LITHUANIAN ENERGY INSTITUTE

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PATTERNS OF LOW FLOW AND HYDROLOGICAL DROUGHT RISK ASSESSMENT IN LITHUANIAN RIVERS UNDER CLIMATE CHANGE

Doctoral Dissertation
Technological Sciences, Environmental Engineering (T 004)

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LIST OF ABBREVIATIONS

30Q – the average of annual consecutive minimum thirty-day flows;
30Q80 – derived from the frequency curve using yearly minimum consecutive thirty-day average flows datasets with 80% threshold;
30Q95 – derived from the frequency curve using yearly minimum consecutive thirty-day average flows datasets with 95% threshold;
7Q10 – the average of a minimum seven-day values series for 10 years;
7Q2 – the average of a minimum seven-day values series for 2 years;
A – catchment area;
ADI – Aggregate Dryness Index;
Agr – agricultural lands;
AMF – Absolute Minimum Flow;
ArcGIS – Geographic Information System software developed by ESRI;
CIS – Common Implementation Strategy for the Water Framework Directive;
C-LT – Central hydrological region;
CORINE – Coordination of information on the environment;
DrinC – Drought Indices Calculator;
EURO-CORDEX – the dataset of regional climate model data for the European region;
FDC – Flow Duration Curve;
For – forested areas;
FREQ – mean annual frequency of zero-flow periods;
GDP – Gross Domestic Product;
GIS – Geographic Information System;
HBV – Hydrologiska Byråns Vattenbalansavdelning model;
HDHI – Hydrological Drought Hazard Index;
HDR – Hydrological Drought Risk;
HDVI – Hydrological Drought Vulnerability Index;
L – lake density;
LCL – light clay loam;
LFFC – Low flow Frequency Curve;
LFI – Low Flow Index;
LHMT – Lithuanian Hydrometeorological Service;
LULC – land use/land cover;
MAM7 – Mean Annual 7-day Minimum flow;
MAR – Mean Annual Runoff;
maxDUR – maximum number of zero-flow days;
MDF – Mean Daily Flow;
mDUR – mean number of zero-flows days;
MF – Median Flow;
MHVL – medium and heavy clay loam;

MIKE SHE – the hydrological modelling system designed to construct and simulate both surface water flow and groundwater flow;
MK – Mann–Kendall test;
P – peat;
PHDI – Palmer Hydrological Drought Index;
Q_P – mean flow during warm period;
R – average precipitation;
RCP – Representative Concentration Pathway;
RD – the dependency of river runoff on rainfall;
RDI – Reconnaissance Drought Index;
S – slope of the watercourse;
SDI – Streamflow Drought Index;
SDTV – severe drought threshold values;
SE-LT – Southeastern hydrological region;
SL – sandy loam;
SMHI – Swedish Meteorological and Hydrological Institute;
SMIRES – Science and Management of Intermittent Rivers and Ephemeral Streams;
SMRI – Standardised Snowmelt and Rain Index;
SPI – Standardised Precipitation Index;
SR – Spearman’s Rho nonparametric tests;
SRI – Standardised Runoff Index;
SRSI – Standardised Reservoir Supply Index;
SSFI – Standardised Streamflow Index;
SVE2 – Šventoji River (Ukmergė WGS);
SWAT – Soil and Water Assessment Tool, river basin scale model;
SWLI – Standardised Water Level Index;
SWSI – Surface Water Supply Index;
T_0 – timing of zero-flows;
TOPMODEL – Topography based Hydrological Model;
VIC – Variable Infiltration Capacity model;
WGS – Water Gauging Station (VMS at Lithuanian);
WLD – hydrological droughts lasting more than 16 days;
W-LT – Western hydrological region;
WSD – hydrological droughts with a duration of 5–16 days.

1. INTRODUCTION

Rivers in different regions have their own hydrological regime[1,2], but it always includes two components, a flood and a low flow. Another important river peculiarity is hydrological drought, which is a natural phenomenon and refers to a lack of water in the river[3,4]. Despite the fact that hydrological drought and low flow reflect the lowest flow of the river in a certain period, they may not coincide in time[3,5]. Each river has its personal indicator (threshold) of low flow and period of hydrological drought.

One of the main drivers of the river runoff formation is the climate (precipitation and temperature)[1,6], and recent studies signal that climate is changing[7-9], which affects low flow[6] and hydrological droughts[3,10,11] patterns. The changes in the occurrence of low flow events and hydrological droughts in the catchments are a growing concern[5,9,12,13], particularly in the context of climate change. Variability of low flow parameters significantly affects water availability, ecological balance, and human activities dependent on water resources[3-6,8,10,12]. Understanding the patterns of low flow in the modern world and assessing the associated hydrological drought risk is crucial for effective water resources management and adaptation strategies. Thus, the main research problem is the change in the rivers' low flow (as a response to climate change) and the spread of hydrological drought in Lithuania.

In light of climate change, it is essential to comprehensively investigate hydrological drought and low flow phenomena, considering their existence at different levels: local[4,6,7,12,14], regional[15-21], and global[10,11,13,22-26]. While the patterns of hydrological drought and low flow are typically well-studied at the regional and global levels, there are often gaps in understanding of these phenomena at the local level (lack of research or their irrelevance to the current time). This is especially important for forecasting of hydrological drought. Conducting a risk assessment of hydrological drought for each country becomes extremely important in this regard.

The forecasting of runoff and hydrological drought is equally important. Currently, there is a significant number of streamflow prediction models, but only several works are focused on low flow, typically orienting towards the general flow. Streamflow forecasting in rivers can occur through various models and software, for example: the HBV model[27], TOPMODEL[28], VIC model[29], MIKE SHE model[30], SWAT model[31], and others. In the context of modelling low flow in Central and Northern Europe[27,32,33], including Lithuania[34], the HBV model stands out due to its popularity. This model already showcased its effectiveness in precisely simulating low flow[32], but it has not yet been implemented within Lithuania.

Low flow periods, often associated with reduced precipitation and increased evapotranspiration[5,6,35,36], can lead to water scarcity, ecological stress, and disruptions in various water-dependent activities[6,12,35,36]. Particularly in regions like Lithuania, where river systems play a crucial role in supporting various sectors of the economy[37,38], understanding the patterns of low flow and assessing the associated hydrological drought risks has become essential. In the case of Lithuania, a country located in North-Eastern Europe, studies focusing on hydrological drought are relatively limited, and there are no studies specifically addressing hydrological drought risk assessment at all. However, given the anticipated effects of climate change on regional hydrology, there is a pressing need to investigate these aspects within the Lithuanian catchments.

Moreover, hydrological drought risk assessment provides a valuable tool for quantifying and evaluating the potential impacts of drought events on water resources and associated socio-economic systems[39,40]. Such assessments enable the development of proactive strategies for water allocation, conservation measures, and the implementation of effective drought management plans[40-42].

The relevance of this work lies in addressing several research gaps, namely: the absence of scientific studies that would identify or investigate intermittent rivers in Lithuania; the analysis of changes in low flow in response to climate change; a comprehensive assessment of hydrological drought in Lithuania; and the lack of hydrological drought risk analysis for Lithuania. The results of this study provide a comprehensive overview of low flow, the phenomenon of river intermittency as an extreme part of low flow, and hydrological drought. The availability of such data will provide valuable insights for policymakers, water resource managers, and stakeholders involved in the sustainable management of Lithuanian rivers. The findings will help decision-making processes, enable the identification of vulnerable regions, and guide the development of adaptation strategies to mitigate the adverse impacts of low flow and hydrological drought events.

1.1. The aim, objectives and scientific novelty

Aim of dissertation

The aim of the dissertation is to investigate the patterns of low flow and hydrological droughts, to evaluate their dependence on climate change, and to perform drought risk assessment for the Lithuanian rivers in the past and future.

Objectives:

1. To investigate the variability of the river intermittence, as extreme part of the river's low flow, within Lithuania.
2. To analyse the spatial and temporal distribution of low flow indicators of rivers in the past.
3. To investigate the phenomenon of hydrological drought according to historical data.
4. To forecast the frequency and severity of hydrological drought in the near and far future.
5. To develop the hydrological drought risk maps and to identify the most vulnerable regions in Lithuania.

Thesis statements:

1. The river intermittency is becoming increasingly widespread in Lithuania, especially this problem is particularly acute in the central hydrological region.

2. The low flow analysis in Lithuanian rivers shows significant changes in trends of the minimal water discharge according to new climate challenges.

3. Climate changes lead to an increase in the frequency and severity of hydrological droughts in Lithuania.

4. Hydrological drought risk analysis is a fundamental tool for addressing environmental, social, and economic problems in the future.

5. Standardised Water Level Index (SWLI) is suitable for the operational assessment of Lithuanian rivers.

Scientific novelty

- **River intermittency is a poorly studied topic for the northern countries.** In Lithuania, as in other humid countries, there are missing studies related to the river intermittency. During the course of the work, the intermittent rivers of Lithuania were investigated for the first time. Intermittency events were studied based on their occurrence date, duration, and frequency. Factors influencing these characteristics were also identified and can be used for investigation in other similar countries.
- **There is a lack of recent studies on the low flow of Lithuanian rivers.** A methodology for assessing changes in low flow in Lithuania has been developed. Changes in low flow based on the 30Q, 30Q95, and 30Q80 indices were studied for a 60-year period and a thirty-year moving average was used to analyse trends in low flow changes during 1961–2020. Low flow indices were employed to calculate hydrological drought, and an analysis of the frequency and duration of droughts was conducted for three Lithuanian hydrological regions.
- **Analysis of trends in the development of hydrological droughts will give an impetus to reducing the costs of eliminating the consequences of an extreme phenomenon.** A comprehensive study of hydrological drought was conducted in the past and future using different climate scenarios. A new Standardised Water Level Index (SWLI) was developed and tested for an operational response to hydrological drought.
- **Unfortunately, no hydrological drought risk map was found for Lithuania, as for the nearest countries.** The need for drought risk maps is an essential tool in identifying the most vulnerable areas. In this research, hydrological drought hazard, vulnerability, and risk maps were created for the entire territory of Lithuania on a catchment scale. It allows early action to increase the resilience of ecosystems to further climate change and human-induced challenges. Creating a hydrological drought risk map for Lithuania opens up a new issue of vulnerable watersheds in climate zones of the Baltic region. It also contributes to the development of similar research in neighbouring countries.

Practical value

The study’s findings offer valuable insights into effective water resource management in Lithuania. Understanding low flow patterns and hydrological drought risks is crucial for optimising water allocation, ensuring sustainable water supply, and implementing water conservation strategies. Knowledge about hydrological drought distribution is essential for warning about potential adverse impacts on human industrial and energy-generation activities, developing different plans of measures to minimise or eliminate extreme consequences and preventing river intermittency in permanent rivers.

Moreover, the research aids in identifying vulnerable regions and predicting future changes, enabling authorities to devise adaptive measures to mitigate climate change adverse effects on water resources. The assessment of hydrological drought risk contributes to disaster risk reduction efforts, allowing development of early warning systems and contingency plans to minimise drought impacts on ecosystems, agriculture, energy production, and other vulnerable sectors. This research bridges crucial gaps for resilient water management and informed policies. Policymakers can utilise the study outcomes to design robust water management policies, addressing challenges presented by changing hydrological conditions.

Research result approbation.

Five scientific articles were published on the topic of this dissertation. All of them were published in ISI Web of Science DB-referred journals with an average IF/AIF of ≥ 0.25. The research results were presented at 9 conferences, including 5 international conferences.

The content and scope of the dissertation.

The doctoral dissertation was prepared based on scientific publications and was done in the English language. The work consists of a list of tables, a list of figures, a list of abbreviations and definitions, an introduction, a review of the articles submitted for defence, conclusions, a list of references, a summary written in Lithuanian, a list of articles, a list of conferences, and copies of scientific articles on which the dissertation is based. The dissertation is 93 pages long, with 20 figures, 8 tables, and 131 references.

1.2. Papers and co-authors' contributions to papers

The thesis is based on 5 scientific articles:

1. ŠARAUSKIENĖ, Diana, AKSTINAS, Vytautas, NAZARENKO, Serhii, KRIAUČIŪNIENĖ, Jūratė and JURGELĖNAITĖ, Aldona. Impact of physico-geographical factors and climate variability on flow intermittency in the rivers of water surplus zone. *Hydrological Processes*. 2020. Vol. 34, no. 24, p. 4727–4739. DOI 10.1002/hyp.13912

Contribution of authors:

Šarauskienė D.: conceptualisation, methodology, formal analysis, investigation, writing – original draft preparation, writing – review and editing,

Akstinas V.: methodology, formal analysis, data curation, writing – original draft preparation, writing – review and editing, visualisation.

Nazarenko S.: methodology, data curation and analysis, writing – original draft preparation.

Kriaučiūnienė J.: conceptualisation, writing – review and editing, supervision.

Jurgelėnaitė A.: investigation, data curation.

2. NAZARENKO, Serhii, MEILUTYTĖ-LUKAUSKIENĖ, Diana, ŠARAUSKIENĖ, Diana and KRIAUČIŪNIENĖ, Jūratė. Spatial and temporal patterns of low flow changes in lowland rivers. *Water*. 2022. Vol. 14, no. 5, p. 801. DOI 10.3390/w14050801

Contribution of authors:

Nazarenko S.: conceptualisation, methodology, software, formal analysis, writing – original draft preparation, visualisation.

Meilutytė-Lukauskienė D.: methodology, formal analysis, data curation, writing – original draft preparation.

Šarauskienė D.: formal analysis, investigation, writing – original draft preparation, writing – review and editing.

Kriaučiūnienė J.: conceptualisation, formal analysis, writing – review and editing.

3. NAZARENKO, Serhii, KRIAUČIŪNIENĖ, Jūratė, ŠARAUSKIENĖ, Diana and JAKIMAVIČIUS, Darius. Patterns of past and future droughts in permanent lowland rivers. *Water*. 2022. Vol. 14, no. 1, p. 71. DOI 10.3390/w14010071

Contribution of authors:

Nazarenko S.: conceptualisation, methodology, software, formal analysis, investigation, data curation, writing – original draft preparation, visualisation.

Kriaučiūnienė J.: conceptualisation, methodology.

Šarauskienė D.: investigation, writing – review and editing.

Jakimavičius D.: software, validation.

4. NAZARENKO, Serhii, KRIAUČIŪNIENĖ, Jūratė, ŠARAUSKIENĖ, Diana and POVILAITIS, Arvydas. The development of a hydrological drought index for Lithuania. *Water*. 2023. Vol. 15, no. 8, p. 1512. DOI 10.3390/w15081512

Contribution of authors:

Nazarenko S.: conceptualisation, methodology, software, modelling, data curation, writing – original draft preparation, visualisation.

Kriaučiūnienė J.: conceptualisation, investigation, writing – review and editing.

Šarauskienė D.: methodology, formal analysis, writing – original draft preparation.

Povilaitis A.: methodology, formal analysis, writing – review and editing.

5. NAZARENKO, Serhii, ŠARAUSKIENĖ, Diana, PUTRENKO, Viktor and KRIAUČIŪNIENĖ, Jūratė. Evaluating hydrological drought risk in Lithuania. *Water*. 2023. Vol. 15, no. 15, p. 2830. DOI 10.3390/w15152830

Contribution of authors:

Nazarenko S.: conceptualisation, methodology, software, formal analysis, investigation, writing – original draft preparation, visualisation.

Šarauskienė D.: investigation, writing – original draft preparation, writing – review and editing.

Putrenko V.: methodology, data curation, supervision.

Kriaučiūnienė J.: conceptualisation, data curation, supervision.

Inter-relation of articles

Comprehending the impact of physical geographical factors and climate variability on flow intermittency is crucial to understanding the development of drought events in lowland rivers. Analysing past and future drought occurrences, along with studying spatial and temporal patterns of low flow changes, can help identify patterns of flow changes in Lithuanian rivers, which are essential in assessing hydrological drought risk. These interconnected topics collectively contribute to a comprehensive understanding of drought risk assessment and management within water deficit zones in lowland river systems. The demonstrable and step-by-step relationship connections of the work are shown in Fig. 1.

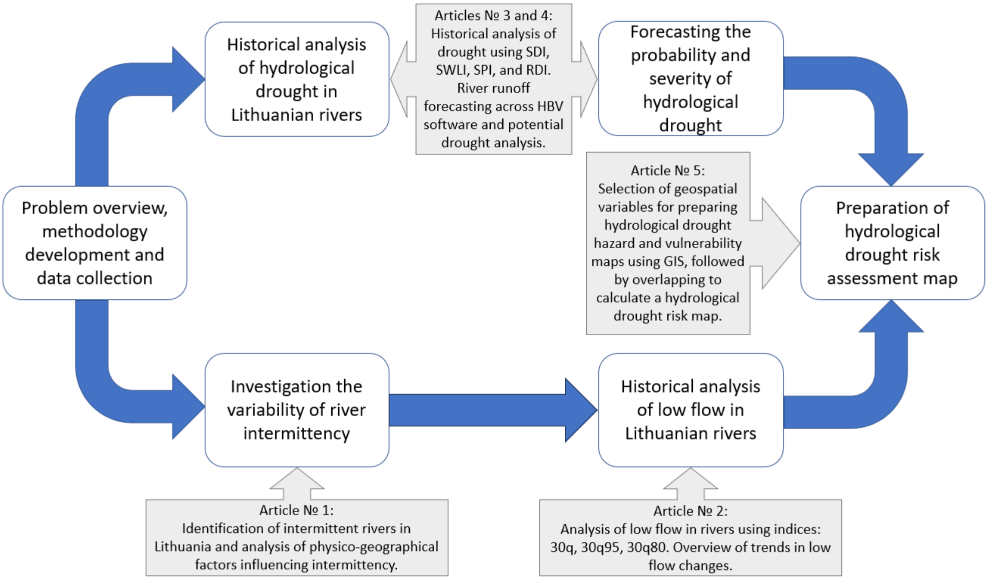


Fig. 1. General concept of work

Overall, the dissertation consists of five articles aimed at a gradual investigation of low flow, its dependence on the physical-geographical characteristics of the territory, and hydrological drought both in the past and the future.

The first article covers objective one and explores the prevalence of river intermittency (the event when the river runoff is equal to 0) cases in Lithuania, their correlation with physical-geographical factors of the territory. The results obtained from this article were also used for modelling river runoff with the HBV software and identifying the most important criteria for hydrological drought risk analysis.

The second article addresses objectives two and investigates changes in low flow over 60 years (1961–2020) in both temporal and spatial dimensions. Similar to the second and fourth articles, it also reflects the most drought-prone periods; however, it employs a different approach based on threshold values (operational indices of the Lithuanian Hydrometeorological Service (30Q, 30Q95, 30Q80) were used as threshold values). The findings of this study were used to determine the threshold value of hydrological drought in the fifth article.

The third and fourth articles cover objectives three and four. Within the article, a study of past hydrological drought events and their local distribution within Lithuania was conducted, allowing for a comparison of the obtained results with the hydrological drought risk map. The third article utilised an accumulation period of 1/3/6/9/12 months for drought indices, while the fourth article employed a ten-day accumulation period. The relationship between meteorological drought indices (standardised precipitation index – SPI and reconnaissance drought index – RDI) and hydrological drought index (streamflow drought index – SDI) was also considered in the third article. In the fourth article, the ability to replace the hydrological drought index based on discharge (SDI) with an index based on river water levels (standardized water level index – SWLI) was analysed. SWLI can replace any other hydrological index based on river discharge since it is capable of using raw input data from the water gauging station (WGS). This approach significantly reduces the time for detecting hydrological drought. Special attention is given to future forecasting, which reveals potential dependencies associated with climate change in the near and far future, considering two climate scenarios – RCP4.5 and RCP8.5. Overall, forecasting models for six rivers in different hydrological regions of Lithuania were developed in two articles.

The fifth article covers objective five. In this article, the results of the previous four articles were used to identify areas with the highest risk of hydrological drought occurrence. The article examines the hazard and vulnerability components of all Lithuanian catchments. The first hydrological drought risk assessment map for Lithuania was created.

Overall, each article is a part of a comprehensive study of minimal flow in Lithuania rivers. The research begins by investigating the intermittency phenomenon as an extreme boundary condition of low flow in rivers. Additionally, it involves low flow analysis and an understanding of its variability under climate change, as well as the study of hydrological drought, which represents a condition characterised by a significant decrease in river flow. The study culminates in the hydrological drought risk assessment map, which summarises and complements the previous research.

1.3. Brief review of scientific literature

Low flow, river intermittency, and hydrological drought are phenomena that are not identical but are interconnected as they all describe the river's minimum flow (or its absence). Therefore, only a comprehensive analysis of all three components will allow an understanding of the territory's resilience to climate change and developing effective spatial planning.

River intermittency

Intermittency is the most extreme component of low flow and is characterised by zero flow or a value very close to it. Intermittent rivers have emerged as a relatively new topic in scientific research, considering that studies have traditionally focused on permanent rivers. However, the interest in understanding intermittent rivers has been increasing in recent years, driven by climate change effects, rising water scarcity concerns, and the recognition of their prominence in river networks[43-47].

Remarkably, existing studies indicate that intermittent rivers make up over half of the total river length worldwide and dominate arid, semi-arid, Mediterranean, and dry-subhumid regions[48-50]. Intermittent rivers are often underestimated in their environmental and societal impact[50-52]. Despite their significance, many countries neglect their resources[52], and with climate change, the number of intermittent rivers is expected to increase at the expense of permanent rivers[52-54].

During the last decade, the research area of intermittent rivers has increased significantly, but some regions are still ignored. The main focus has been on regions historically belonging to warm or semi-arid regions[55], with fewer studies observed in temperate or relatively cooler regions: global scale[55-58], Europe – Mediterranean region[59-61], Europe – alpine region[62,63], Europe – central region[64], Australia[65,66], USA[45]. Only a few articles have been found that discuss intermittent rivers in the Baltic countries[61,67]. It is important to note that these articles are associated with the SMIRES initiative, and one of them was published in 2020 and examines some rivers in Lithuania[61].

Current studies in this field can be categorised into various directions, including the impact of intermittent rivers on ecosystem services[48,52,59], management of intermittent rivers[50,57,60,61,68], their role as habitats for specific plant and animal species[48,50,58,63-65], ecosystem effects of intermittent rivers[55,56,59,69], their use in agriculture[52], classification of intermittent rivers[52], flow intermittency modelling[62] and more.

In Lithuania, which is considered to have relatively abundant water resources, recent extremely warm and dry summers have highlighted the rising problem of water scarcity. A similar situation persists for other Baltic States. Climate change is significantly altering river runoff dynamics, leading to hydrological droughts. However, the challenges related to hydrological droughts have not been adequately addressed.

Low flow

Low flow is a crucial aspect of hydrological studies, representing the minimum discharge of water in a river over a specific period[5,70,71]. Formation of low flow typically occurs through groundwater inflow, lakes, swamps, and sometimes glaciers[5,72]. It occurs due to reduced rainfall or snow precipitation, with summer and winter low flows being the most common in Lithuania. However, in other regions, the observation period may differ depending on environmental conditions, precipitation and research tasks[5,72,73]. Unlike the phenomenon of river intermittency, low flow has been better researched.

Understanding low flow dynamics is crucial for ecological integrity, water quality, and supply in river systems[70,72,74,75]. Under extreme low flow conditions, aquatic ecosystems face habitat reduction, altered food resources, deterioration of water quality, and disrupted species interactions[70,71,76-81]. Moreover, water scarcity poses a threat to communities and economies, demanding sustainable water management solutions[73,75,80,82].

The identification and analysis of low flow events are essential for understanding the vulnerability of water resources to hydrological droughts, particularly under climate change[75], moreover, low flow index can be used as a threshold to identify hydrological droughts[72,73]. Today, there are various approaches for measuring and assessing river low flow depending on the country and the purpose of the calculation, the main ones are:

1. The limit of low flow can be determined through Mean Annual Runoff (MAR), Mean Daily Flow (MDF), Median Flow (MF), as well as Absolute Minimum Flow (AMF)[5,70,81].
2. Low flow detection is also possible across the Flow Duration Curve (FDC), where it is determined by the percentage of probability, in different countries this percentage can vary, for example, 75%, 80%, 90%, 95%[5,73,80,83,84]. FDC is also quite flexible and different time intervals can be used as input data, such as daily average values or averages for 3, 7, 9, 10, 30 days[5]. Another similar method for calculating low flow can be used Low flow Frequency Curve (LFFC), where averaged data are used for a certain period over a year or a number of years (for studies, depending on the requirements, the period from 1 day to 1 year can be taken to average consecutive data)[5]. Unlike the previous approach, here the number of years with a low flow is directly determined[5].
3. Often, more stable indices are used to determine low flows, such as the detection with clear time limits. For example, there is a practice of using the 7Q10 or 7Q2 indices in the US, which consider an average of minimum 7-day values series for 10 and 2 years, respectively[5,85,79]. The MAM7 index (Mean Annual 7-day Minimum flow) or similar is also often used, which describes the average value of a series of data based on the smallest average seven-day flow for the year[5,75,79,83,86]. For Lithuania, a similar calculation is also used and is defined as the average value from a data series of the smallest yearly consecutive thirty-day flows (Q30)[87-89].
4. Since base flow reflects the contribution of groundwater to the total river flow, sometimes it can be used to determine low flow[5,71,90].

