into the regional context, we can better understand (changing) hydrological behaviour across different environmental gradients (Wagener et al. 2007).

The presented findings indicated that the hydrological response varied both spatially and temporarily. It can be concluded that the outcomes based on the new research tools have important implications for the revision of the existing and development of new regionalization not only for Lithuanian river catchments, but also for all lowland river basins. Moreover, only the upper reaches of some studied transboundary river basins (Venta and Lielupė rivers) are located in Lithuania; therefore, the applied methodology can be successfully expanded spatially to the neighboring/transboundary river basins. A further continuation of this research could be the regionalization of rivers in all three Baltic States (Lithuania, Latvia, and Estonia). This would allow a better evaluation of changes in water resources in the selected region, including a more detailed assessment of the hydrological characteristics of the transboundary river basins.

Conclusions

1. A classification scheme has been proposed to delineate homogeneous groups (clusters) of lowland river catchments with similar hydrological properties, based on river feeding sources and selected runoff indices, using long data series. The proposed methodology is simple, flexible and could be widely applied in lowland river catchments of neighbouring countries or other regions.
2. Three clusters (Western, Central, and Southeastern Lithuania) were distinguished using data of 1961–1990. Rain was the dominant feeding type in Western Lithuania (62%), whereas groundwater feeding dominated in Southeastern Lithuania, accounting for 55% of multiannual rivers runoff.
3. The rivers of Central Lithuania were mainly fed by surface sources: rain on average composed 47% of the total runoff, while snow 36%. The share of groundwater feeding was only 17%.
4. Comparison of the obtained regionalization results with the first hydrological classification exposed that only a few catchments from the Central region changed their intra-annual and multiannual flow behaviour. Most of them tended to shift from snow-fed to rain-fed type in the last period.

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Declarations

Conflict of Interest The author declares no conflict of interests.

References

Chiang SM, Tsay TK, Nix SJ (2002) Hydrologic regionalization of watersheds. I: methodology development. J Water Resour Plan Manag 128(1):3–11. https://doi.org/10.1061/(asce)0733-9496(2002)128:1(3)

Curtis JA, Burns ER, Sando R (2020) Regional patterns in hydrologic response, a new three-component metric for hydrograph analysis and implications for ecohydrology, Northwest Volcanic Aquifer Study Area, USA. J Hydrol 30:100698. https://doi.org/10.1016/j.ejrh.2020.100698

Di Prinzio M, Castellarin A, Toth E (2011) Data-driven catchment classification: application to the pub problem. Hydrol Earth Syst Sci 15(6):1921–1935. https://doi.org/10.5194/hess-15-1921-2011

Gailiušis B, Jablonskis J, Kovalenkovienė M (2001) Lithuanian rivers: hydrography and runoff. Lithuanian Energy Institute, Kaunas (**In Lithuanian**)

Gonzales AL, Nonner J, Heijkers J, Uhlenbrook S (2009) Comparison of different base flow separation methods in a lowland catchment. Hydrol Earth Syst Sci 13(11):2055–2068. https://doi.org/10.5194/hess-13-2055-2009

Guo Y, Zhang Y, Zhang L, Wang Z (2021) Regionalization of hydrological modeling for predicting streamflow in ungauged catchments: a comprehensive review. Wiley Interdiscip Rev Water 8(1):e1487. https://doi.org/10.1002/wat2.1487

Jablonskis J, Janukėnienė R (1978) Change of Lithuanian river runoff. Science, Vilnius (**In Lithuanian**)

Jain AK (2010) Data clustering: 50 years beyond K-means. Pattern Recogn Lett 31(8):651–666. https://doi.org/10.1016/j.patrec.2009.09.011

Jain AK, Dubes RC (1988) Algorithms for clustering data. Prentice Hall, New Jersey

Kondoh A, Harto AB, Eleonora R, Kojiri T (2004) Hydrological regions in monsoon Asia. Hydrol Process 18(16):3147–3158. https://doi.org/10.1002/hyp.5754

Kriauciuniene J, Meilutyte-Barauskiene D, Reihan A, Koltsova T, Lizuma L, Sarauskiene D (2012) Variability in temperature, precipitation and river discharge in the Baltic States. Boreal Environ Res 17:150–162

Ley R, Casper MC, Hellebrand H, Merz R (2011) Catchment classification by runoff behaviour with self-organizing maps (SOM). Hydrol Earth Syst Sci 15(9):2947–2962. https://doi.org/10.5194/hess-15-2947-2011

Li Q, Li Z, Zhu Y, Deng Y, Zhang K, Yao C (2018) Hydrological regionalisation based on available hydrological information for runoff prediction at catchment scale. Proc Int Assoc Hydrol Sci 379:13–19. https://doi.org/10.5194/piahs-379-13-2018