However, climate change further impacts low flows, altering the seasonal flow regime through shifts in precipitation patterns and temperature[75,91-93]. In addition to climate factors, low flow is influenced by geographical and anthropogenic factors[35,94], especially with increasing human pressure on the environment.

Recent studies across Europe and the US revealed varying trends in low flows, with some regions experiencing increases while others faced declines[35,75,83,86,91].

Despite its importance and frequent use of low flow indexes[89,95], research on low flow in Lithuania has been limited recently. Only a few papers about complex analysis of low flow changes were published in 2007 (analysis was done for data from 1922/1941/1961 till 2003)[87,88] and in 2014 with a limited number of stations (analysis was done for data from 1960 till 2009)[96]. However, these studies can provide important information about changes in river flow and offer a comprehensive analysis of what to expect with further climate change.

Hydrological drought

Drought is a recurring natural hazard with significant impact on various economic sectors and ecosystems worldwide[3,97,98]. The formation of a drought is associated with a long-term lack of precipitation[4,98]. It affects different climatic regions, occurring in both high and low rainfall areas, and can manifest at any time of the year. In recent decades, the frequency of droughts has significantly increased[99]. Studies show varying trends in drought frequency and severity across Europe[100], and the world[98]. At the same time, in the Europe region, scientists notice increasing drought numbers in the warm period of the year[101]. Climate change projections indicate a potential increase in extreme events, including droughts, with additional global warming[102]. Consequently, there is growing concern among scientists and decision-makers about the complexity and impacts of droughts and the need for preparedness to mitigate their effects[103].

Droughts can be classified into various types based on their impacts and hydro-climatological context. The four commonly recognised types include[3,98,104]: meteorological drought, which is directly formed by insufficient precipitation; agricultural or soil drought, due to lack of water in the soil; hydrological drought, caused by a water shortage in the rivers; socio-economic droughts, which is a consequence of previous droughts on ecosystems and human life. In this study, the main emphasis is on hydrological droughts, which directly impact river discharge levels and low flow during the warm period of the year.

Nowadays, there are various indices and indicators that help to detect, track and analyse hydrological drought, using variables such as precipitation, temperature, streamflow, groundwater levels, and soil moisture[105,106]. Three approaches are most often used to detect hydrological drought:

1. Detecting across meteorological indices. Some meteorological indices can be used as identifiers of hydrological drought, they include: Standardised Precipitation Index (SPI)[105-107]; Deciles[106,108]. SPI calculated over a long-term accumulation period (for example, 12 months) can show changes in rivers, reservoirs, and groundwater levels[105].
2. Hydrological drought indices directly. Such indices include: Palmer Hydrological Drought Index (PHDI)[3,4,106]; Standardised Reservoir Supply Index (SRSI)[106]; Standardised Streamflow Index (SSFI)[3,106]; Standardised Water-level Index (SWI)[106]; Streamflow Drought Index (SDI)[4,106,109]; Surface Water Supply Index (SWSI)[4,106,110]; Aggregate Dryness Index (ADI)[106]; Standardised Snowmelt and Rain Index (SMRI)[106]; Standardised Runoff Index (SRI)[3,111].

3. Threshold Level Method:

3.1 Determining drought due to flow duration curve (FDC). A smoothed monthly threshold with some percentage of FDC (for example 80%) can be used to identify periods, which can be identified as hydrological drought[3].

3.2 Determining drought due to low flow. As already mentioned, low flow is a recurring phenomenon every year, however, the average values of small runoff for a certain period of time can be used as a threshold value for identifying a hydrological drought.

In Lithuania drought events are not uncommon, even though the country belongs to a humid climate zone with abundant rivers and lakes. Over the past three years (2018–2020), due to hot and dry summers, hydrological droughts were declared each year for Lithuania. Based on recent studies, the frequency and intensity of droughts are expected to increase further. There is a need for a comprehensive analysis of hydrological droughts in Lithuania using multiannual hydrometeorological data and used climate models to forecast potential changes in the future.

Hydrological drought risk assessment

Hydrological Drought Risk Assessment is a critical undertaking in the face of the pressing issue of drought, which is a widespread phenomenon occurring in various climate regions globally[102,112-116]. With climate change induced by human activities, the frequency and severity of extreme weather events, including droughts, are on the rise[102,117-119]. Concurrently, population growth has led to increased water demand and deficits[116,119,120], making droughts an even more concerning challenge. Despite being a longstanding issue, the lack of comprehensive methods for assessing and predicting droughts persists[114].

The importance of identifying territory under hydrological drought risk goes beyond simply recognising them, such actions are the first crucial step to mitigating future impacts. The purpose of hydrological drought risk assessment is to detect the most vulnerable areas, in which the highest pressure on water resources, ecosystems, and human activities under hydrological drought are expected. Neglecting drought in strategic development plans can result in severe consequences, such as water scarcity, food insecurity, and economic losses. Unlike sudden natural hazards, droughts have a slow onset and can persist for extended periods, allowing for ample preparation to withstand their pressure[114,121]. Minimising the direct and indirect social, environmental, and economic impacts of droughts becomes a global priority, necessitating targeted risk reduction and adaptation efforts[122].

Basically, hydrological drought risk assessment, as well as any other risk analysis, includes two components: hazard and vulnerability. The hazard component involves examining past droughts across drought indices or low flow indices[42,123,124]. The vulnerability component assesses various factors such as GDP, agricultural lands, land cover, population density, etc[42,123-125].

Prior research has predominantly applied quantitative or mixed-methods approaches to drought risk assessments, with index-based approaches being commonly used[122]. Several studies have attempted global[126] and regional[124,127,128] assessments of drought risk, revealing regions with higher vulnerability due to human activities and exploitation for agriculture and livestock farming. Also, it is worth noting that depending on the research objectives, the variables of both components may vary, which, in turn, complicates the comparison of results between different countries or research areas.

While there has been an increase in drought-related studies in Lithuania, the specific assessment of hydrological drought risk and vulnerability has not been conducted. It is worth mentioning that at the moment, there are some local studies describe hydrological drought risk assessment in the frame of local problems: impact of drought on the saltwater intrusion into rivers[115], drought forecasting[116,129] drought assessment in the past[39,41], paleohydrology and drought assessment in the past (low flow index (LFI) and flow duration curves were used)[130]. Only several studies related to the comprehensive assessment of hydrological drought risk: hydrological drought risk assessment in the past and future for South Korea[131], hydrological drought risk assessment in Malaysia[42].

The author input on the topic

The author provides a deeper understanding of how river intermittency phenomena depend on physical geographical factors in Lithuania. Especially, this topic is relevant for countries with a temperate/humid continental climate and lowland rivers, where river intermittency is poorly studied.

Despite the widespread use of low flow indices in Lithuania, there remains a significant gap in research that considers changes during the first two decades of 21st century. As a result, a comprehensive analysis of low flow and its trends in Lithuanian rivers was performed.

The presented research covers the gap in knowledge by specifically addressing hydrological drought risk in Lithuania. This includes the consideration of the longest and most extreme drought events, identification of the most vulnerable regions, spatial and temporal dynamics of hydrological drought, and forecasts for the future based on two widely used RCP scenarios: RCP4.5 and RCP8.5.

The forecasting was carried out for six rivers from different hydrological regions of Lithuania using the HBV software for the period from 2021 to 2100. During the forecasting process, emphasis was placed on parameters that have the greatest impact on the accuracy of low flow prediction during the warm period of the year. In contrast to other studies, this approach allowed for a better exploration of potential hydrological drought risks in the future.

In collaboration with colleagues, a hydrological drought index based on water levels, known as the Standardised Water Level Index (SWLI), was developed and tested. For rapid hydrological drought identification, an Excel application was prepared, and a 10-day accumulation period was proposed for use as an operational period.

A methodology for calculating hydrological drought risk assessment in Lithuania has been developed, which concentrates mainly on water objects and includes both components of hazard and vulnerability. This work is the first comprehensive evaluation of hydrological drought risk in Lithuania and is among the first globally, with potential applications for other lowland regions. As a result of this study, a detailed map has been generated, depicting the degrees of hazard, vulnerability, and risk for each catchment.

2. DATA AND METHODS

2.1. Input data for the dissertation work

Lithuania is situated on the eastern coastline of the Baltic Sea and covers 65,200 square kilometres. The country primarily features flat terrain, with its highest point rising to 294 meters above sea level. Lithuania has a network of more than 22,000 rivers and streams, with a combined length exceeding 77,000 kilometres.

Typically, Lithuanian rivers exhibit an annual hydrograph characterised by a peak discharge during early spring, a result of the substantial water flow caused by spring snowmelt. However, for the most part, river discharges remain relatively low during the warmer months.

To perform all calculations, a database comprising more than 150 WGSs and 38 meteorological stations, which did measurements in the past and currently active within Lithuania's territory, was analysed. For each specific task, the most suitable stations were selected, considering the characteristics of river flow and the duration of the observation period. The main stations are shown in Figure 2. Primary data were obtained from the Lithuanian Hydrometeorological Service in the daily data series format.

Input data for modelling

To investigate hydrological drought, six forecasting models were developed. Three runoff models (for the Šventoji, Venta, and Minija rivers) were prepared to analyse hydrological droughts according to SDI-12. The another three forecasting models, encompassing the Nemunas River, along with Žeimena and Šešuvis, were prepared to analyse hydrological droughts according to SWLI.

For successful river discharge forecasting, multiple datasets are essential, including historical hydrological and meteorological data, land cover data, and data from regional climate models (RCMs). Historical data from the period 1986–2005 encompassed daily discharge data, as well as daily temperature and precipitation data retrieved from nearby meteorological stations. Physical-geographical data from the CORINE database were collected for each river. The three RCMs (Table 1) used for the 2021–2100 period were obtained from the EURO-CORDEX database (www.euro-cordex.net, accessed on 21 October 2022).

Table 1. Key details of the selected RCMs

№	Driving Model	RCM	Institute	Resolution	Ensemble
1	CNRM-CERFACS-CNRM-CM5	RCA4	SMHI	0.11°	r1i1p1
2	ICHEC-EC-EARTH	RACMO22E	KNMI		
3	MPI-M-MPI-ESM-LR	REMO2009	MPI-CSC		

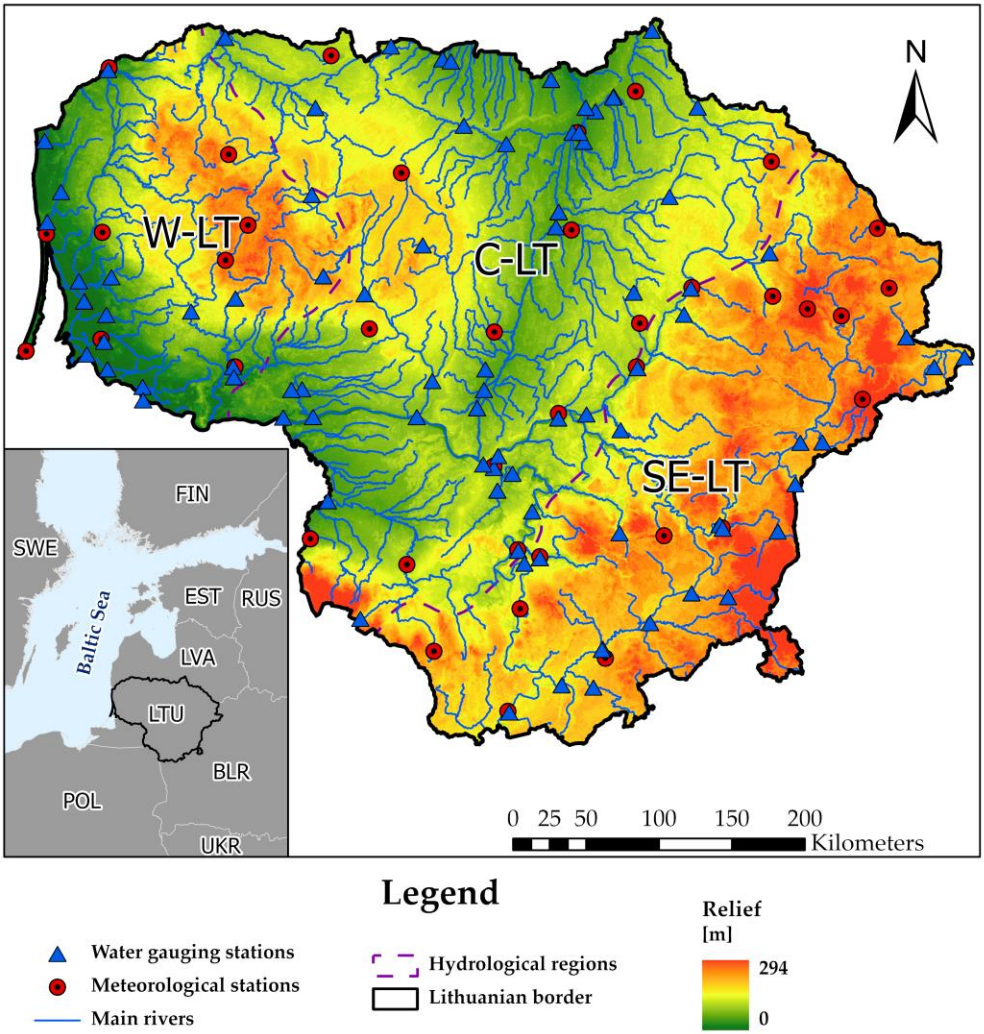


Fig. 2. Location of the main hydrological and meteorological stations

To adapt the RCM data, the quantile mapping method was employed, as per the following equation:

$$St^{Obs}=h(St^{CM\ RP})=ECDF^{Obs-1}(ECDF^{CM\ RP}(St^{CM\ Fut})); \qquad (2)$$

Where St^{Obs} represents the observed meteorological parameter, $St^{CM\ RP}$ stands for the climate model output during the reference period, $ECDF^{Obs}$ refers to the empirical cumulative distribution function for the observation period, $ECDF^{CM\ RP}$ indicates the empirical cumulative distribution function for the climate model's reference period, and $St^{CM\ Fut}$ represents the meteorological parameter projected for the future period by the climate model.

Input data for hydrological drought risk assessment

As already mentioned, daily hydrological and meteorological datasets were taken from the Lithuanian Hydrometeorological Service. 1059 catchments from 19 main Lithuanian basins were taken for extensive analysis of Lithuania. Additionally, SRTM raster data was used with 1 arc-second resolution from the following website: https://earthexplorer.usgs.gov/ (accessed on April 21, 2023). Land cover, soil, and lake data were sourced from https://www.geoportal.lt/geoportal/ (accessed on April 22, 2023).

2.2. Methods of the dissertation work

This dissertation work integrates the methodologies of 5 articles and is presented in the form of 5 subsections corresponding to the objectives. According to that, a distinct methodology was used to achieve each of the objectives. General methodology was presented in Figure 3.

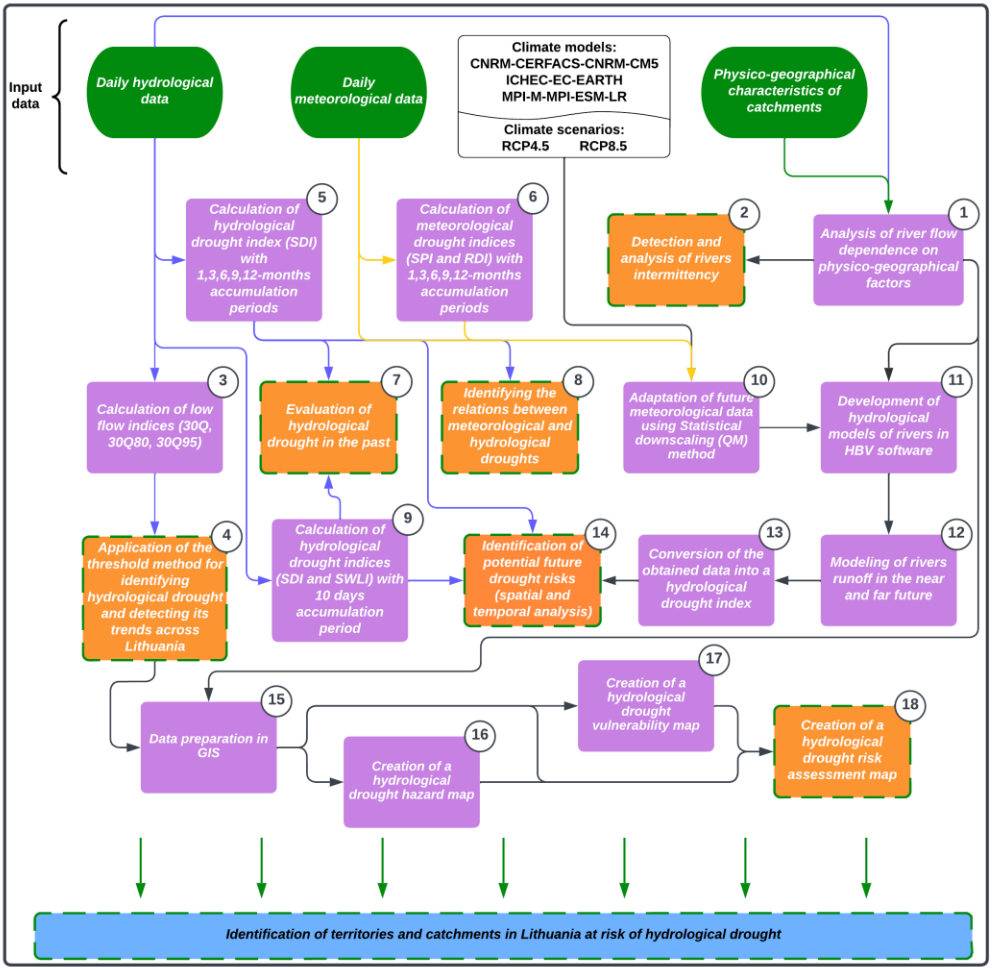


Fig. 3. General methodology of work

According to Figure 3, the overall process of the research methodology can be divided into several main blocks:

1. Study of the river intermittency phenomenon and intermittent rivers in Lithuania (steps 1 and 2).
2. Study of low flow in Lithuanian rivers (steps 3 and 4)
3. Investigation of historical hydrological drought and its dependency on meteorological drought (steps 5–9).
4. River runoff modelling and forecasting hydrological drought in the near and far future (steps 10–14).
5. Creation of a hydrological drought risk assessment map (step 15–18).

According to the presented scheme, steps 2, 4, 7, 14, and 18 allow for the synthesis of the work into a final result, namely: the identification of territories and catchments in Lithuania at risk of hydrological drought.

2.2.1. Detail overview of block 1 (river intermittency)

The study focused on Lithuanian rivers and their flow intermittency during the warm period of the year (May – September). To identify intermittent events, a discharge threshold of 0.001 m^3/s was implemented. The analysis included data from 16 water gauging stations (WGSs) with a duration of intermittent events of at least three days. The hydrological data for these rivers encompass varying observation periods, ranging from 13 to 63 years in length.

Key indices, such as the mean number of zero-flow days (mDUR), the maximum number of zero-flow days (maxDUR), the mean annual frequency of zero-flow periods (FREQ, %), mean flow during the warm period (Q_P, m^3/s), and timing of zero-flows (T_0), were calculated to analyse the intermittent patterns.

Correlation analysis was employed to examine the relationship between flow intermittency indices and geographical factors. Catchment characteristics such as area, slope, land use and soil types were considered.

2.2.2. Detail overview of block 2 (low flow indexes)

Low flow indices were assessed over three time periods: 1961–2020, 1961–1990, and 1991–2020. The 30Q index was calculated as the average of annual consecutive minimum thirty-day flows. Additional low flow indices, namely 30Q95 and 30Q80, were derived from the frequency curve using yearly minimum consecutive thirty-day average flows datasets with 95% and 80% thresholds respectively (Fig. 4). These indices were used to establish thresholds for low flow duration, maximum deviation, and deficit volume. For cross-scale comparisons, specific low flow q values (30q, 30q95, and 30q80) were calculated as $q = Q/A \cdot 1000$ (Q: low flow discharge; A: catchment area), in $l/s \cdot km^2$.

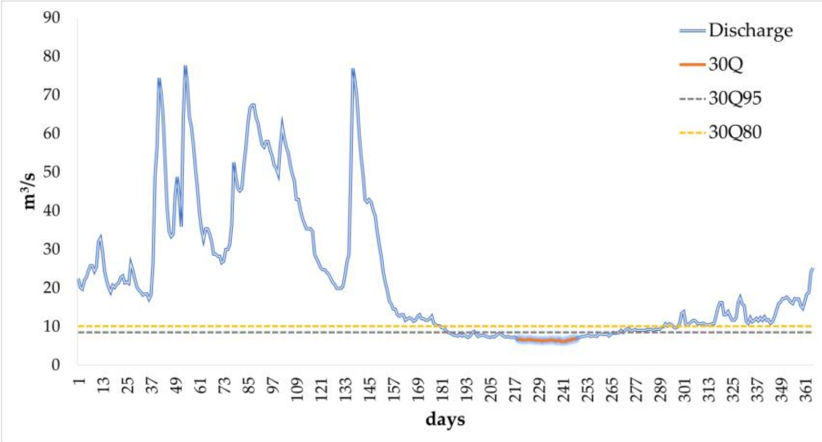


Fig. 4. Principal scheme of low flow index identification (example of the Šventoji at Ukmergė WGS in 1973)

Using the FDC tool (Flow Duration Curves) in the HydroOffice software package (version 2.1), 30Q95 and 30Q80 were computed, while the TLM tool (Threshold Level or Sequence Peak Algorithm Methods) evaluated extreme flow conditions, providing data on drought periods, maximum deviation, and deficit volume. Maps of low flow indices were generated using Kriging interpolation in ArcGIS 10.5 software, based on the assumption that spatial correlation between sample points explains surface variation.

The TREND software (V.1.0.2.) facilitated statistical trend testing in hydrological time series data, utilising the Mann-Kendall (MK) and Spearman's Rho (SR) nonparametric tests. MK detects linear or non-linear trends, while SR identifies trend absence. Trends in 30Q data series were tested at significance levels $\alpha = 0.1$ or 0.05 for both positive/negative or significant positive/negative outcomes.

2.2.3. Detail overview of block 3 (hydrological indexes)

One of the main indices for identifying hydrological droughts is the Streamflow Drought Index (SDI), which is based on the same principles as the Standardised Precipitation Index (SPI) index. The SDI index proves to be a straightforward and efficient measure for tracking hydrological droughts by utilising cumulative streamflow discharge data. In addition to the SDI, it is proposed to use an index based on water levels, known as the Standardised Water Level Index (SWLI). This approach would enable a faster response to the occurrence of hydrological droughts. Mention drought indices were calculated according to Equation 1.

$$I = (x_i - x_{mean})/\sigma; \quad (1)$$

Where I – drought index;

x_i – is the variable of the selected period during the year i;

x_{mean} – is the long term mean data of the variable;

σ – is the standard deviation for the selected period.

As variables, precipitation, river discharge and water levels were used in Equation 1. Also, all indices were calculated for a period of no less than 30 years, in line with the necessary requirements.

To evaluate hydrological drought at different timescales, several accumulation periods were used: 10 days, 1 month, 3 months, 6 months, 9 months, and 12 months. The assessment of indices is carried out using the scale presented in Table 2.

Table 2. Original drought classes according to drought indices[4]

Drought class	Index
Non-drought / wet period	$X \geq 0.0$
Mild drought / near normal conditions	$-1.0 \leq X < 0.0$
Moderate drought	$-1.5 \leq X < -1.0$
Severe drought	$-2.0 \leq X < -1.5$
Extreme drought	$X < -2.0$

Calculations with accumulation periods lasting more than 1 month were performed using the software tool DrinC (Drought Indices Calculator). For the calculation of ten-day accumulation periods, a custom Excel spreadsheet with formulas based on Equation 1 was used, prepared personally.

In theory, there should be a linear (1:1) relationship between SWLI and SDI values. But in practice, there are deviations from this relationship could stem from various processes occurring in the riverbed, such as the growth of aquatic vegetation or changes in the river bed. To assess the extent of variability in the correlation curves between SWLI and SDI, calculations were conducted by inputting an x-value (SDI coefficient) of -1.5 into the determination equation. This x-value represents the threshold for severe drought in the SDI index and is theoretically expected to be the same for the SWLI index. Using this approach, new severe drought threshold values (SDTV) were determined for SWLI through the application of determination equations in each river.

2.2.4. Detail overview of block 4 (river discharge forecasting)

One effective tool for river runoff forecasting is the Hydrologiska Byråns Vattenbalansavdelning (HBV) software. Developed by the Swedish Meteorological and Hydrological Institute (SMHI), this software provides a sophisticated platform for simulating and predicting hydrological processes. By integrating hydrological data, precipitation, temperature, and other relevant variables, the HBV software empowers researchers and hydrologists to model and anticipate future hydrological drought events. The water balance equation forms the basis of this software:

$$P-E-Q=d/dt[SP+SM+UZ+LZ+V]; \qquad (3)$$

Where P represents precipitation, E stands for evaporation, Q denotes discharge, SM indicates soil moisture, SP refers to snow pack, UZ represents the upper groundwater zone, LZ signifies the lower groundwater zone, and V corresponds to the volume of a lake or dam.

The calibration of the developed hydrological models involved adjusting 16 to 19 main parameters, depending on the specific model. In both the calibration and validation periods, the correlation coefficients (r) between the observed and computed water discharges ranged from 0.68 to 0.88. These correlation values highlight the hydrological models' ability to predict runoff under changing climatic conditions. To better investigate low flow conditions, the primary focus was on parameters that directly influence warm-season runoff. This includes parameters such as maximum soil moisture storage (fc), percolation capacity (perc), and the recession of summer and autumn discharges (khq, k4), among others.

2.2.5. Detail overview of block 5 (hydrological drought risk assessment)

The assessment of hydrological drought risk (HDR) comprises two main elements: drought hazard (HDHI) and drought vulnerability (HDVI). The overall calculation procedure is illustrated in Fig. 5.

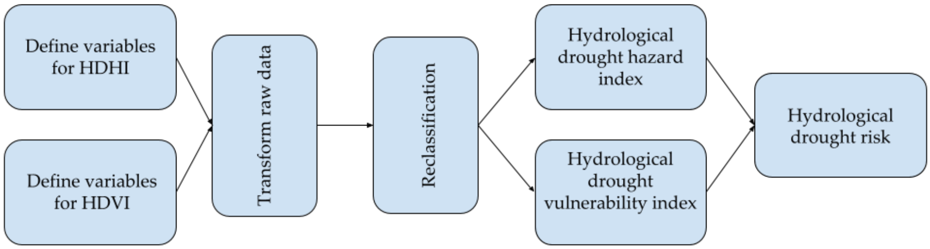


Fig. 5. Overall procedure for calculating HDR

The primary equation was applied to calculate hydrological drought risk:

$$HDR=((WSD+WLD+R+RD)/4+(S+LULC+SL+L)/4)/2; \qquad (4)$$

Where *WSD* represents hydrological droughts with a duration of 5–16 days, *WLD* stands for hydrological droughts lasting more than 16 days, *R* signifies average precipitation, *RD* indicates the dependency of river runoff on rainfall, *S* represents slope, *LULC* represents land use/land cover, *SL* refers to soil morphological composition, and *L* denotes lake density. The first four variables represent the drought hazard component, while the last four represent the drought vulnerability component. The primary data for each variable (Table 3) were reclassified on a scale of 0–1. An exception was only made for the variable "River runoff dependence on rainfall" as there is no river in Lithuania that is entirely dependent or entirely independent of rainfall.

Table 3. Calculations and primary data of variables

Variable	Primary data limits before rescaling	Description
WSD	16–75 events	Q30 was used as a threshold for the identification of drought events. Rescaled before use in GIS
WLD	27–55 events	
R	572–856 mm/yr	The minimum and maximum annual values in Lithuania were taken as limits for rescaling
RD	0–1	The maximum recorded value of river runoff dependence on rainfall in Lithuania is 0.63, the minimum is 0.19.
S	0.0–42.2	Calculated from SRTM
LULC	Water – 0 Forest – 1 Semi-natural area – 2 Pasture/grassland – 3 Agricultural lands – 4 Urban – 5	Classification based on the analysis of consolidated data scales in similar articles.
SL	Sand – 1 ↓ Heavy clay – 10	Given that clayey soils are associated with higher surface runoff, while sandy soils contribute to groundwater formation, it was decided to assign the highest vulnerability score to clayey soils, which are less conducive to groundwater feeding source formation.
L	0–30%	A lake density of 30% percent was taken as 0

Consequently, the minimum and maximum values for this variable do not extend to 0 and 1, respectively. For spatial analysis, ArcGIS 10.5 software was used to address specific tasks, including analysis of spatial patterns, interpolation, raster processing, and raster calculations.

3. OUTCOMES OF THE RESEARCH

Comprehensive research on the low flow of Lithuanian rivers is not possible without considering its individual parameters or components. Therefore, only multidimensional research can provide a comprehensive overview of the issue and identify the most vulnerable areas. All components of the study (intermittency, low flow, hydrological drought) are focused on examining the river flow, which is smaller than the annual average flow, and describing how it changes due to climate change. The relationship between the components of this work is presented in Figure 6. The first four articles fully cover the analysis of the intermittency, low flow, hydrological drought, while the fifth is overarching and reflects the catchments in Lithuania that face the highest hydrological drought risk due to climate change.

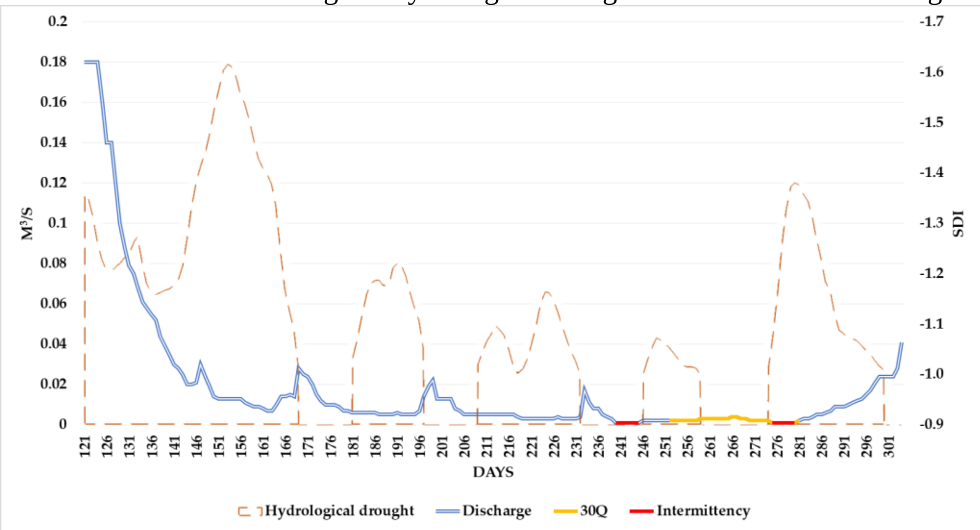


Fig. 6. Interconnections between intermittency (m^3/s), low flow (m^3/s) and hydrological drought (SDI) for Svyla river at 2002

3.1. The variability investigation of the river intermittence, as an extreme part of the river low flow, within Lithuania.

Climate change is causing widespread and inevitable alterations to the hydrological patterns of water bodies around the globe. These same drivers are also leading to changes in the prevalence and intensity of river intermittency. Since intermittency is quite common, especially in small catchments, these events play a vital role in ecosystems. Uncontrolled changes can cause irreparable damage to both natural and anthropogenic environments. Accordingly, investigating their dynamics and the factors influencing them is crucial.

Article 1: ŠARAUSKIENĖ, Diana, AKSTINAS, Vytautas, NAZARENKO, Serhii, KRIAUČIŪNIENĖ, Jūratė and JURGELĖNAITĖ, Aldona. Impact of physico-geographical factors and climate variability on flow intermittency in the rivers of water surplus zone. Hydrological Processes. 2020. Vol. 34, no. 24, p. 4727–4739. DOI 10.1002/hyp.13912

Chapter place in the thesis work: This chapter provides a brief review of Article 1, which addresses Objective 1 and describes the most extreme aspects of low flow and hydrological drought in general. Intermittent rivers are still relatively understudied in Lithuania, despite their significant importance for ecosystems. Consequently, this section aims to investigate this scientific gap.

Variability of river intermittency:

Except for one river (Daugyvenė with an area of 487 km^2), all the investigated rivers range in size from 10.1 km^2 to 206 km^2, and the average annual discharge does not exceed 2.56 m^3/s (Akmena river), with a 2–4 times reduction in average summer discharge (Table 4). Notably, the key indicators of flow intermittency, including zero-flow duration and frequency, revealed considerable variation among the selected rivers. Among the studied rivers, the Agluona, Svyla, and Akmena displayed the shortest mean flow intermittency durations (less than a day), along with a more consistent flow throughout the year. This unique feature was observed in the South-Eastern hydrological region and Western hydrological region of Lithuania.

Table 4. Characteristics of river intermittency during the May – September period

River	WGS	Q_P	mDUR	maxDUR	FREQ	T_0
Šešuva	Kalnėnai	0.475	3.00	24	14.3	195
Dotnuvėlė	Dotnuva	0.232	1.26	23	13.0	231
Smilga	Pasmilgys	0.318	15.2	100	25.9	190
Šušvė	Šiaulėnai	0.536	1.70	54	3.17	221
Alsa	Paalsys	0.129	7.68	81	28.9	208
Pedamė	Antkalniai	0.032	77.1	152	90.5	156
Imsrė	Jakaičiai	0.024	85.4	151	92.9	144
Pilvė	Papilvis	0.274	19.9	79	50.0	206
Milupė	Stoškai	0.050	53.6	129	88.9	157
Svyla	Guntauninkai	0.396	0.11	6	1.89	241
Agluona	Dirvonakiai	0.159	0.73	29	2.50	242
Daugyvenė	Rimšoniai	0.671	4.15	30	15.4	244
Yslykis	Kyburiai	0.095	33.6	116	58.3	181
Platonis	Vaineikiai	0.113	18.2	122	23.1	182
Sidabra	Šarkiai	0.083	10.9	142	7.69	133
Akmena	Tūbausiai	0.842	0.26	11	2.33	174

The Pedamė and Imsrė (the smallest rivers) showed highly intermittent behaviour, an average of 77 to 85 days of zero-flow per year, respectively, during the observation period. The Pedamė (152 zero-flow days) and Imsrė (151 zero-flow days) also showed the maximum recorded durations of flow cessation. Moreover, the mean annual frequency of zero-flow occurrences pointed to regular flow interruptions in the Pedamė, Imsrė, and Milupė, spanning 89–93% of the observation years. This characteristic classified these rivers as extremely intermittent. At the same time, six rivers had only a few instances of intermittency (these include Svyla, Agluona, Akmena, Šušvė, Sidabra, and Šešuva).

Examining the observation period, the onset of flow cessation varied, from the beginning of May (as seen in the Pedamė, Imsrė, and Smilga) to the first part of September (observed in the Daugyvenė and Smilga). Analysis of available data revealed that the highest frequency of zero-flow events occurred towards the end of the warm season, particularly in August and September.

Assessing historical trends of stream intermittency in the studied rivers proves challenging due to the absence of a unified observation framework. It is noteworthy, however, that within the last two decades (2000–2018), the highest number of zero-flow days were documented in 2006, 2015, and 2018.

River intermittency dependence on physical-geographical factors:

Physical-geographical factors, or catchment characteristics, included the following indicators: catchment area (A), slope of the watercourse (S), forested areas (For), agricultural lands (Agr), and various soil types (sandy loam (SL), light clay loam (LCL), medium and heavy clay loam (MHCL), and peat (P)). These catchment characteristics were correlated with indices of river intermittency to identify interconnections between them. The analysis assessed the strength of relationships between variables, focusing on moderate (0.50 to 0.70 or -0.50 to -0.70), high (0.70 to 0.90 or -0.70 to -0.90), and very high (0.90 to 1.00 or -0.90 to -1.00) correlation coefficients.

Linear correlation analysis demonstrated that the mean discharge during the warm period has a high correlation with the catchment area (Fig. 7). In addition to its influence on river discharge, the catchment area also had a moderate negative impact on the mean and maximum duration of zero-flow days, frequency, and a positive correlation with the timing of intermittency indices (Table 5).

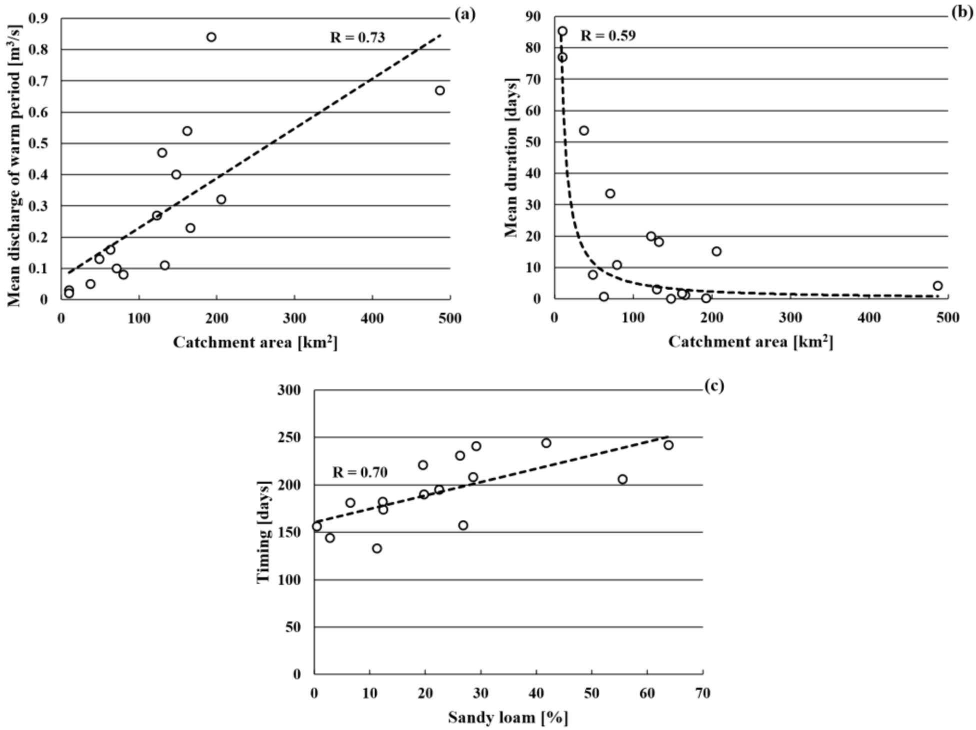


Fig. 7. Relationships between variables

Watercourse slope emerged as the most influential factor in this analysis, highlighting its impact on flow intermittency indices. The frequency and maximum duration of intermittent events showed a moderate positive correlation with the watercourse slope (r = 0.63 and r = 0.65 respectively), while the relation with the index of mean duration had a high positive correlation (r = 0.77). Also, the timing of zero-flow events exhibited a moderate negative relation (r = -0.68). In essence, a steeper watercourse slope corresponds to earlier, more frequent, and longer-lasting zero-flow events.

Indices of river intermittency did not significantly correlate with forest or agricultural land percentages.

Table 5. Linear correlation coefficients between variables

Indices	A, km^2	S, m/km	For, %	Agr, %	Soils, %			
					SL	LCL	MHCL	P
QP	**0.74**	-0.42	0.23	-0.29	0.18	-0.13	-0.42	0.43
mDUR	-0.52	**0.77**	0.14	-0.07	-0.49	-0.14	0.64	-0.44
maxDUR	-0.53	0.65	-0.09	0.12	-0.53	0.20	0.49	-0.44
FREQ	-0.50	0.63	0.10	-0.02	-0.36	-0.14	0.56	-0.47
T0	0.53	-0.68	-0.07	0.04	**0.70**	-0.27	-0.46	0.52

The indices of zero-flow events are ambiguously correlated with different soil types (Table 2). Sandy loam showed a strong positive relation with the timing of the intermittent period (r = 0.70) (Fig. 3c). According to Table 2, one can observe the difference between trends for different soil types (specifically SL and MHCL). From this, we can conclude that the permeability of predominant soils in the river catchment significantly influences groundwater storage and river supply during low flow periods.

In general, intermittent rivers can occur in water surplus zones, and Lithuania is no exception to this phenomenon. The majority of the identified intermittent rivers are located in the Central hydrological region, where physical geographical factors are the most suitable for their formation. The intermittency of rivers in Lithuania is primarily influenced by factors such as the catchment area, slope, and soil type.

3.2. The spatial and temporal analyses of rivers' low flow indicators in the past.

Low flow, a fundamental aspect of river flow regimes, emerges as a result of reduced rainfall. Unlike river intermittency, low flow is a constant phenomenon and is divided into winter and summer. Usually, summer low flow is more pronounced and pernicious, and this study primarily focuses on it.

Article 2: NAZARENKO, Serhii, MEILUTYTĖ-LUKAUSKIENĖ, Diana, ŠARAUSKIENĖ, Diana and KRIAUČIŪNIENĖ, Jūratė. Spatial and temporal patterns of low-flow changes in lowland rivers. Water. 2022. Vol. 14, no. 5, p. 801. DOI 10.3390/w14050801

Chapter place in the thesis work: This chapter provides a brief review of Article 2, which addresses Objective 2 and describes the variability of low flow indexes in Lithuania. Prolonged low flow situations lead to habitat deterioration, issues with species dispersion, endanger ecosystems and communities and, in some cases, contributes to river intermittency. Escalating global temperatures exacerbate the concern, and this research aims to enhance our understanding of low flow behaviour in lowland river catchments.

<u>Variability of low flow indices: spatial and temporal analysis:</u>

To assess regional low flow patterns, specific flow indices (30q, 30q95, and 30q80) were employed for the selected periods (1961–1990, and 1991–2020) for three hydrological regions of Lithuania (Table 6). The Southeastern hydrological region (SE-LT) exhibited a rise in lower values across all indices during 1991–2020 compared to 1961–1990. In the Western (W-LT) and Central (C-LT) hydrological regions, the distribution of low flow indices do not have clear tendencies.

Table 6. The range of selected low flow indices

	1961–1990			1991–2020		
	30q	30q95	30q80	30q	30q95	30q80
W-LT	1.28–2.63	0.45–1.13	0.75–1.56	1.04–2.32	0.49–1.23	0.74–1.69
C-LT	0.63–3.31	0.15–2.38	0.32–2.71	0.46–3.39	0.18–2.42	0.24–2.91
SE-LT	2.24–5.07	1.20–3.77	1.66–4.84	2.62–5.06	1.51–3.77	1.87–4.25

In the Western (W-LT) region, the analysis of low flow index distribution revealed a 30q average of 2.07 l/s·km^2 for 1961–1990, which decreased to 1.83

l/s·km^2 in 1991–2020 (Fig. 8). Notably, the 30q values for the selected periods exhibited little difference in the Central (C-LT) region, measuring 1.49 and 1.46 l/s·km^2, and in the Southeastern (SE-LT) region, maintaining a consistent 3.97 l/s·km^2. The highest index values were consistently observed in the SE-LT region for both periods, while the lowest values were found in the C-LT region.

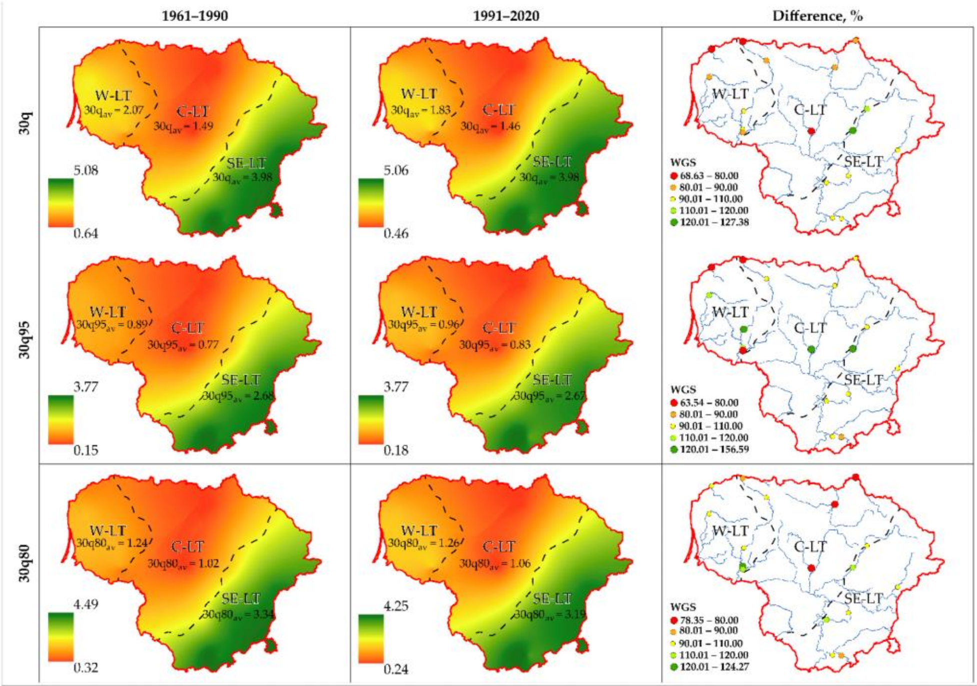


Fig. 8. Distribution and changes of low flow indices across Lithuania

According to Fig. 8, all rivers in the western and central hydrological regions show slight changes or decreases in the value of the 30q index by a minimum of 10%. Such results may indicate an increase in the frequency of extreme low flow events, but without a corresponding increase in their severity (except for some stations). In the case of the SE-LT region, characterised by consistently high index values, there are mainly minor changes in low flow, suggesting greater stability in this region.

Changes in low flow indices: trend analysis:

To examine changes in low flow patterns over time, the approach of utilising thirty-year moving averages for trend analysis was adopted. Trend analysis for 17 datasets with 30Q data spanning the period from 1961 to 2020 was conducted using the Mann–Kendall test, results are illustrated in Fig. 9. This methodology offers a more detailed understanding of the evolution and dynamics of low flows. Prior to 1973, the majority of WGSs demonstrated positive or significantly positive trends, with the exception of one WGS (Ūla river) in the SE-LT region, which exhibited a contrary trend. Subsequent to 1973, WGSs in the W-LT and C-LT regions predominantly showed negative or significantly negative trends, while trends in the

SE-LT region often lacked statistical significance. Notably, a solitary WGS at Šventoji river (SVE2) in the SE-LT region exhibited substantial and sustained increases in 30Q until 1976, standing out as the sole instance of consistent upward trends across the observation period.

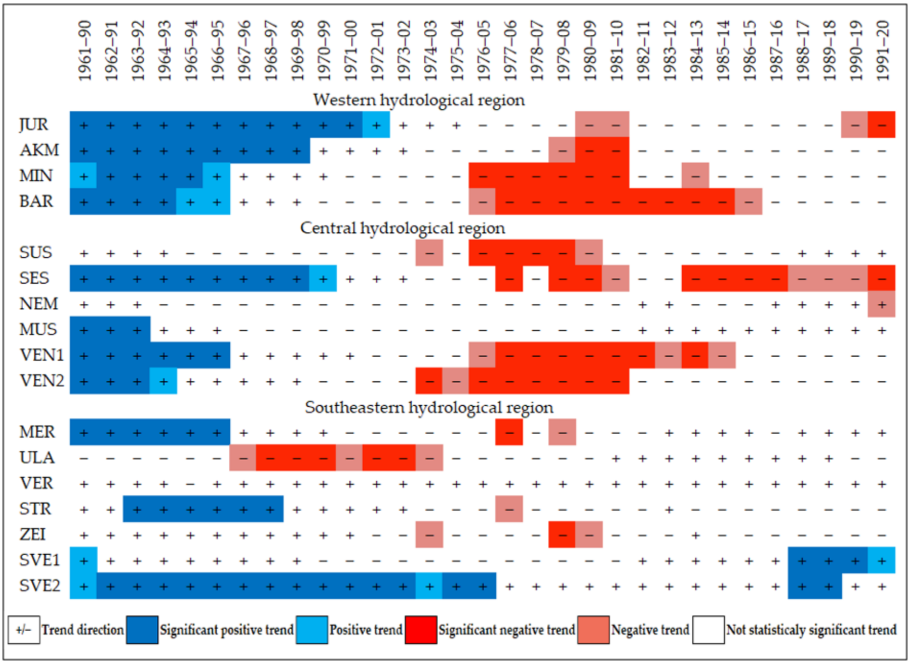


Fig. 9. Trend analyses using the Mann-Kendall test for 30Q

Broadly, the first half of the observation period in the W-LT and C-LT regions was marked by statistically significant positive trends, whereas negative trends were more concentrated in the middle and latter portions of the 1973–2020 timeframe. In contrast, the SE-LT region's WGSs displayed varying trend directions, particularly over the entire observation period.

<u>Identification of dry days based on low flow indices:</u>

The indices 30Q80 and 30Q95 were used as threshold values for identifying dry days. The first analysis was conducted within the three hydrological regions of Lithuania. The temporal distribution of the average number of dry days for each region (shown in Fig. 10) revealed that, for both thresholds, the average annual number of dry days per river tended to decrease in the W-LT and SE-LT regions, while increasing in the C-LT region. Generally, the highest concentration of dry days occurred during the periods 1963–1976, 1992–2006, and 2015–2020. Specifically, the driest years in different regions were: 1969 – W-LT region (33 days for 30Q95, 76.5 days for 30Q80); 1971 and 2006 – C-LT region (47.3 days for 30Q80, 21.5 days for 30Q95, respectively); 1971 – SE-LT region (33.7 days for 30Q95, 64.4 days for 30Q80).