McDonnell JJ, Woods R (2004) On the need for catchment classification. J Hydrol 299(1–2):2–3. https://doi.org/10.1016/j.jhydrol.2004.09.003

Meilutytė-Lukauskienė D, Akstinas V, Kriaučiūnienė J, Šarauskienė D, Jurgelėnaitė A (2017) Insight into variability of spring and flash flood events in Lithuania. Acta Geophys 65(1):89–102. https://doi.org/10.1007/s11600-017-0009-x

Merz R, Blöschl G, Parajka J (2006) Regionalization methods in rainfall-runoff modelling using large catchment samples. In: Large Sample Basin Experiments for Hydrological Model Parameterization: Results of the Model Parameter Experiment–MOPEX. IAHS, Wallingford, Oxfordshire, UK vol 307 pp 117–125

Montanari A, Young G, Savenije HHG et al (2013) "Panta Rhei—Everything Flows": change in hydrology and society—The IAHS scientific decade 2013–2022. Hydrol Sci J 58(6):1256–1275. https://doi.org/10.1080/02626667.2013.809088

Olden J, Liermann CR, Pusey B, Kennard M (2009) Protocols for hydrologic classification and a review of Australian applications: Appendix 2. In: Ecohydrological regionalisation of Australia: A Tool for Management and Science. Land & Water Australia, Canberra, Australia

Oudin L, Andréassian V, Perrin C, Michel C, Le Moine N (2008) Spatial proximity, physical similarity, regression and ungaged catchments: A comparison of regionalization approaches based on 913 French catchments. Water Resour Res 44(3):W03413. https://doi.org/10.1029/2007wr006240

Oudin L, Kay A, Andréassian V, Perrin C (2010) Are seemingly physically similar catchments truly hydrologically similar? Water Resour Res 46(11):W11558. https://doi.org/10.1029/2009wr008887

Pagliero L, Bouraoui F, Diels J, Willems P, McIntyre N (2019) Investigating regionalization techniques for large-scale hydrological modelling. J Hydrol 570:220–235. https://doi.org/10.1016/j.jhydrol.2018.12.071

Peñas FJ, Barquín J, Álvarez C (2016) Sources of variation in hydrological classifications: time scale, flow series origin and classification procedure. J Hydrol 538:487–499. https://doi.org/10.1016/j.jhydrol.2016.04.049

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC (1997) The natural flow regime. Bioscience 47(11):769–784. https://doi.org/10.2307/1313099

Razavi T, Coulibaly P (2013) Streamflow prediction in ungauged basins: review of regionalization methods. J Hydrol Eng 18(8):958–975. https://doi.org/10.1061/(asce)he.1943-5584.0000690

Salami Y, Buehler A (2020) Catchment classification in a transboundary river using runoff and sub-basin characteristics. Int J River Basin Manag 18(1):117–126. https://doi.org/10.1080/15715124.2019.1628033

Šarauskienė D, Akstinas V, Kriaučiūnienė J et al (2018) Projection of Lithuanian river runoff, temperature and their extremes under climate change. Hydrol Res 49(2):344–362. https://doi.org/10.2166/nh.2017.007

Šarauskienė D, Akstinas V, Nazarenko S, Kriaučiūnienė J, Jurgelėnaitė A (2020) Impact of physico-geographical factors and climate variability on flow intermittency in the rivers of water surplus zone. Hydrol Process 34(24):4727–4739. https://doi.org/10.1002/hyp.13912

Sawicz KA, Kelleher C, Wagener T, Troch P, Sivapalan M, Carrillo G (2014) Characterizing hydrologic change through catchment classification. Hydrol Earth Syst Sci 18(1):273–285. https://doi.org/10.5194/hess-18-273-2014

Sharghi E, Nourani V, Soleimani S, Sadikoglu F (2018) Application of different clustering approaches to hydroclimatological catchment regionalization in mountainous regions, a case study in Utah State. J Mt Sci 15(3):461–484. https://doi.org/10.1007/s11629-017-4454-4

Sivakumar B, Singh VP, Berndtsson R, Khan SK (2015) Catchment classification framework in hydrology: challenges and directions. J Hydrol Eng. https://doi.org/10.1061/(asce)he.1943-5584.0000837

Swain JB, Patra KC (2019) Impact of catchment classification on streamflow regionalization in ungauged catchments. SN Appl Sci. https://doi.org/10.1007/s42452-019-0476-6

Toth E (2013) Catchment classification based on characterisation of streamflow and precipitation time series. Hydrol Earth Syst Sci 17(3):1149–1159. https://doi.org/10.5194/hess-17-1149-2013

Wagener T, Sivapalan M, Troch P, Woods R (2007) Catchment classification and hydrologic similarity. Geogr Compass 1(4):901–931. https://doi.org/10.1111/j.1749-8198.2007.00039.x