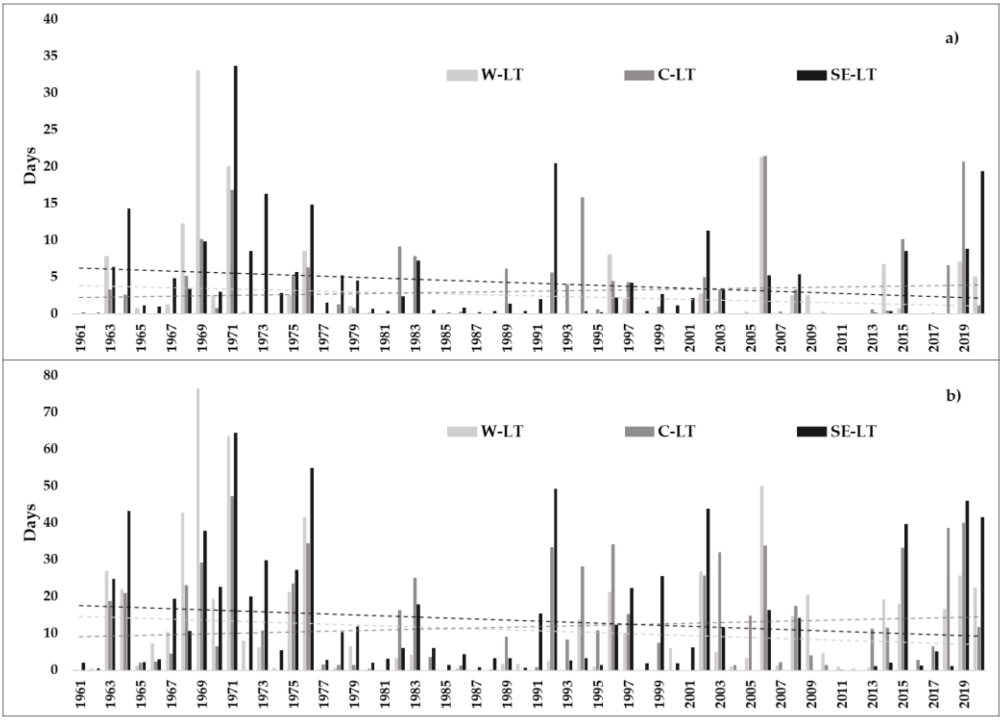


Fig. 10. The mean count of dry days within the three regions: (a) using the 30Q95 threshold, (b) employing the 30Q80 threshold

Based on the above, the highest low flow indices were observed in the SE-LT region, while the lowest were found in the C-LT region. The period from 1961 to 1990 is characterised by positive trends in low flow indices growth. There are no significant trends for hydrological regions at the end of the studied period. In the C-LT region, a trend towards an increase in dry days has been identified based on the threshold indices of 30Q95 and 30Q80.

3.3. Investigation of the hydrological drought phenomenon according to historical data.

Hydrological drought is a natural phenomenon in any ecosystem, but it has wide-ranging impacts across various economic sectors and ecosystems, making it one of the costliest natural disasters. Unlike low flow, hydrological drought is not part of the river's annual regime; it often covers longer time spans and leads to consequences that cannot be restored by the usual rise in water levels. Therefore, in the case of insufficient precipitation, it can persist continuously for several years. At the same time, due to climate changes, drought is becoming stronger and more frequent, leaving limited opportunities for adaptation.

Article 3: NAZARENKO, Serhii, KRIAUČIŪNIENĖ, Jūratė, ŠARAUSKIENĖ, Diana and JAKIMAVIČIUS, Darius. Patterns of past and future droughts in permanent lowland rivers. Water. 2022. Vol. 14, no. 1, p. 71. DOI 10.3390/w14010071

Article 4: NAZARENKO, Serhii, KRIAUČIŪNIENĖ, Jūratė, ŠARAUSKIENĖ, Diana and POVILAITIS, Arvydas. The development of a hydrological drought index for Lithuania. Water. 2023. Vol. 15, no. 8, p. 1512. DOI 10.3390/w15081512

Chapter place in the thesis work: This chapter provides a brief review of Article 3 and Article 4, which addresses Objective 3 and providing insights into the analysis of historical hydrological droughts. Investigating hydrological drought represents a distinct approach to analysing river conditions from low flow analysis. Given that hydrological drought is less studied in Lithuania than meteorological or agricultural droughts, there is a need to fill this research gap.

Variability of hydrological drought at different time scales:

Duration represents one of the fundamental attributes of droughts. The interval of drought was identified as the time frame starting from the month when the SDI value reached or fell below -1 and ending when value become higher than -1. At Fig. 11, the duration of the most extensive droughts increased in tandem with the increasing of the accumulation period. On average, hydrological droughts in the W-LT region exhibited briefer durations compared to those in the SE-LT and C-LT regions.

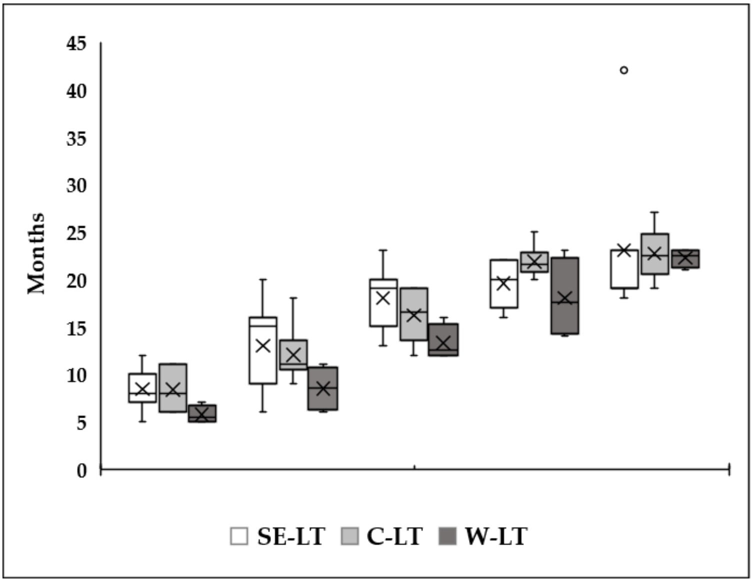


Fig. 11. The duration of hydrological drought in months (with increasing accumulation periods from left to right: 1, 3, 6, 9, and 12 months, respectively)

The maximum duration of drought was recorded within the SE-LT region (specifically in the Šventoji catchment) during a 12-month accumulation period. This protracted drought endured for 42 months, spanning from May 1971 to October 1974. Notably, the extreme SDI-12 values for this river (-2.46) were also recorded in this time period, specifically in October 1972. Comparatively, the W-LT region had the shortest maximum drought duration, spanning 23 months based on SDI-12. This timespan was observed in two rivers within the region, namely the Akmena and Minija, during the period from December 1975 to October 1977.

Based on SDI-1 (Fig. 12), the Western hydrological region exhibited the least number of Severely Dry and Extremely Dry months, whereas the Southeastern hydrological region recorded the highest count. Although SDI-3 displayed similar distinctions between regions, they were less pronounced. The analysis of SDI-6 indicated no significant variations among regions. SDI-9 and SDI-12 highlighted extended droughts being more prevalent in the W-LT and C-LT regions, with catchments in the SE-LT experiencing fewer dry months.

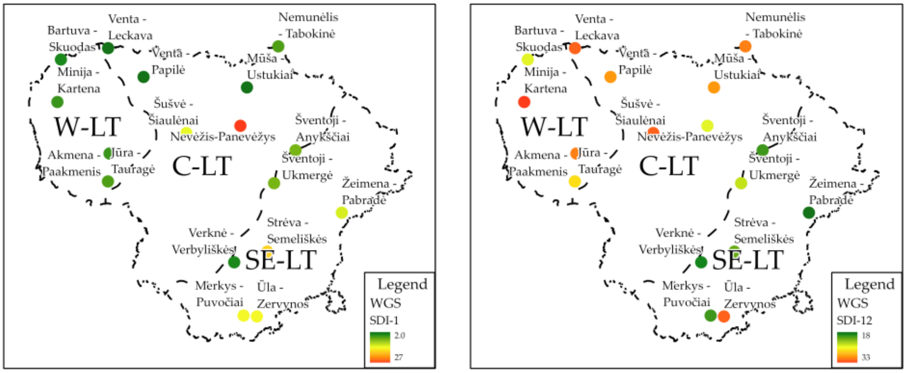


Fig. 12. The number of mounts with hydrological drought (left figure – SDI-1, right figure – SDI-12)

From Fig. 12, it can also be concluded that more frequent river feeding through short-term rains reduces the risk of hydrological drought development (SDI-1). However, with an increase in the accumulation period, underground feeding in the SE-LT contributes to greater resilience against droughts (SDI-12), as short-term rains cannot fill a prolonged water deficit.

<u>Historical analysis of hydrological drought:</u>

- Based on SDI-12

According to the SDI analysis with a 12-month accumulation period (Fig. 13), a prolonged period of drought extended from late 1964 to the latter part of 1977 within Lithuania, marked by peaks in 1969, 1972, and the interval of 1976-1977. From 1977 to 2003, a predominantly moist period or near-normal conditions were observed, with minor interactions of dry periods (characterised by drought values up to -1.5) that affected the majority of Lithuania, especially in 1993 (mainly prevalent in the C-LT region), as well as in 1996 and 2001. In 2003 and 2006, droughts formed with extreme values (index values <-2.0). Starting from 2009, the drought index mostly remained within the range of near-normal conditions. From 2018 onwards, a prolonged hydrological drought began to develop across the entirety of Lithuania until the end of the studied period.

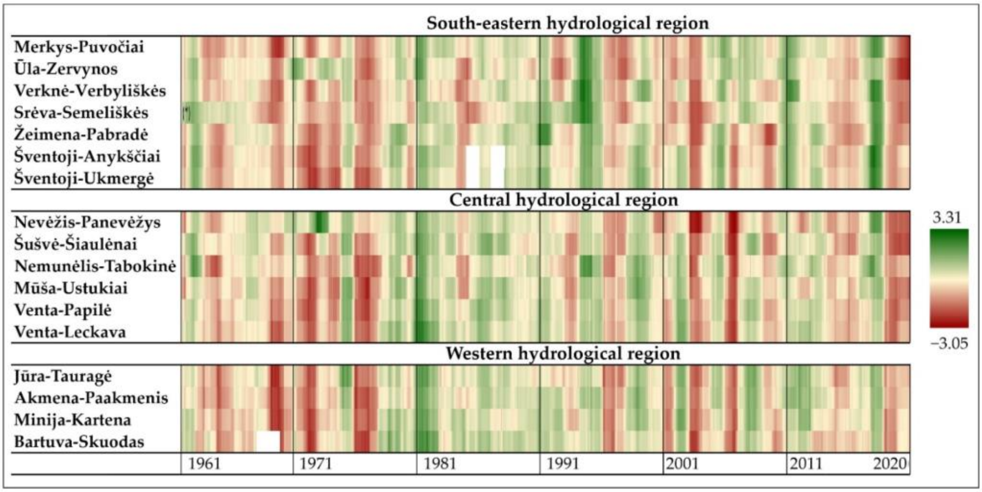


Fig. 13. Graphical representation of the SDI-12 index during 1961–2020 (where green represents months with higher moisture levels, red signifies drier months, and white corresponds to periods with no available data, the intensity of the events is reflected through the colour brightness)

- Based on SWLI

The SWLI index (with SDTV) was used to identify hydrological drought over a span of 30 years (from 1991 to 2020). Fig. 14 depicts the count of days with hydrological drought (only severe drought and extreme drought) during the warm period of the year (May – October) for each river.

The most significant occurrence of drought was documented in 2006, 2019, and 2020, with 2019 standing out as the driest year. Additionally, specific and prolonged occurrences of severe drought were identified in 1992 and 2002. It is worth highlighting a general pattern suggesting an increase in the frequency of days marked by severe dryness.

Year:	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	SUM
Nem-Sma	0	65	0	0	0	0	0	0	0	6	0	41	0	0	0	0	0	0	4	0	0	0	0	0	35	2	0	0	92	83	328
Mer-Puv	0	4	0	0	0	0	0	0	19	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	24	8	0	0	83	161	304
Ner-Jon	0	61	33	0	0	7	10	0	6	15	0	40	4	0	0	0	0	0	37	0	0	0	0	0	13	0	0	0	82	17	325
Zei-Pab	0	48	0	0	0	0	0	0	0	0	0	0	16	0	0	57	0	0	42	0	0	0	0	0	3	0	0	14	100	40	320
Sve-Ukm	54	134	59	13	0	0	0	0	3	8	0	0	3	0	0	49	9	4	35	0	0	0	0	2	0	0	0	0	6	14	393
Nev-Pan	0	0	0	0	0	0	0	0	0	6	0	25	30	10	10	112	0	0	0	0	0	0	0	0	1	11	0	36	131	59	431
Dub-Lyd	0	2	30	0	0	0	0	0	0	3	0	0	0	0	0	24	0	4	0	0	0	0	0	0	0	0	0	0	16	9	88
Mit-Zin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	15	0	5	0	0	0	0	0	6	0	0	0	14	7	17	72
Ses-Ski	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	5	48	9	0	14	114	8	210
Min-Kar	0	0	3	10	0	0	0	0	0	5	0	13	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	9	0	51
Svy-Gun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
Nem-Tab	0	8	35	0	0	11	0	0	1	21	0	48	0	2	0	28	0	0	0	0	0	0	0	0	0	0	0	0	13	4	171
Mus-Ust	0	30	5	0	0	0	0	0	68	0	0	126	12	0	0	30	0	15	0	0	0	0	0	0	17	0	0	0	16	5	324
Ven-Lec	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39	0	0	0	0	0	0	0	0	24	4	0	34	57	60	218
Bar-Sku	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	3	10	0	0	0	17	15	0	0	5	24	52	142

Fig. 14. Distribution of hydrological drought events over time (1991–2020) using SWLI with SDTV (dry days were depicted using a colour gradient, with green indicating years without dry days and red signifying the highest count of dry days per year)

At this stage, it is worth noting that Fig. 14 differs from Fig. 13 in certain aspects, as a smaller observation period is employed (a longer analysis term yields a more precise distribution of index values). Additionally, the accumulation period differs (10 days for SWLI and 12 months for SDI), impacting the detection of droughts with varying durations and formation patterns. For instance, a continuous 30-day drought according to SWLI might not be accounted for in SDI due to the other 11 months, which are relatively wet and negate the impact of one dry month. Conversely, a scenario can arise where no strong drought is observed over a prolonged period with a 10-day SWLI calculation, but extreme values might emerge in the SDI-12 index due to the cumulative synergistic effect of all 10-day segments with small runoff deficits. Therefore, for comprehensive hydrological drought identification, combining short accumulation periods with longer ones is advisable to detect droughts at all levels.

Relation between SDI and SWLI:

For a comprehensive comparison, 15 Lithuanian rivers from distinct sub-basins were selected. According to both indices, the analysis revealed that May has the highest count of severely dry days in Lithuania during the warm period. This trend was identified across 7 out of the 15 rivers and is presented in Fig. 15. Generally, SWLI and SDI exhibit similar trends; however, SWLI demonstrates a greater number of dry days. This discrepancy could stem from more pronounced water fluctuations due to the steepness of the riverbed in WGSs.

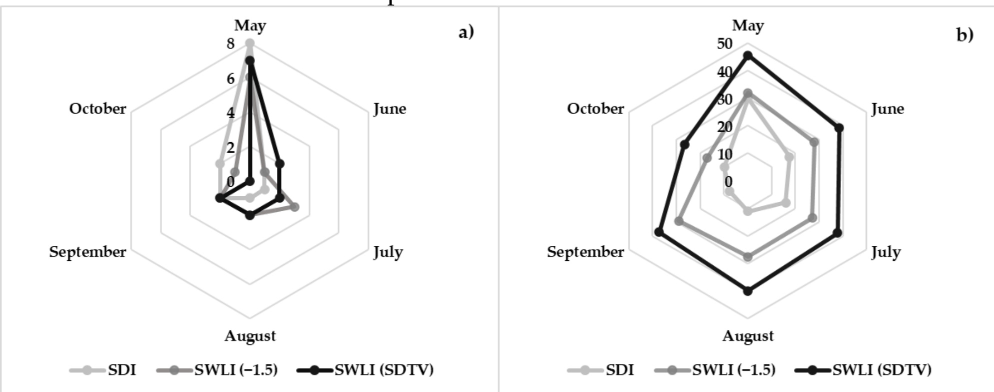


Fig. 15. Relationship between SWLI and SDI: (a) the number of rivers according to month with the highest count of severely dry days; (b) average number of severely dry days per month (from 1991 to 2020)

For a detailed comparison of the indices, 3 rivers were selected. The fluctuations of both the SWLI and SDI indices are illustrated in Fig. 16. Essentially, the fluctuations in index values are replicated.

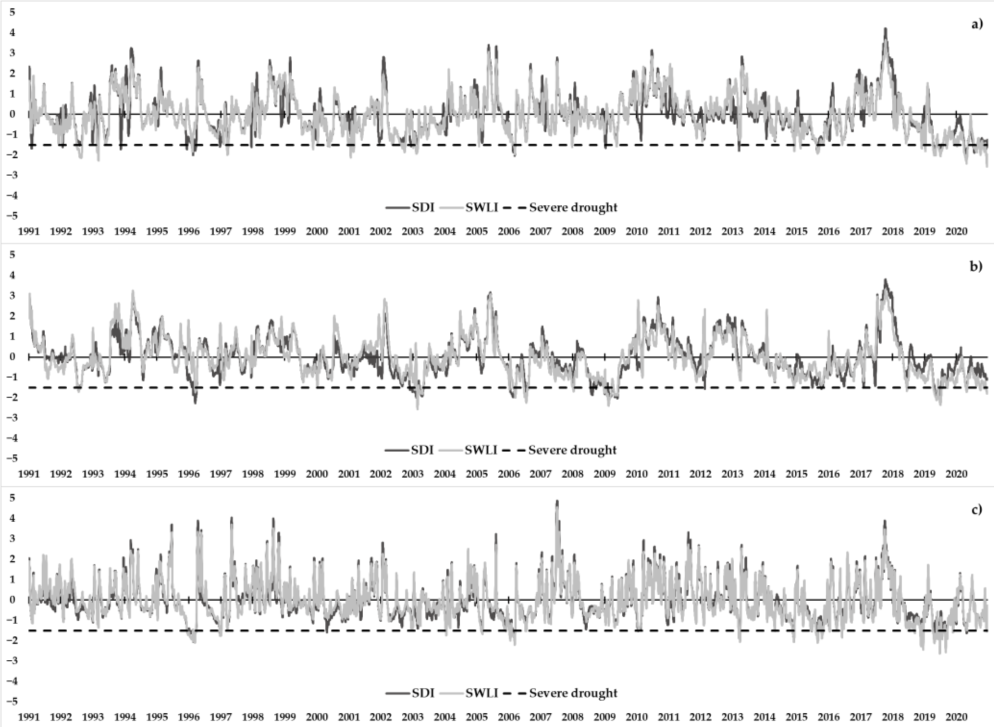


Fig. 16. Relationship between SWLI and SDI for the years 1991–2020: (a) Nemunas-Smalininkai; (b) Žeimena-Pabradė; (c) Šešuvis-Skirgailai

The analysis of hydrological drought revealed disparities among hydrological regions regarding maximum drought duration, extreme values, and drought distribution based on accumulation periods. The most severe hydrological droughts were observed during the dry periods of 1961–1977, 2000–2007, and 2018–2020. It is worth noting that the results obtained through SDI are quite similar to those from SWLI, and the index based on water levels can be applied for operational drought response.

3.4. The frequency and severity forecast of hydrological drought in the near and far future.

In the face of climate change, the adaptation and mitigation of hydrological droughts have gained heightened importance. Since water resources play a pivotal role in sustaining ecosystems, agriculture, industries, and communities, the ability to predict periods of water scarcity and their potential impacts is of utmost importance. Therefore, forecasting is an essential component in hydrological drought investigation.

Article 3: NAZARENKO, Serhii, KRIAUČIŪNIENĖ, Jūratė, ŠARAUSKIENĖ, Diana and JAKIMAVIČIUS, Darius. Patterns of past and future droughts in permanent lowland rivers. Water. 2022. Vol. 14, no. 1, p. 71. DOI 10.3390/w14010071

Article 4: NAZARENKO, Serhii, KRIAUČIŪNIENĖ, Jūratė, ŠARAUSKIENĖ, Diana and POVILAITIS, Arvydas. The development of a hydrological drought index for Lithuania. Water. 2023. Vol. 15, no. 8, p. 1512. DOI 10.3390/w15081512

Chapter place in the thesis work: This chapter provides a brief review of Article 3 and Article 4, which addresses Objective 4 and lays out insights into the forecast of hydrological droughts. Hydrological drought research should not be limited to the analysis of past events alone; forecasting is a crucial aspect of drought investigation. Regional climate models, in conjunction with hydrological models, enable the assessment of potential risks associated with future hydrological drought occurrences.

<u>Analysis of modelled data according to SDI-12:</u>

Based on the SDI-12 calculated using the RCP 4.5 scenario, the projected severe and extreme dry months are expected to remain similar to the historical period for the Venta River, decrease for the Šventoji River, and increase for the Minija River (Table 7 and Fig. 17a,c). For the RCP 8.5 scenario, a decrease in the severely and extremely dry categories is noted, while an increase in the moderate drought category is observed (Table 6 and Fig. 17b,d). The percentage of drought decreases for the Šventoji River and slightly decreases for the Minija River, while a slight increase is observed for the Venta River under the RCP 8.5 scenario. In general, for both scenarios and all rivers, an increase in drought is expected in the latter half of the 21st century.

Table 7. Percentage distribution of drought classes in the past and future according to SDI-12

	Period	Drought class	Šventoji–Ukmergė	Venta–Leckava	Minija–Kartena
Historical	1961-2020 (100%)	Moderate	10.98	6.35	7.19
		Severe	4.83	6.77	6.63
		Extreme	2.49	1.97	3.53
RCP 4.5	2021-2060 (50%)	Moderate	4.38	4.48	4.27
		Severe	1.56	2.29	2.71
		Extreme	0.83	0.21	1.04
	2061-2100 (50%)	Moderate	5.52	5.10	5.42
		Severe	2.61	4.27	4.06
		Extreme	1.56	1.98	1.15
RCP 8.5	2021-2060 (50%)	Moderate	5.21	3.85	5.73
		Severe	0.73	0.52	1.46
		Extreme	0.00	0.00	0.11
	2061-2100 (50%)	Moderate	5.94	6.98	6.46
		Severe	3.13	3.44	1.56
		Extreme	0.73	0.83	0.94

Overall, based on the modelled data for the near future under both climate scenarios, the Minija River appears to be more susceptible to drought compared to the Venta and Šventoji rivers (Fig. 17). Furthermore, in the far future, the Šventoji River is anticipated to experience a higher occurrence of extreme dry events compared to the Minija and Venta rivers.

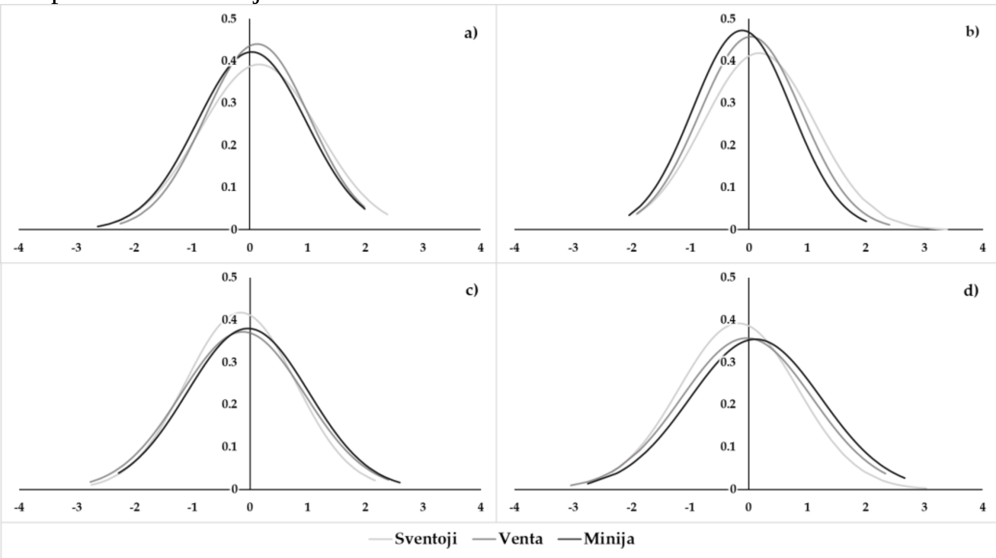


Fig. 17. Changes of SDI-12 in future: (a) RCP 4.5 near future; (b) RCP 8.5 near future; (c) RCP 4.5 far future; (d) RCP 8.5 far future

Analysis of modelled data according to SWLI:

The analysis of hydrological droughts in the future, as indicated by SWLI, suggests that a majority of drought events are anticipated in the distant future (Table 8). An exception is noted in the case of the Šešuvis River under the RCP4.5 scenario. A comparison between projected and historical data has uncovered an increase in the percentage of severe and extreme droughts in rivers such as the Žeimena and Šešuvis. However, a converse trend was identified for the Nemunas River. This contrast may stem from the larger catchment area of the Nemunas River and a narrowing of water level fluctuations.

Table 8. Percentage distribution of drought in the past and future scenarios according to SWLI

	Period	Nemunas–Smalininkai	Žeimena–Pabradė	Šešuvis–Skirgailai
Historical	1991–2020	5.94	5.80	3.80
RCP 4.5	2021–2060	2.98	3.65	5.10
	2061–2100	5.88	10.67	5.04
RCP 8.5	2021–2060	0.34	3.98	2.91
	2061–2100	9.52	10.34	6.55

According to the forecasting results, the majority of hydrological droughts are projected to occur at the end of the 21st century. Under both climate scenarios

(RCP4.5 and RCP8.5), there will be an increase in the amplitude between the highest and lowest extreme values. This, in turn, will compel aquatic ecosystems to adapt to the abrupt changes between flood and low flow periods. Meanwhile, hydrological drought trends in Lithuanian rivers may vary depending on the chosen RCP scenario and hydrological region.

3.5. Development of the hydrological drought risk map and identification of the most vulnerable regions in Lithuania.

In recent years, a surge in the development and application of diverse techniques for drought assessment, ranging from statistical analyses to sophisticated modelling approaches, is being witnessed. However, in cases where extreme weather events, including droughts, increase in frequency and severity, it is crucial not only to identify drought occurrences but also to comprehend their origins and assess the vulnerability of regions to minimise future impacts. Ignoring drought patterns in strategic planning can lead to dire consequences, including water scarcity, food insecurity, and substantial economic losses. According to that, building resilience or adapting to drought must be underpinned by a thorough analysis of a region’s risk.

Article 5: NAZARENKO, Serhii, ŠARAUSKIENĖ, Diana, PUTRENKO, Viktor and KRIAUČIŪNIENĖ, Jūratė. Evaluating hydrological drought risk in Lithuania. Water. 2023. Vol. 15, no. 15, p. 2830. DOI 10.3390/w15152830

Chapter place in the thesis work: This chapter provides a brief review of Article 5, which addresses Objective 5 and describes the hydrological drought risk map of Lithuania. This section concludes the general research and summarises all the achievements of previous chapters in the form of a hydrological drought risk assessment map. Building resilience and adapting to drought necessitate a comprehensive regional risk analysis. Considering the existing research gap in hydrological drought risk assessment in Lithuania, this chapter aims to address it.

Assessment of Hydrological Drought Hazard by hydrological regions:

The distribution map of the HDHI (Fig. 18) highlights the formation of two poles: the northern part exhibits the highest hazard scores, whereas the southern part displays the lowest. This pattern corresponds to Lithuania’s topography and the distribution of hydrological regions. Notably, the central hydrological region holds the largest proportion of areas classified as high and very high risk, comprising 65.1%. The lower hazard in the western hydrological region is largely attributed to the impact of a maritime climate and precipitation, which create less favourable conditions for drought occurrences. In contrast, the south-eastern hydrological region stands out with the highest percentage of low and moderate hazard classes, accounting for 83.3%.

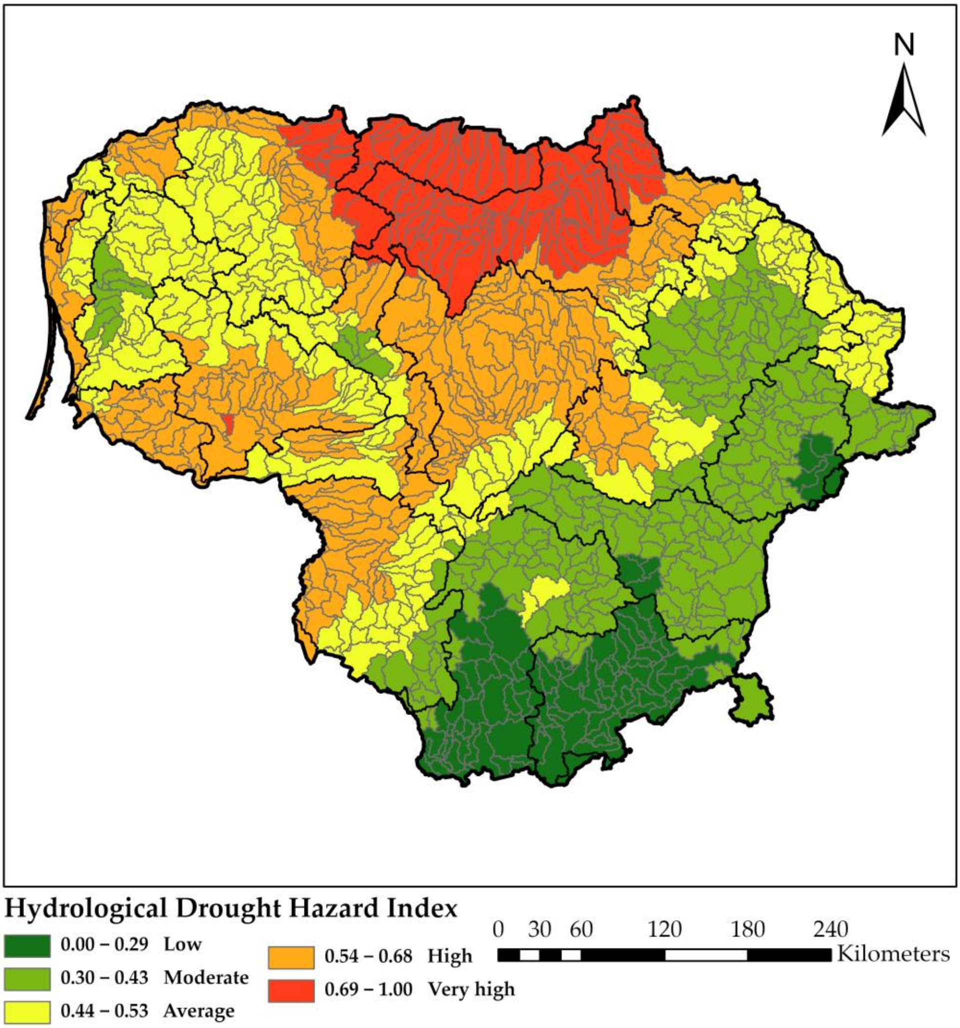


Fig. 18. Map of the hydrological drought hazard index

Assessment of Hydrological Drought Vulnerability by hydrological regions:

The HDVI map shows slightly different trends and does not clearly exhibit distinct clusters with uniform vulnerability levels (Fig. 19). Only the northern part of the central hydrological region can be recognised as the most consistent area with high vulnerability indicators. Conversely, the map of drought vulnerability displays a notably broader distribution of values corresponding to high and very high categories. This variance might be attributed to the diverse nature of variables affecting vulnerability assessment, as some of them are directly influenced by human activity, such as LULC. Similarly, to the drought hazard map, the central and western hydrological regions display the highest proportion of territory categorised under high and very high classes, specifically: 88.6% and 77.0% respectively.

Meanwhile, for the Southeastern hydrological region, this percentage stands at 52.5%.

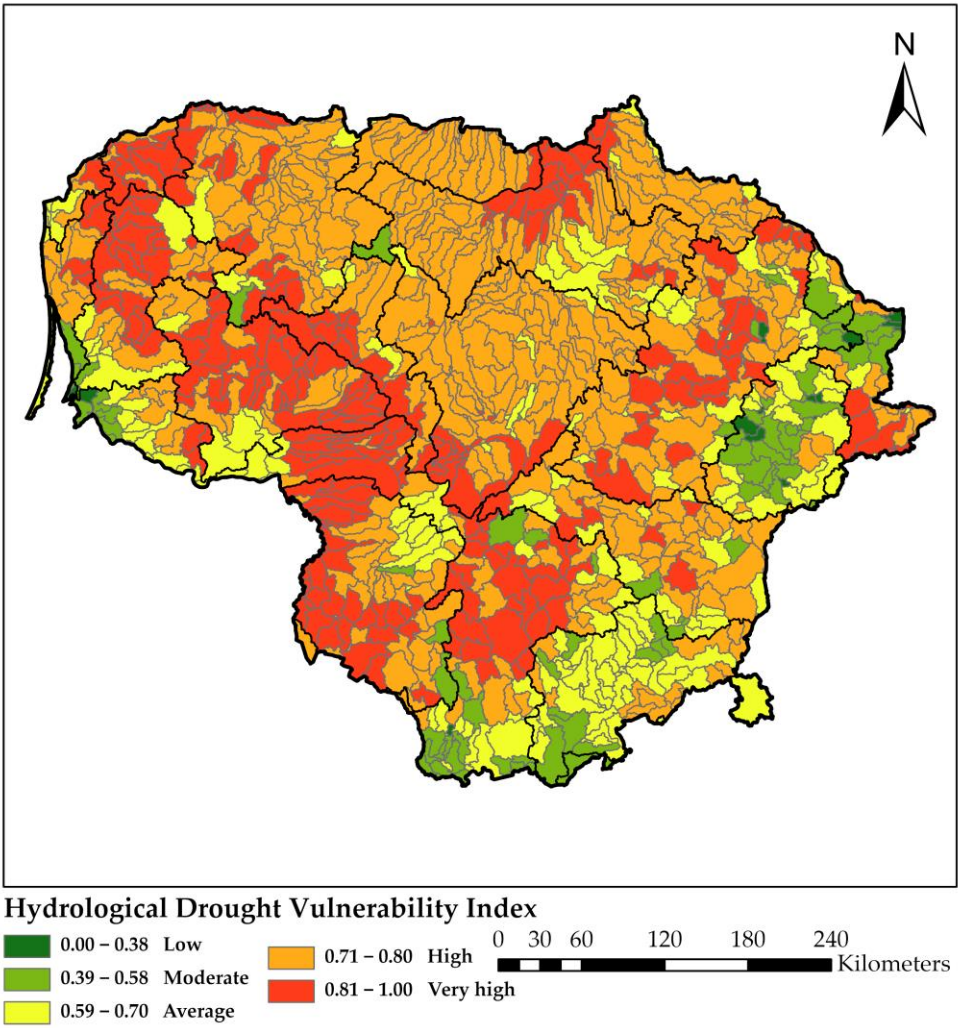


Fig. 19. Map of the hydrological drought vulnerability index

<u>Assessment of Hydrological Drought Risk by hydrological regions:</u>

The hydrological drought risk (HDR) map (Fig. 20) exhibits distinct cluster formations with notably high values in the northern region and an elongated cluster characterised by low to moderate risk levels in the southeast. Such results in the southeast are closely related to the southeastern hydrological region. The low risk values in the southern and eastern areas can be elucidated by the presence of numerous lakes and forests, as well as the elevation influence. Conversely, the high hydrological drought risk values in the north can be attributed to the lack of lakes and forests, precipitation, and, to some extent, soil attributes.

The generated map reveals that a substantial portion of Lithuania falls within the high and very high-risk categories (49.8%), while only approximately 24.4% falls within the low and moderate-risk categories.

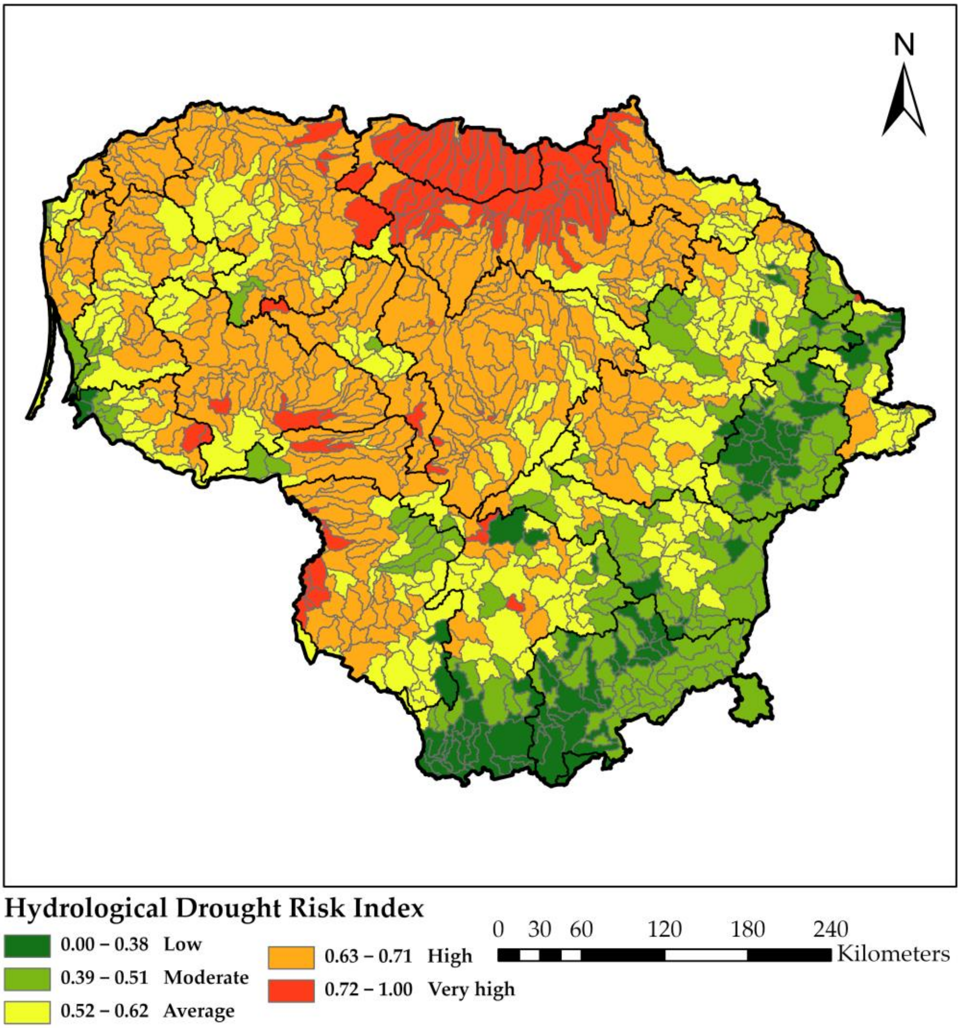


Fig. 20. Map of the hydrological drought risk index

Regarding the hydrological drought risk, the patterns observed in the hydrological regions persist across HDHI and HDVI. In line with this, the Southeastern hydrological region continues to exhibit the lowest percentage of hydrological drought risk, encompassing 10.4% of the territory classified under the high and very high-risk categories. Conversely, the western and central hydrological regions demonstrate higher values, accounting for 61.1% and 72.7% respectively.

According to the results, more than 70% of Lithuania is classified as having high and very high vulnerability, with 39% falling into the same hazard class.

Moreover, nearly half of the country belongs to the high-risk category for hydrological drought (49.8%). Notably, the SE-LT region of Lithuania stands out from other areas due to its lower risk indices for hydrological drought and its physical-geographical characteristics. The highest concentration and value of very high risk correspond to the Musa and Lielupe River basins in the northern part of the C-LT region.

4. CONCLUSIONS

After analysing changes in river runoff and hydrological droughts, assessing their dependence on climate change, and conducting a hydrological drought risk assessment for Lithuanian rivers in the past and future, the following patterns have been identified:

1. During the research, 16 intermittent rivers were identified in Lithuania. The highest concentration of intermittent rivers is found in the Central hydrological region. Currently, indices of intermittency show significant correlations with catchment area (r=0.74) and watercourse slope (r=0.77). However, these indices also depend on climate change, it is expected that the number of intermittent rivers, occurrences of intermittent events, and their duration will increase in the future.
2. Within Lithuania, low flow indices are distributed unevenly. The highest values are observed in the SE-LT region ($30q_{av}$=3.98 l/s·km^2), while the lowest are in the C-LT region ($30q_{av}$=1.47 l/s·km^2). With climate change, the positive trend of increasing low flow indices in the past disappeared after 1973. In the last 30 years, there are no consistent trends in hydrological regions, except for few individual rivers with significant negative or positive trends.
3. The hydrological regions of Lithuania differ from each other in terms of the duration and severity of hydrological drought. The most severe hydrological droughts were identified during the arid periods of 1961–1977, 2000–2007, and 2018–2020. The longest hydrological drought was recorded in the SE-LT region (lasting 42 months from 1971 to 1974); however, the highest number of drought months, as well as the most extreme droughts during the warm period of the year, were observed in the C-LT and W-LT regions.
4. According to forecasting models based on climate scenarios RCP4.5 and RCP8.5, there will be an intensification of extreme drought values in the future, leading to a greater amplitude of river flow between wet and dry periods. According to forecasted data, the frequency of hydrological droughts will be highest in the distant future (2061–2100). Out of the six forecasting models, only the model for the Venta River (which represent C-LT region) shows a stable trend to increasing severity of drought events in both scenarios, while the trends of other models change according to the RCP scenario.
5. According to the assessment of hydrological drought risk, about half of Lithuania’s territory is within the range of high and very high risk, while only 24.4% of the catchments area falls within the low and moderate risk. The largest cluster of high-risk values is identified within the northern part of the C-LT region (Musa and Lielupe River basins). The lowest risk indices are observed in the SE-LT region, which can be attributed to the influence of soil types, groundwater feeding sources, wide spread of lakes and forests, as well as the impact of the Baltic Highlands on the local climate.

6. Also, within the scope of the study, several gaps were identified that should be investigated in the future: 1) currently, there is a lack of data from water gauging stations on the small river catchments (usually hydrological measurements are conducted in large river basins where cases of river intermittency are not recorded), which complicates the study of intermittence phenomenon; 2) due to the ongoing climate changes, the analysis of hydrological drought in both short and long accumulation periods should be conducted continuously; 3) irreversible climate changes necessitate research that explores adaptation possibilities and increasing the resilience of existing ecosystems and, directly, catchments; 4) this research was focused on the risk analysis of hydrological drought for hydrological objects; however, to assess the impact of hydrological drought risk on society, additional risk analysis is required, with including socio-economic indicators.

5. SANTRAUKA

1. ĮVADAS

Skirtingų hidrologinių regionų upės pasižymi savitu hidrologiniu režimu[1,2], tačiau išsiskiria dvi nuotėkio fazės – potvynis ir nuosėkis. Pasikartojantis reiškinys hidrologinė sausra reiškia vandens trūkumą upėje[3,4]. Dėl hidrologinės sausros ir nuosėkio laikotarpio upės debitai tam tikru laikotarpiu sumažėja[3,5]. Upių nuosėkio ir hidrologinių sausrų dėsningumai priklauso nuo fizinių geografinių sąlygų bei meteorologinių veiksnių.

Vienas iš pagrindinių upių nuotėkio formavimosi veiksnių yra krituliai ir temperatūra[1,6]. Naujausi tyrimai rodo, kad klimato kaita[7–9] turi didelės įtakos upių minimalių debitų[6] ir hidrologinių sausrų[3,10,11] kaitai bei jų dėsningumams. Hidrologinių sausrų dažnėjimas bei nuosėkio debitų mažėjimas upių baseinuose kelia vis didesnį susirūpinimą[5,9,12,13]. Minėti hidrologiniai reiškiniai reikšmingai veikia vandens ekosistemų ekologinę pusiausvyrą ir nuo vandens išteklių priklausančią žmogaus veiklą[3–6,8,10,12]. Norint veiksmingai valdyti vandens išteklius ir įgyvendinti prisitaikymo strategijas, labai svarbu suprasti upių nuosėkio laikotarpio debitų dėsningumus klimato kaitos kontekste ir įvertinti hidrologinės sausros riziką.

Ypač dėl klimato kaitos svarbu visapusiškai ištirti upių nuosėkio ir hidrologinės sausros reiškinius įvairiais lygmenimis: vietiniu[4,6,7,12,14], regioniniu[15–21] ir pasauliniu[10,11,13,22–26]. Hidrologinių sausrų ir upių nuosėkio dėsningumai yra gerai ištirti regioniniu ar pasauliniu lygmeniu, tačiau vietiniu lygmeniu tokių tyrimų atlikta žymiai mažiau. Tai ypač svarbu prognozuojant hidrologines sausras tam tikrų upių baseinuose. Hidrologinės sausros rizikos vertinimas tiek vietiniu, tiek šalies ar regioniniu lygmeniu tampa itin svarbus dėl klimato kaitos.

Ne mažiau yra svarbi upių nuotėkio ir hidrologinių sausrų prognozė. Šiuo metu yra daug upių nuotėkio prognozavimo skaitmeninių modelių, tačiau tik keli iš jų yra specialiai orientuoti upių nuosėkiui (minimaliems debitams) prognozuoti. Upių hidrologiniam režimui skaičiuoti gali būti naudojami įvairūs modeliai ir programinė įranga, pavyzdžiui: HBV modelis[27], TOPMODEL[28], VIC modelis[29], MIKE SHE modelis[30], SWAT modelis[31] ir kt. Modeliuojant upių nuosėkio laikotarpio debitus Vidurio ir Šiaurės Europoje[27,32,33], įskaitant Lietuvą[34], HBV modelis išsiskiria savo populiarumu. Šis modelis gali tiksliai vertinti minimalius vandens debitus[32], tačiau jis upių nuosėkio debitams prognozuoti Lietuvoje dar nenaudotas.

Nuosėkio laikotarpiais, kurie susiję su sumažėjusiu kritulių kiekiu ir padidėjusia evapotranspiracija[5,6,35,36], upėse trūksta vandens (arba upės visai išdžiūsta), tai sukelia ekologinį stresą vandens ekosistemoms ir įvairius nuo vandens priklausomų veiklų sutrikimus[6,12,35,36] Lietuvoje, kur upių vandens ištekliai turi įtakos įvairiems ekonomikos sektoriams[37,38]. Todėl labai svarbu nustatyti upių nuosėkio kaitos dėsningumus ir įvertinti su tuo susijusią hidrologinės sausros riziką. Lietuvoje hidrologinės sausros tyrimų nėra daug, o specialiai hidrologinės sausros rizikos vertinimui skirtų tyrimų apskritai nėra. Todėl, atsižvelgiant į numatomą klimato kaitos poveikį regioninei hidrologijai, būtina detaliai ištirti upių nuosėkio aspektus Lietuvos upių baseinuose.

Disertacinio darbo tyrimo rezultatai pateikia išsamų Lietuvos upių nuosėkio (minimalių vandens debitų ir upių išdžiūvimo parametrų) ir hidrologinių sausrų dėsningumų vertinimą praeityje ir ateityje. Tokių duomenų prieinamumas suteiks vertingų įžvalgų gamtosaugos politikos formuotojams, vandens išteklių valdytojams ir suinteresuotoms šalims, dalyvaujančioms įgyvendinant subalansuotą Lietuvos upių vandens išteklių valdymą. Gauti rezultatai suteiks naujos informacijos nustatant pažeidžiamus rajonus dėl sausrų ir padės kuriant prisitaikymo strategijas, siekiant švelninti neigiamą dažnėjančių hidrologinių sausrų poveikį.

1.1. Darbo tikslas, uždaviniai ir mokslinis naujumas

Darbo tikslas. Ištirti Lietuvos upių nuosėkio ir hidrologinių sausrų dėsningumus, jų priklausomybę nuo klimato kaitos bei įvertinti sausrų riziką Lietuvos upėms praeityje ir ateityje.

Uždaviniai:

1. Ištirti nuosėkio ekstremumų (upių išdžiūvimas) kaitos dėsningumus Lietuvos teritorijoje.
2. Remiantis istoriniais duomenimis, išanalizuoti upių minimalaus debito rodiklių erdvinį ir laikinį pasiskirstymą.
3. Remiantis istoriniais duomenimis, ištirti Lietuvos upių hidrologinių sausrų kaitą ir jos dėsningumus.
4. Prognozuoti hidrologinės sausros dažnumą ir intensyvumą artimoje ir tolimoje ateityje.
5. Sukurti hidrologinių sausrų rizikos žemėlapius ir identifikuoti labiausiai pažeidžiamus Lietuvos regionus.

Ginamieji teiginiai:

1. Lietuvoje dažnėja upių išdžiūvimo reiškiniai.
2. Vykstant klimato kaitai, Lietuvos upių nuosėkio analizė rodo reikšmingus minimalių vandens debitų pokyčių trendus.
3. Klimato kaita lemia hidrologinių sausrų dažnumą ir intensyvumą Lietuvoje.
4. Hidrologinių sausrų rizikos žemėlapiai bus naudingi sprendžiant ateityje ekologines, socialines ir ekonomines problemas.

Mokslinis naujumas:

- Upių išdžiūvimo reiškiniai gan menkai tirti Lietuvoje. Darbe pirmą kartą pagal istorinius duomenis buvo ištirti Lietuvos upių išdžiūvimo parametrai (data, trukmė ir pasikartojimo dažnis) bei nustatyti veiksniai, lemiantys išdžiūvimo procesus.
- Lietuvoje šiuo metu trūksta naujausių upių nuosėkio tyrimų. Disertaciniame darbe sukurta originali upių nuosėkio ir hidrologinių sausrų

vertinimo kaitos metodika ir nustatytos minimalių vandens debitų (30Q, 30Q95 ir 30Q80 indeksai) pokyčių tendencijos 1961–2020 m. laikotarpiu. Naudojant minimalaus debito indeksus hidrologinei sausrai vertinti, atlikta trijų Lietuvos hidrologinių rajonų sausrų dažnio ir trukmės analizė.

- Iki šiol Lietuvoje hidrologinių sausrų kaita buvo vertinta tik pagal istorinius duomenis. Šiame darbe pirmą kartą Lietuvoje atlikta hidrologinės sausros indeksų prognozė ateities laikotarpiams, naudojant įvairius klimato scenarijus ir modelius. Naujas standartizuotas vandens lygio indeksas (SWLI) buvo pritaikytas ir testuotas Lietuvos upių operatyviniam hidrologinių sausrų vertinimui.
- Kai kuriose Europos šalyse, taip pat ir Lietuvoje, dar nėra sukurta hidrologinių sausrų rizikos vertinimo žemėlapių. Tokie žemėlapiai reikalingi norint nustatyti labiausiai pažeidžiamas sritis. Disertaciniame darbe buvo sudaryti visos Lietuvos teritorijos upių baseinų hidrologinių sausrų grėsmės, pažeidžiamumo ir rizikos žemėlapiai. Įvertinus žemėlapių informaciją, galima iš anksto imtis veiksmų, siekiant padidinti ekosistemų atsparumą tolesniems klimato pokyčiams ir išvengti nuostolių žmogaus vykdomoms veikloms.

Praktinė darbo reikšmė

Atlikti tyrimai gali būti pritaikyti efektyvesniam Lietuvos vandens išteklių valdymui. Norint optimizuoti vandens paskirstymą tarp naudotojų, užtikrinti tvarų vandens tiekimą ir įgyvendinti vandens geros būklės išsaugojimo strategijas, labai svarbu suprasti upių nuosėkio dėsningumus ir hidrologinės sausros riziką. Moksliniai tyrimai padėjo nustatyti dėl hidrologinių sausrų pažeidžiamus rajonus ir upių baseinus bei numatyti būsimus pokyčius. Tai leistų valdžios institucijoms parengti priemones, kurios sumažintų neigiamą klimato kaitos poveikį vandens ištekliams. Hidrologinės sausros rizikos įvertinimas prisideda prie pastangų mažinti nelaimių riziką, leidžiant sukurti išankstinio įspėjimo sistemas ir nenumatytų atvejų planus, kad būtų sumažintas sausros poveikis ekosistemoms, žemės ūkiui, energijos gamybai ir kitiems pažeidžiamiems sektoriams. Šio tyrimo rezultatai galėtų būti naudingi įgyvendinant vandens valdymo planus siekiant geros vandens būklės. Vandens politikos formuotojai gali panaudoti tyrimo rezultatus spręsdami kintančių hidrologinių sąlygų keliamus iššūkius.

Darbo aprobacija moksliniuose straipsniuose ir konferencijose. 5 moksliniai straipsniai disertacijos tema publikuoti *ISI Web of Science* referuojamuose žurnaluose su citavimo indeksais. Disertacijos tema atliktų tyrimų rezultatai pristatyti 9 mokslinėse konferencijose, iš kurių 5 tarptautinėse konferencijose.

Darbo apimtis ir struktūra. Disertaciją sudaro santrumpų sąrašas, įvadas, literatūros apžvalga, tyrimo metodika, rezultatai ir jų aptarimas, išvados, literatūros sąrašas, publikacijų sąrašas, gyvenimo aprašymas, santrauka lietuvių kalba. Disertacijos apimtis – 91 puslapis, 20 paveikslų, 8 lentelės ir 131 literatūros šaltinis.

1.2. Moksliniai straipsniai ir bendraautorių indėlis

Disertacijos tematika paskelbti 5 moksliniai straipsniai:

1 straipsnis: ŠARAUSKIENĖ, Diana, AKSTINAS, Vytautas, NAZARENKO, Serhii, KRIAUČIŪNIENĖ, Jūratė and JURGELĖNAITĖ, Aldona. Impact of

physico-geographical factors and climate variability on flow intermittency in the rivers of water surplus zone. *Hydrological Processes*. 2020. Vol. 34, no. 24, p. 4727–4739. DOI 10.1002/hyp.13912

2 straipsnis: NAZARENKO, Serhii, MEILUTYTĖ-LUKAUSKIENĖ, Diana, ŠARAUSKIENĖ, Diana and KRIAUČIŪNIENĖ, Jūratė. Spatial and temporal patterns of low-flow changes in lowland rivers. *Water*. 2022. Vol. 14, no. 5, p. 801. DOI 10.3390/w14050801

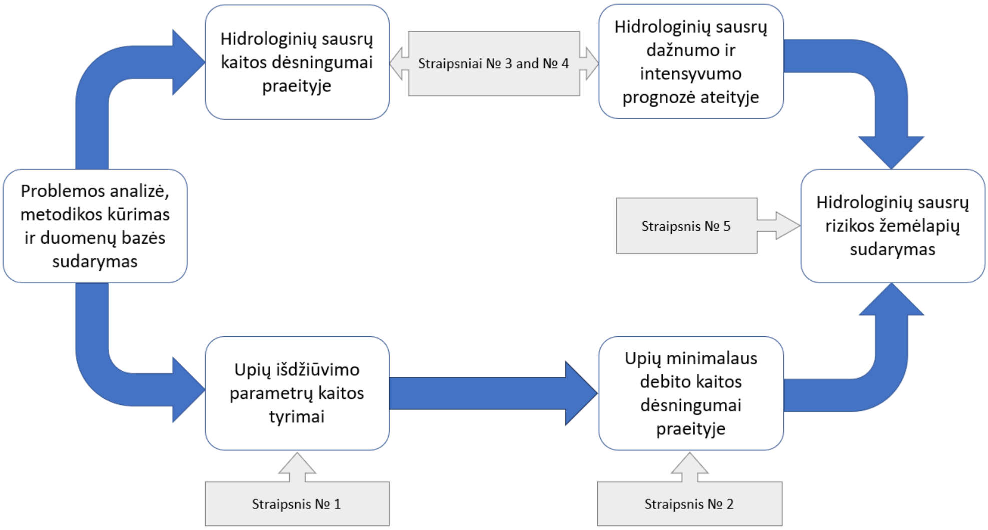
3 straipsnis: NAZARENKO, Serhii, KRIAUČIŪNIENĖ, Jūratė, ŠARAUSKIENĖ, Diana and JAKIMAVIČIUS, Darius. Patterns of past and future droughts in permanent lowland rivers. *Water*. 2022. Vol. 14, no. 1, p. 71. DOI 10.3390/w14010071

4 straipsnis: NAZARENKO, Serhii, KRIAUČIŪNIENĖ, Jūratė, ŠARAUSKIENĖ, Diana and POVILAITIS, Arvydas. The development of a hydrological drought index for Lithuania. *Water*. 2023. Vol. 15, no. 8, p. 1512. DOI 10.3390/w15081512

5 straipsnis: NAZARENKO, Serhii, ŠARAUSKIENĖ, Diana, PUTRENKO, Viktor and KRIAUČIŪNIENĖ, Jūratė. Evaluating hydrological drought risk in Lithuania. *Water*. 2023. Vol. 15, no. 15, p. 2830. DOI 10.3390/w15152830

Ryšys tarp iškeltų disertacijos uždavinių ir paskelbtų straipsnių

Tiriant upių nuosėkio ir hidrologinių sausrų dėsningumus, pirmiausia svarbu ištirti upių išdžiūvimo, kaip nuosėkio ekstremumo, procesus bei jų priklausomybę nuo fizinių-geografinių ir klimato veiksnių. Praeities ir ateities hidrologinių sausrų analizė bei minimalių vandens debitų erdvinių ir laikinių kaitos dėsningumų tyrimai leido įvertinti Lietuvos upių hidrologinių sausrų riziką. Šie tarpusavyje susiję tyrimai prisideda prie visapusiško supratimo apie sausros rizikos vertinimą ir valdymą. Sąsajos tarp iškeltų darbo uždavinių ir paskelbtų publikacijų pateiktos 1 paveiksle.



1 pav. Disertacinio darbo koncepcija (sąsajos tarp iškeltų darbo uždavinių ir paskelbtų publikacijų)

Disertaciją sudaro penki straipsniai, skirti upių minimalių debitų, jų priklausomybės nuo fizinių-geografinių teritorijos charakteristikų ir hidrologinių sausrų praeityje bei ateityje tyrimui.

1 straipsnis skirtas pirmajam disertacijos uždaviniui pasiekti. Jame nagrinėtas upių išdžiūvimo (kai vandens debitas vandens telkinyje mažesnis nei 0,001 m^3/s) atvejų paplitimas Lietuvoje, jų ryšys su teritorijos fiziniais-geografiniais veiksniais. Šiame straipsnyje gauti rezultatai taip pat panaudoti modeliuojant upių nuotėkį HBV programine įranga bei nustatant svarbiausius hidrologinės sausros rizikos analizės kriterijus.

2 straipsnyje sprendžiamas antras darbo uždavinys: tiriami upių nuosėkio periodo minimalių debitų erdviniai ir laikiniai pokyčiai per 60 metų (1961–2020 m.). Tyrimams taikomas metodas, paremtas slenkstinėmis reikšmėmis (kaip slenkstinės reikšmės panaudoti minimalūs 30 parų vidutiniai, 95 % ir 80 % tikimybių debitai 30Q, 30Q95, 30Q80). Šio tyrimo išvados buvo naudotos 5 straipsnyje, nustatant hidrologinės sausros slenkstinę vertę.

3 ir 4 straipsniai skirti trečiam ir ketvirtam tikslui įgyvendinti. 3 straipsnyje aprašytas praeities hidrologinių sausrų ir jų pasiskirstymo Lietuvoje tyrimas, leidžiantis gautus rezultatus palyginti su hidrologinių sausrų rizikos žemėlapiu. Trečiajame straipsnyje sausrų indeksams apibrėžti buvo naudojamas 1/3/6/9/12 mėnesių vandens kaupiamasis laikotarpis, o 4 straipsnyje – dešimties dienų kaupiamasis laikotarpis. 3 straipsnyje taip pat nagrinėtas meteorologinės sausros indeksų (SPI ir RDI) ir hidrologinio sausros indekso (SDI) ryšys. 4 straipsnyje analizuota galimybė hidrologinį sausros indeksą, pagrįstą vandens debitais (SDI), pakeisti indeksu, grįstu upių vandens lygiu (SWLI). SWLI gali pakeisti bet kurį kitą upių nuotėkiu pagrįstą hidrologinį indeksą, nes jis gali naudoti neapdorotus įvesties duomenis (vandens lygius) iš vandens matavimų stočių. Šis metodas gerokai

sutrumpina hidrologinės sausros nustatymo laiką. Ypatingas dėmesys skirtas ateities sausrų prognozėms (3 straipsnis), kurios atskleidė galimas priklausomybes, susijusias su klimato kaita artimoje ir tolimoje ateityje, atsižvelgiant į du klimato scenarijus RCP4.5 ir RCP8.5. Sukurti šešių upių, esančių skirtinguose Lietuvos hidrologiniuose rajonuose, hidrologinių sausrų prognozės modeliai.

5 straipsnyje aprašomas penktojo uždavinio įgyvendinimas. Šiame straipsnyje, remiantis ankstesnių keturių straipsnių rezultatais, buvo nustatytos teritorijos, kuriose yra didžiausia hidrologinės sausros rizika, buvo nagrinėti visų Lietuvos pagrindinių upių baseinų pavojaus ir pažeidžiamumo dėl sausrų komponentai. Sudarytas pirmasis Lietuvos hidrologinių sausrų rizikos vertinimo žemėlapis.

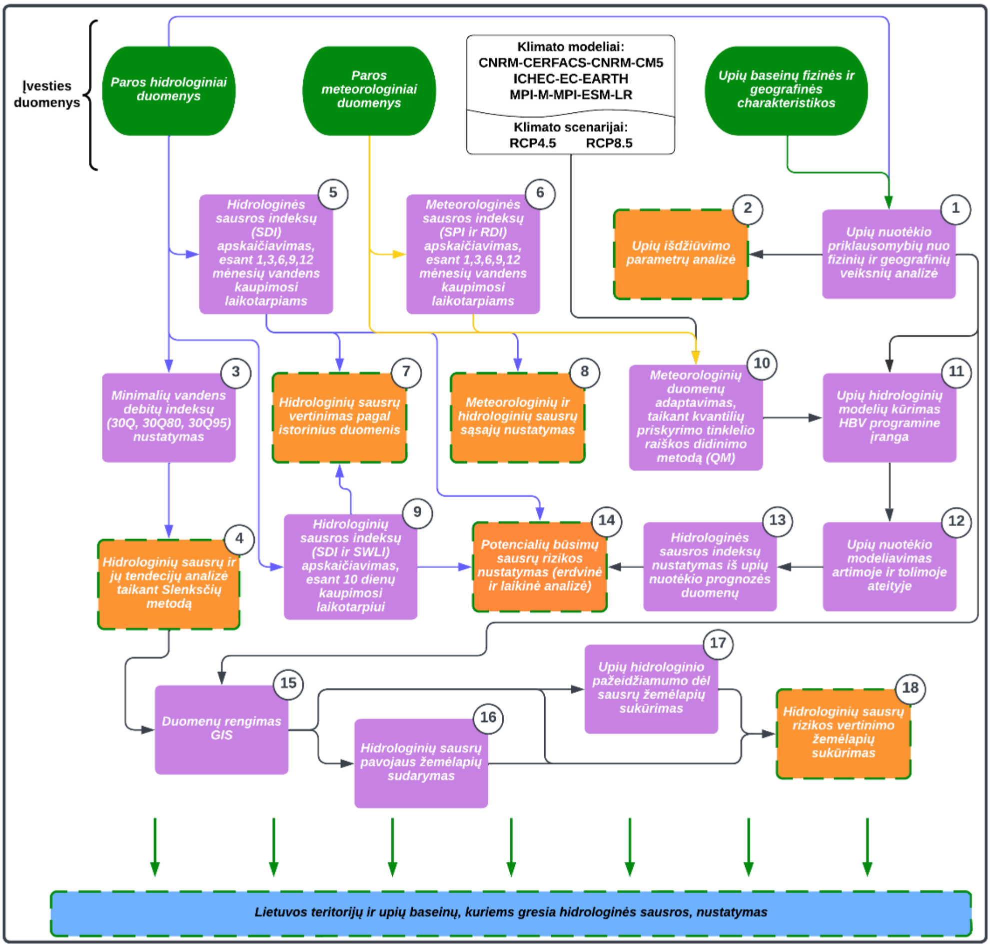
Pateiktuose penkiuose moksliniuose straipsniuose išsamiai aprašyti tyrimai, susiję su visais iškeltais darbo uždaviniais. Pateikta tyrimų medžiaga išsamiai atsako į suformuluotą tyrimų tikslą – ištirti upių nuosėkio ir hidrologinių sausrų dėsningumus, įvertinti jų priklausomybę nuo klimato kaitos bei atlikti Lietuvos upių sausrų rizikos vertinimą praeityje ir ateityje.

Darbo metodika

Bendra tyrimo metodikos schema pavaizduota 2 paveiksle. Visą tyrimo metodikos procesą galima suskirstyti į penkis pagrindinius blokus:

1. Upių išdžiūvimo reiškinio Lietuvoje tyrimas (1 ir 2 etapai).
2. Lietuvos upių nuosėkio (minimalių vandens debitų) analizė (3 ir 4 etapai).
3. Istorinių hidrologinių sausrų ir jų priklausomybės nuo meteorologinių sausrų tyrimas (5–9 etapai).
4. Upių nuotėkio modeliavimas ir hidrologinių sausrų prognozė artimoje ir tolimoje ateityje (10–14 etapai).
5. Hidrologinės sausros rizikos vertinimo žemėlapio sudarymas (15–18 etapai).

Pagal pateiktą schemą, 2, 4, 7, 14 ir 18 etapų tyrimai leidžia apibendrinti galutinį rezultatą, t. y. nustatyti Lietuvos teritorijas ir baseinus, kuriems gresia hidrologinės sausros.



2 pav. Bendroji darbo metodologijos schema

Pirmasis metodikos blokas grindžiamas statistinės analizės metodais. Tiriant upių išdžiūvimo procesus, kai konstatuota, kad vandens debitas yra mažesnis už ribinę vertę (0,001 m^3/s) arba lygus 0, fiksuojamas upės išdžiūvimas. Vertinami tik tie upių išdžiūvimo įvykiai, kurių trukmė buvo ne trumpesnė kaip trys dienos. Išsamesnė metodika aprašyta 1 straipsnyje.

Antrojo bloko metodika buvo pagrįsta trijų minimalių 30 parų vidutinių, 95 % ir 85 % tikimybių debitų (30Q, 30Q95 ir 30Q80), kaip ribinių verčių, taikymu. Siekiant automatizuoti mažesnių už slenkstines reikšmių paiešką, naudota įrankio „HydroOffice“ FDC programinė įranga. Be to, analizuojant minimalių debitų kaitos tendencijas, naudotas TREND programinės įrangos paketas.

Trečiasis metodikos blokas taip pat išsamiai aprašytas 3 ir 4 straipsniuose. Šio bloko pagrindas – 1 lygtis, pagal kurią apskaičiuojamas standartizuotas kritulių indeksas (SPI) bei hidrologinės sausros indeksai (SWLI ir SDI). Atskirai apskaičiuojamas sausros atpažinimo indeksas (angl. Reconnaissance Drought Index, RDI). Meteorologinei ir hidrologinei sausrai tirti buvo naudojami keli vandens kaupimosi laikotarpiai: 1, 3, 6, 9 ir 12 mėnesių bei dešimties dienų kaupimosi laikotarpis specialiai SWLI ir SDI indeksams apskaičiuoti. Visi indeksai apskaičiuoti ne trumpesniam kaip 30 metų laikotarpiui:

$$I = (x_i - x_{mean})/\sigma; \qquad (1)$$

čia I – sausros indeksas;

x_i – pasirinkto laikotarpio kintamasis *i* metais;

x_{mean} – pasirinkto laikotarpio vidutiniai kintamojo duomenys;

σ – pasirinkto laikotarpio standartinis nuokrypis.

Kaip kintamieji 1 lygtyje buvo naudojami krituliai, vandens debitai ir vandens lygiai.

Ketvirtasis metodikos blokas išsamiau aprašytas 3 ir 4 straipsniuose. Kaip įvesties duomenys upių nuotėkiui prognozuoti naudoti trys regioniniai klimato modeliai (pagal RCP4.5 ir RCP8.5 scenarijus) iš EURO-CORDEX duomenų bazės ir Lietuvos hidrometeorologijos tarnybos (LHMT) istoriniai vandens debito, temperatūros ir kritulių duomenys. Klimato duomenims adaptuoti Lietuvos sąlygoms taikytas kvantilių metodas. Naudojant HBV programinę įrangą buvo sudaryti šešių upių hidrologiniai modeliai.

Penktasis bendros metodikos blokas išsamiai aprašytas 5 straipsnyje. Hidrologinės sausros rizikos vertinimo žemėlapiai sudaryti remiantis dviem pagrindiniais rizikos analizės komponentais, t. y. pavojumi ir pažeidžiamumu. Kiekviename komponente buvo nagrinėjami keturi kintamieji, kurių kiekvienas buvo perklasifikuotas į skalę nuo 0 iki 1, kiekvienam kintamajam priskiriant vienodą svorį. Pavojaus, pažeidžiamumo ir rizikos indeksai buvo apskaičiuoti kaip vidutinė kintamųjų reikšmė.

Įvairių indeksų ir parametrų erdvinei analizei atlikti naudota programinė įranga „ArcGIS 10.5“, kurią pasitelkus atlikta erdvinių modelių analizė, interpoliacija, rastrų apdorojimas ir rastrų skaičiavimai.

1.3. Trumpa literatūros šaltinių apžvalga

Upių nuosėkis, išdžiūvimas ir hidrologinė sausra – tai reiškiniai, kurie nėra tapatūs, bet yra tarpusavyje susiję, nes visi jie apibūdina mažiausią upės debitą (arba jo nebuvimą). Todėl tik išsami visų trijų komponentų analizė leis suprasti teritorijos atsparumą klimato kaitai ir parengti veiksmingą sausrų rizikos valdymo planą.

Upių išdžiūvimas

Pastaraisiais metais dėl klimato kaitos susidomėjimas išdžiūstančiomis upėmis didėja dėl didėjančio vandens trūkumo ir jų svarbos upių sistemose[43–47]. Esami tyrimai rodo, kad išdžiūstančios upės sudaro daugiau nei pusę viso pasaulio upių ilgio ir vyrauja sausringuose, pusiau sausringuose ir sausuose regionuose[48–50]. Šiauriniuose regionuose[50–52], kur dėl klimato kaitos išdžiūstančių upių skaičius ateityje nuolat didės[52–54], išdžiūstančių upių poveikis aplinkai ir visuomenei nepakankamai įvertintas.

Per pastarąjį dešimtmetį išdžiūstančių upių mokslinių tyrimų gerokai pagausėjo. Daugiausiai dėmesio buvo skiriama šiltiems ar pusiau sausringiems regionams[55], tačiau mažiau tyrimų pastebėta vidutinio klimato ar santykinai vėsesniuose regionuose. Išdžiūstančios upės tirtos pasauliniu mastu[55–58], Europoje (Viduržemio jūros regione[59–61], Alpių regione[62,63], centriniame regione[64]), Australijoje[65,66] bei JAV[45]. Rasti tik keli straipsniai, kuriuose aptariama Baltijos šalių išdžiūstančių upių problematika[61,67]. Svarbu pažymėti, kad šie straipsniai yra susiję su COST veiklos SMIRES iniciatyva, o viename iš jų nagrinėtos kai kurios Lietuvos upės[61].

Dabartinius išdžiūstančių upių tyrimus galima suskirstyti į kelias kryptis: išdžiūstančių upių poveikį ekosistemoms[48,52,59], šių upių vandens išteklių valdymo problemas[50,57,60,61,68], jų poveikį ekosistemoms[55,56,59,69], išdžiūstančių upių klasifikavimą[52] bei jų nuotėkio modeliavimą[62] ir kt.

Lietuva yra priskiriama prie šalių, turinčių palyginti daug vandens išteklių, bet itin šiltos ir sausos pastarojo meto vasaros išryškino didėjantį vandens trūkumą. Panaši padėtis yra ir kitose Baltijos šalyse. Dažnėja upių išdžiūvimo dažnis, todėl reikalingi detalūs šių hidrologinių ekstremumų tyrimai Lietuvos teritorijoje.

Upių nuosėkis

Upių nuosėkis yra labai svarbi hidrologinio režimo dalis. Nuosėkio parametrai yra susiję su vandens minimaliais debitais per tam tikrą laikotarpį[5,70,71]. Dėl sumažėjusio kritulių ar sniego kiekio minimalius vandens debitus įprastai papildo požeminio vandens prietaka, ežerų, pelkių ir kartais ledynų vanduo[5,72]. Lietuvoje dažniausiai vertinami vasaros ir žiemos sezonų minimalūs debitai. Tačiau kituose užsienio regionuose upių nuosėkio stebėjimo laikotarpis gali skirtis priklausomai nuo aplinkos sąlygų, kritulių kiekio ir tyrimų užduočių[5,72,73]. Skirtingai nei upių išdžiūvimo reiškinys, minimalių debitų kaita yra geriau ištirta.

Minimalūs vandens debitai yra labai svarbūs upių ekologiniam vientisumui bei vandens kokybei[70,72,74,75]. Esant ekstremaliai mažiems debitams, vandens ekosistemose sumažėja buveinių, pakinta maisto ištekliai, pablogėja vandens kokybė ir sutrinka rūšių sąveika[70,71,76–81]. Be to, vandens trūkumas kelia grėsmę bendruomenėms ir ekonomikai, todėl reikalingi tvarūs vandentvarkos sprendimai[73,75,80,82].

Minimalių vandens debitų nustatymas ir analizė yra labai svarbūs siekiant įvertinti vandens išteklių pažeidžiamumą dėl hidrologinių sausrų, ypač klimato kaitos sąlygomis[75]. Be to, skirtingi minimalių vandens debitų indeksai gali būti naudojami kaip ribinės vertės hidrologinėms sausroms nustatyti[72,73]. Šiuo metu sukurti įvairūs upių minimalių debitų vertinimo metodai, priklausomai nuo šalies ir skaičiavimo tikslo:

1. Ribinį minimalų vandens debitą galima nustatyti pagal vidutinį paros debitą (MDF) ar absoliučiai mažiausią debitą (AMF)[5,70,81].
2. Minimalų vandens debitą galima vertinti ir pagal nuotėkio trukmės kreivę (angl. Flow Duration Curve, FDC), kuris nustatomas pagal procentinę tikimybės dalį. Skirtingose šalyse ši procentinė dalis gali skirtis, pavyzdžiui, 75 %, 80 %, 90 %, 95 %[5,73,80,83,84].
3. Minimaliems debitams nustatyti dažnai naudojami indeksai su aiškiomis laiko ribomis. Pavyzdžiui, JAV praktikuojama naudoti 7Q10 arba 7Q2 indeksus, kuriuose atsižvelgiama į septynių dienų mažiausių debitų verčių seriją atitinkamai

per 10 ar 2 metus[5,79,85]. Lietuvoje taip pat naudojamas panašus skaičiavimas, kuris apibrėžiamas kaip duomenų eilučių, sudarytų iš mažiausių metinių iš eilės trisdešimties parų debitų, vidutinė reikšmė (Q30)[87-89].

Tačiau klimato kaita daro vis didesnį poveikį minimalių vandens debitų svyravimui bei pasiskirstymui, nes dėl kritulių kiekio ir temperatūros pokyčių keičiasi sezoninis upių nuosėkio režimas[75,91-93]. Be klimato veiksnių, minimaliems debitams formuotis įtakos turi geografiniai veiksniai[35,94] bei ypač didėjanti žmogaus veiklos įtaka aplinkai.

Naujausi tyrimai Europoje ir JAV atskleidė skirtingas minimalių vandens debitų kaitos tendencijas: kai kuriuose regionuose jie didėjo, o kituose mažėjo[35,75,83,86,91]. Nepaisant minimalaus vandens debito įvertinimo svarbos[89,95], pastaruoju metu Lietuvoje upių nuosėkio tyrimų atlikta mažai. Tik keletas darbų apie kompleksinę minimalių vandens debitų pokyčių analizę buvo paskelbta 2007 m. (tirti 1922 / 1941 / 1961 m. – 2003 m. duomenys)[87,88] ir 2014 m., kai analizuoti riboto vandens matavimo stočių skaičiaus duomenys 1960–2009 m. laikotarpiu[96]. Tik naujausių duomenų analizė gali suteikti svarbios informacijos apie upių nuotėkio pokyčius ir pasiūlyti įžvalgas, ko galima tikėtis toliau keičiantis klimatui.

Hidrologinės sausros

Sausra yra pasikartojantis gamtinis reiškinys, darantis neigiamą poveikį įvairiems ekonomikos sektoriams ir ekosistemoms visame pasaulyje[3,97,98]. Sausros susidarymas siejamas su ilgalaikiu kritulių trūkumu[4,98]. Pastaraisiais dešimtmečiais sausros dažnėja[99]. Tyrimai rodo skirtingas sausrų dažnumo ir stiprumo tendencijas Europoje[100] ir pasaulyje[98]. Tuo pat metu Europos regione mokslininkai pastebi didėjantį sausrų skaičių šiltuoju metų laikotarpiu[101]. Klimato kaitos prognozės rodo, kad gali padaugėti ekstremalių reiškinių, įskaitant sausras[102]. Todėl mokslininkai ir sprendimus priimantys asmenys vis labiau nerimauja dėl sausrų poveikio ir dėl būtinybės pasirengti jų padarinius sušvelninti[103].

Sausros gali būti skirstomos į įvairius tipus, atsižvelgiant į jų poveikį ir hidroklimatologinį kontekstą. Dažniausiai išskiriami keturi tipai[3,98,104]: meteorologinė sausra dėl nepakankamo kritulių kiekio; žemės ūkio arba dirvožemio sausra dėl vandens trūkumo dirvožemyje; hidrologinė sausra, kurią sukelia vandens trūkumas upėse; socialinė ir ekonominė sausra, kuri yra ankstesnių sausrų pasekmė ekosistemoms ir žmonių gyvenimui. Disertaciniame darbe daugiausia dėmesio skiriama hidrologinėms sausroms, kurios tiesiogiai veikia upių nuotėkio lygį ir minimalų vandens debitą šiltuoju metų laikotarpiu (turi įtakos ne tik šiltajam).

Yra įvairių indeksų ir rodiklių, padedančių nustatyti, stebėti ir analizuoti hidrologinę sausrą, naudojant tokius kintamuosius kaip krituliai, temperatūra, upių vandens debitai, požeminio vandens lygis ir dirvožemio drėgmė[105,106]. Hidrologinei sausrai nustatyti dažniausiai taikomi trys metodai:

1. Meteorologiniai indeksai. Standartizuotas kritulių indeksas (SPI)[105–107] gali būti naudojamas kaip hidrologinės sausros identifikatorius.

2. Hidrologinės sausros indeksai. Tai Palmerio hidrologinės sausros indeksas (PHDI)[3,4,106]; standartizuotas nuotėkio indeksas (SSFI)[3,106]; standartizuotas

vandens lygio indeksas (SWI)[106]; nuotėkio sausros indeksas (SDI)[4,106,109]; bendrasis sausros indeksas (ADI)[106] ir kt.

3. Slenksčio lygio metodai. Sausros nustatymas galimas pagal nuotėkio trukmės kreivę (FDC). Siekiant nustatyti laikotarpius, kurie gali būti laikomi hidrologine sausra, galima naudoti mėnesio slenkstį su tam tikra FDC procentine dalimi (pvz., 80 %)[3]. Kaip jau minėta, minimalus nuotėkis yra kiekvienais metais pasikartojantis reiškinys, tačiau tam tikro laikotarpio minimalaus debito vidutinės reikšmės gali būti naudojamos kaip slenkstinė vertė hidrologinei sausrai nustatyti.

Nors Lietuva priklauso drėgno klimato zonai, kurioje gausu upių ir ežerų, sausros neretas reiškinys. Per pastaruosius trejus metus (2018–2020 m.) dėl karštų ir sausų vasarų kiekvienais metais Lietuvoje buvo skelbiamos hidrologinės sausros. Remiantis naujausiais tyrimais, manoma, kad sausros bus dažnesnės ir intensyvesnės. Būtina atlikti išsamią hidrologinių sausrų Lietuvoje analizę, naudojant daugiamečius hidrometeorologinius duomenis ir klimato modelius bei scenarijus, kad būtų galima prognozuoti galimus sausrų pokyčius ateityje.

Hidrologinių sausrų rizikos vertinimas

Hidrologinis sausros rizikos vertinimas yra labai svarbus uždavinys, atsižvelgiant į opią sausros problemą įvairiuose pasaulio klimato regionuose[102,112–116]. Dėl žmogaus veiklos sukeltos klimato kaitos ekstremalių meteorologinių reiškinių, sausros dažnėja ir stiprėja[102,117–119]. Dėl gyventojų skaičiaus augimo padidėjo vandens poreikis[116,119,120], todėl sausros tampa dar didesne problema. Deja, vis dar trūksta išsamių hidrologinių sausrų vertinimo ir prognozavimo metodų[114].

Teritorijų, kurioms gresia hidrologinės sausros, nustatymas yra pirmas svarbus žingsnis siekiant sušvelninti būsimą poveikį. Hidrologinės sausros rizikos vertinimo tikslas yra nustatyti labiausiai pažeidžiamas teritorijas, kuriose tikimasi didžiausio poveikio vandens ištekliams, ekosistemoms ir žmonių veiklai. Jei strateginiuose plėtros planuose į sausrą nebus atsižvelgta, tai gali sukelti sunkių padarinių, pavyzdžiui, vandens trūkumą, maisto trūkumą ir ekonominius nuostolius. Skirtingai nuo staigių gamtinių pavojų, sausros prasideda lėtai ir gali tęstis ilgą laiką, todėl galima joms pasirengti ir sušvelninti jų poveikį[114,121]. Tiesioginio ir netiesioginio socialinio, aplinkosauginio ir ekonominio sausrų poveikio mažinimas tampa pasauliniu prioritetu, todėl būtina imtis tikslingų rizikos mažinimo ir prisitaikymo veiksmų[122].

Iš esmės hidrologinės sausros rizikos vertinimą, kaip ir bet kokią kitą rizikos analizę, sudaro du komponentai: pavojus ir pažeidžiamumas. Pavojaus komponentas apima ankstesnių sausrų analizę pagal sausrų indeksus arba minimalaus debitoindeksus[42,123,124]. Pažeidžiamumo komponentas įvertina įvairius veiksnius, tokius kaip BVP, žemės ūkio naudmenos, žemės danga, gyventojų tankumas ir t. t.[42,123–125].

Ankstesniuose moksliniuose tyrimuose sausros rizikai vertinti daugiausia buvo taikomi kiekybiniai arba mišrūs metodai, dažniausiai indeksais pagrįsti metodai[122]. Yra tyrimų, kuriuose įvertinta pasaulinė[126] ir regioninė[124,127,128] sausrų rizika, atskleidžiant regionus, kuriuose pažeidžiamumas yra didesnis dėl žmogaus veiklos ir žemės ūkio bei gyvulininkystės.

Nors su sausromis susijusių tyrimų Lietuvoje padaugėjo, konkretus hidrologinės sausros rizikos ir pažeidžiamumo vertinimas nebuvo atliktas. Verta paminėti, kad užsienio šalyse šiuo metu yra atlikta keletas tyrimų, kuriuose aprašomas hidrologinės sausros rizikos vertinimas, atsižvelgiant į vietines problemas: sausros poveikis sūraus vandens patekimui į upes[115], sausrų prognozė[116,129] sausrų vertinimas praeityje[39,41]. Tik keli tyrimai yra susiję su išsamiu hidrologinės sausros rizikos vertinimu: Pietų Korėjos hidrologinės sausros rizikos vertinimas praeityje ir ateityje[131] bei Malaizijos hidrologinės sausros rizikos vertinimas[42].

Autoriaus indėlis į tematiką

Upių išdžiūvimo tematika taip pat aktuali ir šalims, kuriose vyrauja vidutinio arba drėgno žemyninio klimato juostos ir žemumų upės. Lietuvoje upių išdžiūvimo reiškiniai beveik netirti. Todėl disertaciniame darbe buvo tiriami Lietuvos upių išdžiūvimo reiškiniai bei jų priklausomybė nuo fizinių-geografinių veiksnių.

Nepaisant to, kad Lietuvoje upių minimalūs debitai buvo tirti, vis dėlto išlieka didelė mokslinių tyrimų, nagrinėjančių upių nuosėkio pokyčius per pirmuosius du XXI a. dešimtmečius, spraga. Todėl buvo atlikta išsami upių nuosėkio parametrų ir jų kaitos tendencijų analizė, naudojant XX–XXI a. duomenų eilutes.

Studijuojant literatūros šaltinius nustatyta, kad kai kuriose užsienio šalyse mokslininkai daug dėmesio skyrė hidrologinėms sausroms prognozuoti. Lietuvoje beveik nėra informacijos apie hidrologinių sausrų kaitą pagal klimato scenarijus. Ši žinių spraga bus užpildyta nagrinėjant hidrologinės sausros riziką Lietuvoje. Tai apima ilgiausių ir ekstremalių sausrų nagrinėjimą, labiausiai pažeidžiamų regionų nustatymą, hidrologinių sausrų erdvinę ir laikinę dinamiką bei ateities prognozes, paremtas dviem plačiai naudojamais RCP scenarijais: RCP4.5 ir RCP8.5. Naudojant HBV programinę įrangą, 2021–2100 m. laikotarpiui buvo atliktas šešių upių iš skirtingų Lietuvos hidrologinių regionų hidrologinių sausrų prognozavimas.

Beveik nerasta tyrimų, kaip užsienio šalyse atliekamas operatyvinis hidrologinių sausrų vertinimas. Darbe sukurtas ir išbandytas hidrologinis sausros indeksas, pagrįstas vandens lygiu, vadinamas standartizuotu vandens lygio indeksu (SWLI). Norint kuo greičiau nustatyti hidrologines sausras, buvo parengta „Excel“ skaičiuoklė, o kaip operacinį laikotarpį pasiūlyta naudoti dešimties dienų vandens lygių akumuliacijos laikotarpį.

Sukurta hidrologinės sausros Lietuvoje rizikos vertinimo metodika apima du komponentus – pavojų ir pažeidžiamumą. Šis darbas yra pirmasis išsamus hidrologinės sausros rizikos vertinimas Lietuvoje. Sukurtą metodiką galima pritaikyti ir kituose žemumų upių regionuose. Atlikus šį tyrimą, buvo sudarytas detalus žemėlapis, kuriame pavaizduoti kiekvieno baseino pavojaus, pažeidžiamumo ir rizikos laipsniai.

2. STRAIPSNIŲ APŽVALGA

2.1. Nuosėkio ekstremumų – upių išdžiūvimo parametrų – kaitos dėsningumai Lietuvos teritorijoje.

Klimato kaita sukelia neišvengiamus vandens telkinių hidrologinio režimo pokyčius visame pasaulyje. Tie patys veiksniai lemia ir upių išdžiūvimo, kaip ekstremalaus hidrologinio reiškinio, paplitimo bei intensyvumo pokyčius. Kadangi upių išdžiūvimo atvejai gana dažni, ypač mažuose baseinuose, tai šie nekontroliuojami reiškiniai gali padaryti nepataisomą žalą aplinkai ir vandens ekosistemoms. Upių išdžiūvimo procesams didžiausią įtaką daro nuotėkio režimą lemiantys veiksniai, įskaitant klimato sąlygas, vietos geologiją, reljefą, dirvožemio sudėtį, augalinę dangą ir žmogaus sukeltą poveikį. Nors išdžiūstančių upių daugėja, Baltijos regione jos vis dar menkai ištirtos, ne išimtis ir Lietuva.

Atlikus visų vandens matavimo stočių išmatuotų vandens debitų analizę, detaliems išdžiūstančių upių tyrimams pasirinktos šiltojo metų laikotarpio (gegužės–rugsėjo) 16 upių daugiametės hidrologinių duomenų eilutės. Upių išdžiūvimo faktams nustatyti buvo taikoma 0,001 m^3/s vandens debito riba, kai išdžiūvimo trukmė ilgesnė nei 3 paros. Pasirinktų upių hidrologiniai duomenys apima 13–63 metų trukmės stebėjimo laikotarpius.

Pagrindiniai upių išdžiūvimo parametrai, tokie kaip vidutinis ir maksimalus upių išdžiūvimo laikotarpio parų skaičius (mDUR ir maxDUR), išdžiūvimo periodo pasikartojimo dažnis (FREQ, %), vidutinis metinis vandens debitas (QP, m^3/s) šiltuoju laikotarpiu ir pirmojo išdžiūvimo atvejo metuose diena (T0), buvo apskaičiuoti siekiant išanalizuoti išdžiūstančių upių hidrologinius dėsningumus. Koreliacinė analizė taikyta siekiant ištirti ryšį tarp išvardintų parametrų ir fizinių-geografinių veiksnių.

Upių išdžiūvimo parametrų kaita

Išskyrus vieną upę, visų tirtų upių plotas neviršija 206 km^2, o vidutinis metinis debitas 2,56 m^3/s (Akmenos upė). Vidutinis šiltojo laikotarpio upių debitas sumažėja 2–4 kartus (1 lentelė), lyginant su metiniu debitu. Pedamės ir Imsrės upės labai dažnais išdžiūsta, atitinkamai vidutiniškai 77–85 paros per metus. Šiose upėse taip pat užfiksuota ilgiausia išdžiūvimo laikotarpio trukmė. Be to, upių išdžiūvimo dažnis rodo, kad Pedamės, Imsrės ir Milupės upės reguliariai išdžiūsta 89–93 % stebėjimo metų. Pagal šį parametrą šios upės priskiriamos prie labai nepastovaus hidrologinio režimo upių. Dažniausiai tirtos upės išdžiūdavo rugpjūčio ir rugsėjo mėnesiais.

1 lentelė. Upių išdžiūvimo parametrų kaita gegužės–rugsėjo mėn. laikotarpiu

Upė	**VMS**	**Q_P**	**mDUR**	**maxDUR**	**FREQ**	**T_0**
Šešuva	Kalnėnai	0,475	3,00	24	14,3	195
Dotnuvėlė	Dotnuva	0,232	1,26	23	13,0	231
Smilga	Pasmilgys	0,318	15,2	100	25,9	190
Šušvė	Šiaulėnai	0,536	1,70	54	3,17	221
Alsa	Paalsys	0,129	7,68	81	28,9	208
Pedamė	Antkalniai	0,032	77,1	152	90,5	156
Imsrė	Jakaičiai	0,024	85,4	151	92,9	144
Pilvė	Papilvis	0,274	19,9	79	50,0	206
Milupė	Stoškai	0,050	53,6	129	88,9	157
Svyla	Guntauninkai	0,396	0,11	6	1,89	241
Agluona	Dirvonakiai	0,159	0,73	29	2,50	242
Daugyvenė	Rimšoniai	0,671	4,15	30	15,4	244
Yslykis	Kyburiai	0,095	33,6	116	58,3	181
Platonis	Vaineikiai	0,113	18,2	122	23,1	182
Sidabra	Šarkiai	0,083	10,9	142	7,69	133
Akmena	Tūbausiai	0,842	0,26	11	2,33	174

Upių išdžiūvimo parametrų priklausomybė nuo fizinių-geografinių veiksnių

Tiesinė koreliacinė analizė parodė, kad vidutinis upių nuotėkis (QP) šiltuoju laikotarpiu labai priklauso nuo baseino ploto (A). Be įtakos upės nuotėkiui formuotis, baseino plotas taip pat turėjo vidutinę neigiamą įtaką vidutiniam ir maksimaliam upių išdžiūvimo laikotarpiui (mDUR ir maxDUR) ir išdžiūvimo periodo pasikartojimo dažniui (FREQ) (2 lentelė). Upių nuolydžio dydis (S) turėjo teigiamą vidutinę koreliaciją su mDUR ir maxDUR trukmėmis. Upių išdžiūvimo parametrai reikšmingai nekoreliavo su miško (For) ar žemės ūkio naudmenų (Agr) procentine dalimi. Smėlingas priemolis (SL) turėjo stiprų teigiamą ryšį su pirmojo upių išdžiūvimo atvejo metuose dienos (T0) nustatymu ($r = 0,70$).

2 lentelė. Tiesinės koreliacijos koeficientai tarp kintamųjų

Parametrai	A, km^2	S, m/km	For, %	Agr, %	Dirvožemiai, %			
					SL	LCL	MHCL	P
QP	**0,74**	-0,42	0,23	-0,29	0,18	-0,13	-0,42	0,43
mDUR	-0,52	**0,77**	0,14	-0,07	-0,49	-0,14	0,64	-0,44
maxDUR	-0,53	0,65	-0,09	0,12	-0,53	0,20	0,49	-0,44
FREQ	-0,50	0,63	0,10	-0,02	-0,36	-0,14	0,56	-0,47
T0	0,53	-0,68	-0,07	0,04	**0,70**	-0,27	-0,46	0,52

Lietuvoje, esančioje vandens pertekliaus zonoje, taip pat yra periodiškai išdžiūstančių upių. Jų daugiausiai nustatyta vidurio Lietuvos hidrologiniame rajone.

Upių išdžiūvimo trukmę ir dažnį labiausiai lemia tokie veiksniai: upių baseino plotas, upės nuolydis ir dirvožemio tipas.

2.2. Upių minimalaus debito rodiklių erdvinis ir laikinis pasiskirstymas pagal istorinius duomenis.

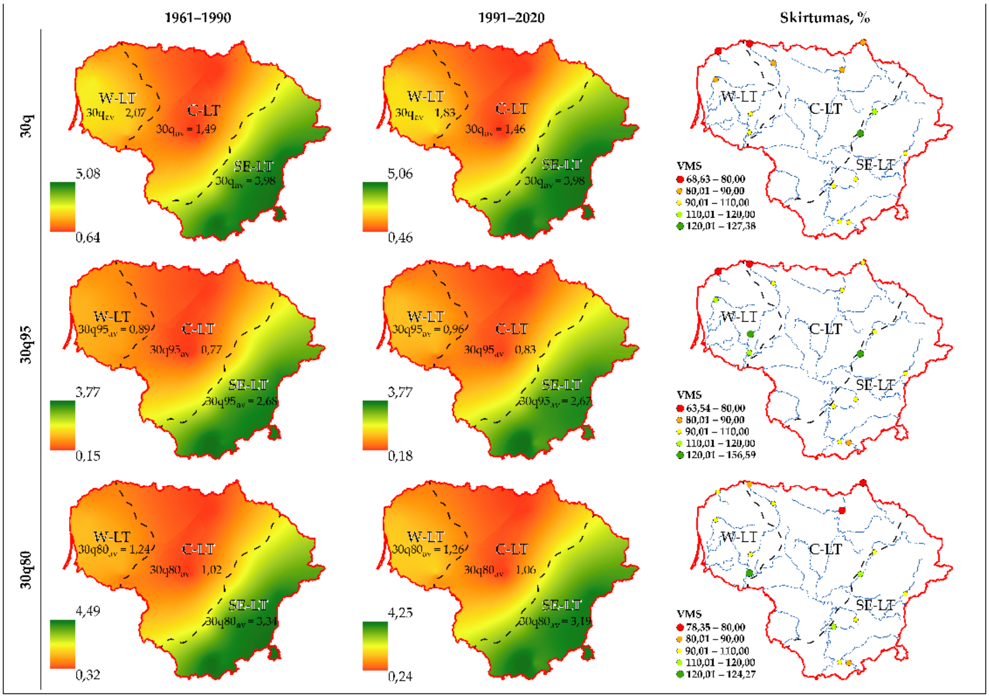
Upių nuosėkio laikotarpis, kai vandens debitas yra mažesnis už vidutinį metinį debitą, yra svarbus hidrologinio režimo aspektas. Ilgai trunkantis sausmetis upėse blogina buveinių būklę, turi neigiamos įtakos maisto ištekliams ir ekologinei dinamikai, taip pat vandens trūkumas kelia pavojų ekosistemoms ir bendruomenėms. Didėjanti pasaulinė temperatūra dar labiau keičia upių hidrologinį režimą bei minimalius vandens debitus. Šiuo tyrimu siekiama įvertinti regioninius upių minimalių debitų skirtumus ir istorines tendencijas, kad geriau suprastume upių nuosėkio procesus žemumų upių baseinuose.

Buvo tiriami trys upių minimalių debitų laikotarpiai: 1961–2020 m., 1961–1990 m. ir 1991–2020 m. Vidutinis metinis minimalus debitas 30Q apskaičiuotas kaip iš eilės einančių mažiausių 30 parų debitų vidurkis metuose. Minimalaus debito indeksai 30Q95 ir 30Q80 buvo apskaičiuoti pagal 30Q laiko eilutę, atitinkamai taikant 95 % ir 80 % tikimybinius slenksčius. Kad būtų galima palyginti skirtingo vandeningumo upes, minimalūs debitai buvo perskaičiuoti į specifinio minimalaus debito q reikšmes (30q, 30q95 ir 30q80) pagal formulę $q = Q/A \cdot 1000$ (Q: minimalus debitas; A: baseino plotas), išreikštas $l/s \cdot km^2$.

Naudojant programinės įrangos paketo „HydroOffice“ (2.1 versija) įrankį FDC (Flow Duration Curves), buvo apskaičiuoti minimalūs debitai 30Q95 ir 30Q80, o įrankiu TLM (Threshold Level or Sequence Peak Algorithm Methods) buvo įvertintos ekstremalios nuotėkio sąlygos, pateikti duomenys apie sausringus laikotarpius, didžiausią nuokrypį ir vandens deficito tūrį. Minimalių debitų indeksų žemėlapiai buvo sudaryti naudojant Kriging interpoliaciją programinėje įrangoje ArcGIS 10.5. TREND programine įranga (V.1.0.2.) buvo atliekamas statistinis hidrologinių laiko eilučių duomenų tendencijų testavimas, naudojant Manno-Kendalio (Mann-Kendall, MK) ir Spearmano Rho (Spearman's Rho, SR) neparametrinius testus. MK nustato tiesines arba netiesines tendencijas, o SR – tendencijos nebuvimą.

Minimalių debitų indeksų kaita: erdvinė ir laikinė analizė

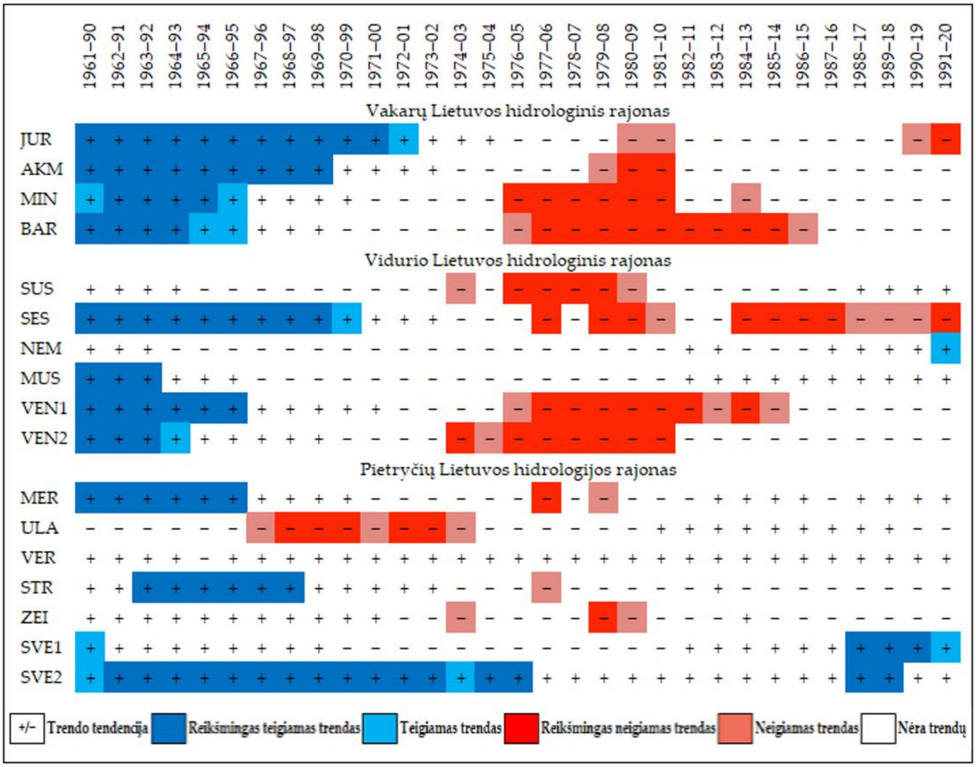
Analizuojant specifinio vidutinio metinio minimalaus debito pasiskirstymą vakarų Lietuvos hidrologiniame rajone, nustatyta, kad 1961–1990 m. 30q vidurkis buvo 2,07 $l/s \cdot km^2$, o 1991–2020 m. jis sumažėjo iki 1,83 $l/s \cdot km^2$ (3 pav.). Pažymėtina, kad 30q vertės pasirinktais laikotarpiais mažai skyrėsi vidurio Lietuvos hidrologiniame rajone (atitinkamai 1,49 ir 1,46 $l/s \cdot km^2$), o pietryčių Lietuvos rajone išliko pastovios (3,97 $l/s \cdot km^2$). Didžiausios 30q indekso vertės abiem laikotarpiais buvo nustatytos pietryčių rajone, o mažiausios – vidurio Lietuvos rajone. Visose vakarų ir vidurio Lietuvos rajonų upėse stebimi nedideli 30q indekso reikšmės pokyčiai (sumažėjimas mažiausiai 10 %). Tokie rezultatai rodo, kad ekstremalių minimalių debitų reiškiniai dažnėja, tačiau atitinkamai nedidėja jų stiprumas (išskyrus kai kurių stočių duomenis). Pietryčių Lietuvos rajone, kuriam būdingos didelės 30q indekso reikšmės, daugiausia stebimi nedideli minimalių debitų pokyčiai, tai rodo didesnį vandens išteklių stabilumą minėtame rajone.



3 pav. Specifinių minimalių debitų indeksų pasiskirstymas ir kaita 1961–1990 ir 1991–2020 m. laikotarpiais Lietuvos teritorijoje (vakarų Lietuvos hidrologinis rajonas – W-LT, vidurio Lietuvos hidrologinis rajonas – C-LT, pietryčių Lietuvos hidrologijos rajonas – SE-LT)

<u>Minimalių debitų indeksų kaita: trendų analizė</u>

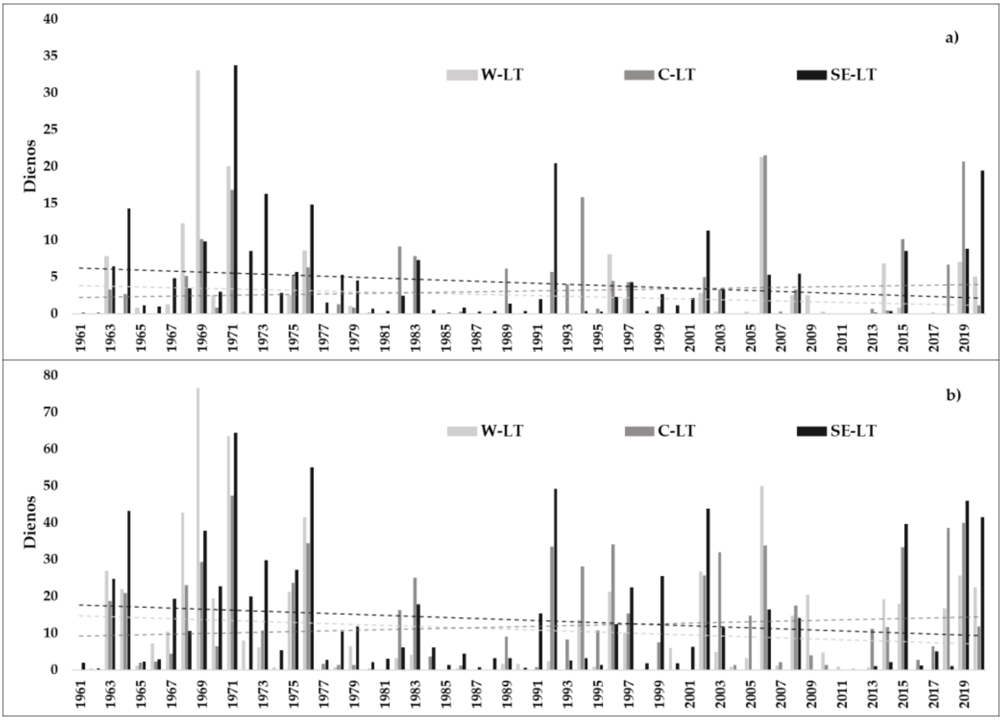
17 upių vidutinių metinių minimalių debitų (30Q) duomenų rinkinių, apimančių 1961–2020 m. laikotarpį, tendencijos analizuotos taikant Manno-Kendallo testą (4 pav.). Iki 1973 m. daugumoje VMS buvo stebimos teigiamos arba reikšmingai teigiamos 30Q kaitos tendencijos, išskyrus vieną VMS (Ūlos upė) pietvakarių hidrologiniame rajone. Nuo 1973 m. vakarų ir vidurio Lietuvos hidrologinių rajonų upėse 30Q daugiausia turėjo neigiamas arba labai neigiamas tendencijas (minimalių debitų mažėjimas), o tendencijos pietvakarių rajone dažnai nebuvo statistiškai reikšmingos. Pažymėtina, kad pietvakarių rajono vienintelėje Šventosios upėje (SVE2) iki 1976 m. buvo stebimas žymus ir nuolatinis 30Q didėjimas. Ta yra vienintelis atvejis, kai per visą stebėjimo laikotarpį buvo stebimos nuosekliai didėjančios minimalaus debito tendencijos.



4 pav. Tirtų upių vidutinių metinių minimalių debitų (30Q) trendų analizė 1961–2020 m. laikotarpiu (vakarų Lietuvos hidrologinis rajonas – W-LT, vidurio Lietuvos hidrologinis rajonas, C-LT, pietryčių Lietuvos hidrologijos rajonas – SE-LT)

<u>Sausų dienų nustatymas pagal minimalių debitų indeksų ribines vertes</u>

Minimalaus debito indeksai 30Q80 ir 30Q95 buvo naudojami ribinės vertės sausoms dienoms nustatyti, kai upės vandens debitas mažesnis už ribinę vertę. Kiekvienais metais kiekvienai upei buvo suskaičiuotas dienų skaičius, kai upėje tekėjo debitas, mažesnis už 30Q80 ar 30Q95 vertes. Trijuose Lietuvos hidrologiniuose rajonuose vidutinio sausringų dienų skaičiaus pasiskirstymas laike (5 pav.) atskleidė, kad abiejų slenksčių atveju vidutinis metinis sausų dienų skaičius turėjo tendenciją mažėti vakarų ir pietryčių rajonuose, o didėti – vidurio Lietuvos rajone. Didžiausias sausų dienų skaičius nustatytas 1963–1976, 1992–2006 ir 2015–2020 m. laikotarpiais. Sausringiausi metai skirtinguose rajonuose buvo šie: 1969 m. – vakarų rajone (33 dienos esant 30Q95 ribinei vertei; 76,5 dienos esant 30Q80 ribinei vertei); 1971 m. ir 2006 m. – vidurio Lietuvos rajone (atitinkamai 47,3 dienos 30Q80; 21,5 dienos 30Q95); 1971 m. – pietvakarių rajone (33,7 dienos 30Q95, 64,4 dienos 30Q80).



5 pav. Vidutinis sausų dienų skaičius trijuose hidrologiniuose rajonuose 1961–2020 m. laikotarpiu: (a) kai ribinė vertė yra 30Q95, (b) kai ribinė vertė yra 30Q80 (vakarų Lietuvos hidrologinis rajonas – W-LT, vidurio Lietuvos hidrologinis rajonas, C-LT pietryčių Lietuvos hidrologinis rajonas – SE-LT)

Didžiausios specifinio minimalaus nuotėkio reikšmės nustatytos pietvakarių hidrologiniame rajone, mažiausios – vidurio Lietuvos rajone.

1961–1990 m. laikotarpiu būdingos teigiamos upių minimalių debitų didėjimo tendencijos. Tiriamu laikotarpiu (1991–2020 m.) visose hidrologiniuose rajonuose reikšmingų minimalių debitų kaitos tendencijų nepastebėta.

Vakarų ir pietvakarių hidrologiniuose rajonuose vidutinis sausų dienų skaičius (esant 30Q95 ir 30Q80 ribinėms vertėms) per tyrimų laikotarpį mažėjo, o vidurio Lietuvos rajone – didėjo.

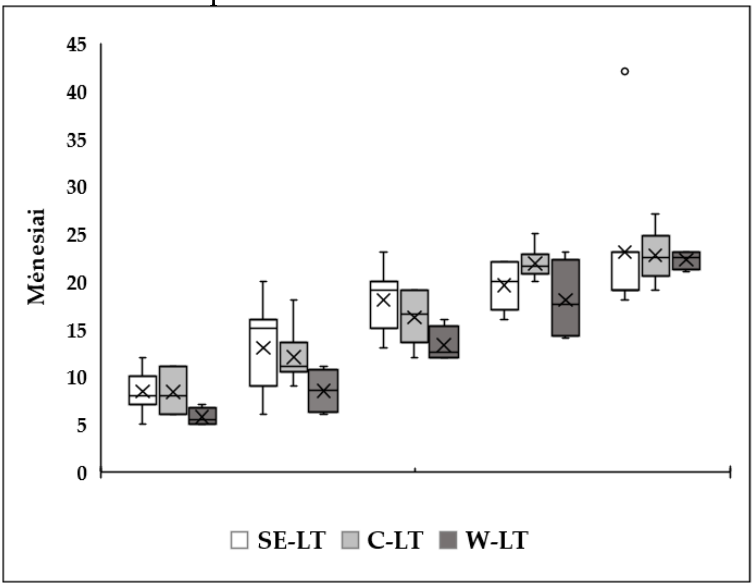
2.3. Lietuvos upių hidrologinių sausrų kaita ir dėsningumai pagal istorinius duomenis

Hidrologinė sausra yra natūralus reiškinys, tačiau ji daro didelį poveikį įvairiems ekonomikos sektoriams ir ekosistemoms, todėl yra viena brangiausiai kainuojančių stichinių nelaimių. Dėl klimato kaitos sausros tampa vis stipresnės ir dažnesnės, todėl prisitaikymo galimybės prie besikeičiančių gamtinių sąlygų yra ribotos. Sausroms vertinti naudojami įvairūs sausrų indeksai. Tačiau iki šiol daugiausia dėmesio buvo skiriama meteorologinėms ir žemės ūkio sausroms, o hidrologinių sausrų tyrimų dar mažai atlikta.

Vienas iš pagrindinių hidrologinių sausrų nustatymo indeksų yra nuotėkio sausros indeksas (SDI), kuris grindžiamas tais pačiais principais kaip ir standartizuotas kritulių indeksas (SPI). SDI indeksas yra paprasta ir veiksminga priemonė hidrologinėms sausroms nustatyti, nes naudojamasi pasirinkto periodo vandens debito duomenimis. Be SDI, siūloma naudoti ir vandens lygiu pagrįstą indeksą, vadinamą standartizuotu vandens lygio indeksu (SWLI). Norint įvertinti hidrologinę sausrą skirtingais laikotarpiais, buvo naudojami keli vandens kaupimosi laikotarpiai: 10 dienų, 1/3/6/9/12 mėnesių. Skaičiavimai atlikti DrinC (Drought Indices Calculator) programine įranga. 10 dienų kaupiamojo laikotarpio indekso skaičiavimams naudota asmeniškai parengta „Excel“ skaičiuoklė.

Hidrologinės sausros indekso kaita pagal įvairius vandens kaupimosi laikotarpius

6 paveiksle matyti, kad didžiausių sausrų trukmė didėjo kartu su vandens kaupimosi laikotarpio ilgėjimu. Didžiausia sausros trukmė buvo užfiksuota pietvakarių Lietuvos hidrologiniame rajone (konkrečiai Šventosios baseine) per 12 mėnesių akumuliacijos laikotarpį. Ši užsitęsusi sausra truko 42 mėnesius, nuo 1971 m. gegužės iki 1974 m. spalio. Pažymėtina, kad ekstremalios SDI-12 reikšmės šioje upėje (-2,46) taip pat buvo užfiksuotos šiuo laikotarpiu, konkrečiai 1972 m. spalį. Vertinant pagal tą patį indeksą SDI-12, vakarų hidrologiniame rajone didžiausia sausra truko trumpiausiai – 23 mėnesius.

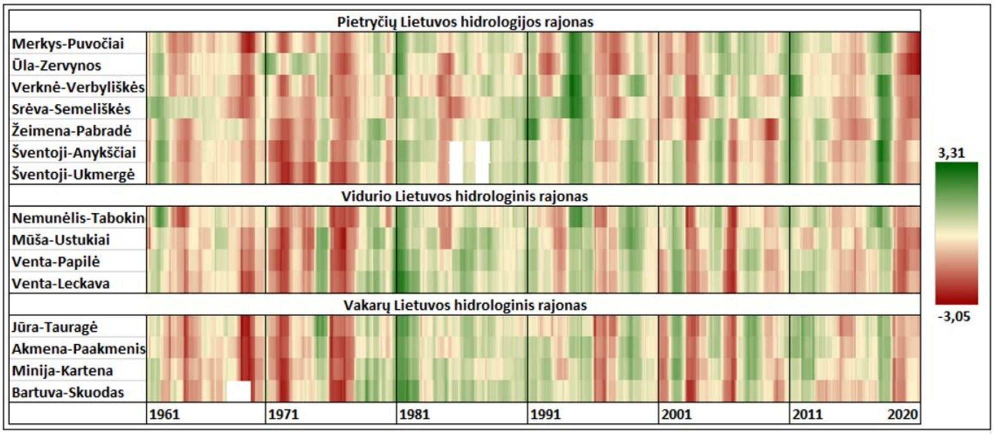


6 pav. Hidrologinių sausrų trukmė mėnesiais trijuose hidrologiniuose rajonuose (stulpeliai pateikti nuo kairės į dešinę įvairiems vandens kaupimosi periodams – 1, 3, 6, 9 ir 12 mėnesių, atitinkamai) (vakarų Lietuvos hidrologinis rajonas – W-LT, vidurio Lietuvos hidrologinis rajonas, C-LT, pietryčių Lietuvos hidrologijos rajonas – SE-LT)

Hidrologinių sausrų analizė pagal istorinius duomenis

- Pagal indeksą SDI-12

Remiantis nuotėkio sausros indeksų SDI analize, kai vandens kaupimo laikotarpis yra 12 mėnesių (7 pav.), Lietuvoje nuo 1964 m. pabaigos iki 1977 m. antrosios pusės tęsėsi ilgas sausros laikotarpis, kuriame ypač ekstremalūs buvo 1969, 1972 ir 1976–1977 metai. Nuo 1977 m. iki 2003 m. daugiausia vyravo vandeningas laikotarpis arba sąlygos, artimos normai, su nedideliais sausringais laikotarpiais (apibūdinama sausros reikšmėmis iki -1,5), kurie paveikė didžiąją Lietuvos dalį (ypač 1993 m., taip pat 1996 m. ir 2001 m.). Nuo 2003 ir 2006 m. pradėjo formuotis sausros, pasižyminčios ekstremaliomis reikšmėmis (indekso reikšmės <-2,0). Nuo 2018 m. visoje Lietuvoje iki tiriamojo laikotarpio pabaigos pradėjo formuotis ilgalaikės hidrologinės sausros.



7 pav. Nuotėkio sausros indeksų SDI-12 kaita 1961–2020 m. laikotarpiu (žalia spalva pažymėti mėnesiai be hidrologinių sausrų, ruda spalva – mėnesiai su hidrologinėmis sausromis ir balta spalva – nėra duomenų (vakarų Lietuvos hidrologinis rajonas – W-LT, vidurio Lietuvos hidrologinis rajonas – C-LT, pietryčių Lietuvos hidrologinis rajonas – SE-LT)

- Pagal indeksą SWLI

Standartizuotas vandens lygio indeksas (SWLI) naudotas 30 metų laikotarpio (nuo 1991 iki 2020 m.) hidrologinei sausrai nustatyti. 8 pav. pavaizduotas dienų skaičius, kai šiltuoju metų laikotarpiu (gegužės–spalio mėn.) kiekvienoje upėje buvo didelė ir ekstremali hidrologinė sausra. Daugiausia sausrų užfiksuota 2006, 2019 ir 2020 m., o 2019 m. išsiskyrė kaip itin sausringi metai. Verta atkreipti dėmesį į bendrą dėsningumą – pastaraisiais metais daugėja dienų, kurioms būdinga didelė sausra.

Metai:	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Suma
Nem-Sma	0	65	0	0	0	0	0	0	0	6	0	41	0	0	0	0	0	0	4	0	0	0	0	0	35	2	0	0	92	83	328
Mer-Puv	0	4	0	0	0	0	0	0	19	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	24	8	0	0	83	161	304
Ner-Jon	0	61	33	0	0	7	10	0	6	15	0	40	4	0	0	0	0	0	37	0	0	0	0	0	13	0	0	0	82	17	325
Zei-Pab	0	48	0	0	0	0	0	0	0	0	0	0	16	0	0	57	0	0	42	0	0	0	0	0	3	0	0	14	100	40	320
Sve-Ukm	54	134	59	13	0	0	0	0	3	8	0	0	3	0	0	49	9	4	35	0	0	0	0	2	0	0	0	0	6	14	393
Nev-Pan	0	0	0	0	0	0	0	0	0	6	0	25	30	10	10	112	0	0	0	0	0	0	0	0	1	11	0	36	131	59	431
Dub-Lyd	0	2	30	0	0	0	0	0	0	3	0	0	0	0	0	24	0	4	0	0	0	0	0	0	0	0	0	0	16	9	88
Mit-Zin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	15	0	5	0	0	0	0	0	6	0	0	0	14	7	17	72
Ses-Ski	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	5	48	9	0	14	114	8	210
Min-Kar	0	0	3	10	0	0	0	0	0	5	0	13	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	9	0	51
Svy-Gun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
Nem-Tab	0	8	35	0	0	11	0	0	1	21	0	48	0	2	0	28	0	0	0	0	0	0	0	0	0	0	0	0	13	4	171
Mus-Ust	0	30	5	0	0	0	0	0	68	0	0	126	12	0	0	30	0	15	0	0	0	0	0	0	17	0	0	0	16	5	324
Ven-Lec	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39	0	0	0	0	0	0	0	0	24	4	0	34	57	60	218
Bar-Sku	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	3	10	0	0	0	17	15	0	0	5	24	52	142

8 pav. Hidrologinių sausrų įvykių (dienų) skaičius 1991–2020 m. laikotarpiu pagal SWLI indeksus (žalia spalva – metai, kai nebuvo hidrologinių sausrų, ruda spalva – dienų skaičius metuose su hidrologinėmis sausromis)

Hidrologinių sausrų analizė atskleidė hidrologinių rajonų skirtumus, susijusius su didžiausia sausros trukme, ekstremaliomis vertėmis ir sausrų pasiskirstymu pagal vandens kaupimosi laikotarpius.

Didžiausios hidrologinės sausros (per 60 metų laikotarpį naudojant indeksą SDI-12) buvo stebimos 1961–1977 m., 2000–2007 m. ir 2018–2020 m. sausringais laikotarpiais.

Rezultatai (naudojant indeksą SWLI) parodė, kad intensyviausios sausros per 30 metų laikotarpį buvo 1992 m., 2002 m., 2006 m., 2019 m. ir 2020 m.

Hidrologinių sausrų tyrimų rezultatai, gauti naudojant indeksus SDI ir SWLI, yra gana panašūs, todėl šių indeksų naudojimas Lietuvos teritorijoje yra tinkamas.

2.4. Hidrologinės sausros dažnumo ir intensyvumo prognozė artimoje ir tolimoje ateityje.

Hidrologinių sausrų tyrimai negali apsiriboti vien praeities įvykių analize; prognozė yra esminis sausrų tyrimo komponentas. Kadangi vandens ištekliai atlieka pagrindinį vaidmenį palaikant ekosistemas, žemės ūkį, pramonę ir bendruomenes, gebėjimas prognozuoti hidrologines sausras ir jų poveikį yra labai svarbus. Pasauliniai klimato modeliai kartu su hidrologiniais modeliais suteikia galimybę įvertinti galimą hidrologinės sausros pasireiškimo riziką ateityje. Tačiau Lietuvoje ir Baltijos šalyse trūksta mokslinių tyrimų, skirtų hidrologinėms sausroms ateityje prognozuoti.

Hidrologinės sausros nustatymo metodika (naudojant SDI ir SWLI indeksus), taip pat klasifikavimas į sausros klases yra toks pat, kaip ir 3 uždavinio atveju.

Hidrologinei sausrai tirti buvo sukurti Lietuvos šešių upių hidrologiniai modeliai. Trečiame straipsnyje hidrologinei sausrai prognozuoti pagal indeksą SDI-12 buvo pasirinktos trys upės – po vieną iš trijų skirtingų hidrologinių rajonų (Šventoji, Venta ir Minija). Ketvirtajame straipsnyje pasirinktos dar trys upės, kurioms sukurti hidrologiniai modeliai bei prognozuotos sausros pagal indeksą

SWLI. Tai didžiausia Lietuvos upė Nemunas bei dvi mažesnės upės iš skirtingų hidrologinių rajonų – Žeimena ir Šešuvis.

Sėkmingai prognozuoti upių nuotėkį būtini keli duomenų rinkiniai, įskaitant istorinius hidrologinius ir meteorologinius duomenis, žemės dangos duomenis iš CORINE bazės bei regioninių klimato modelių duomenis iš EURO-CORDEX bazės.

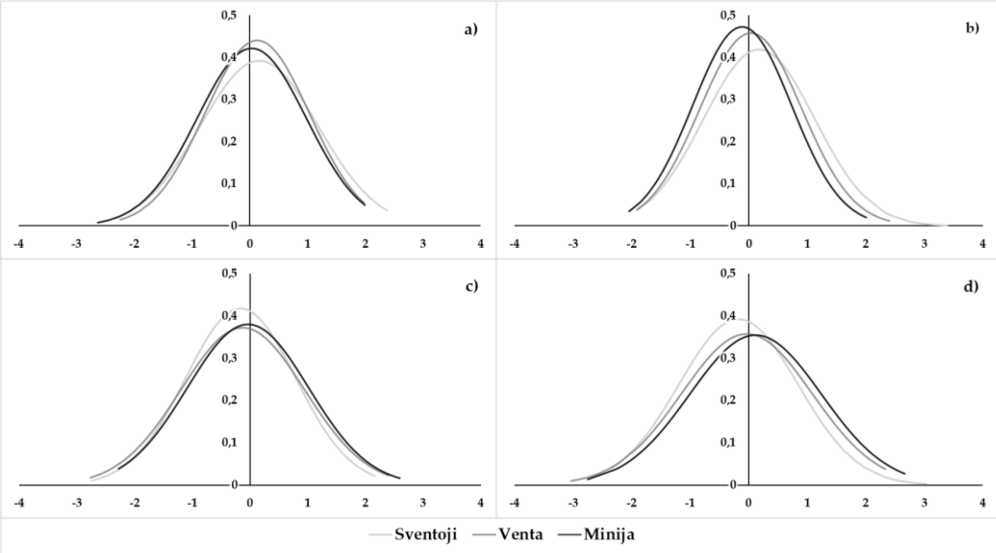
Upių hidrologiniams modeliams sudaryti pasirinkta Hydrologiska Byråns Vattenbalansavdelning (HBV) programinė įranga. Ši programinė įranga, sukurta Švedijos meteorologijos ir hidrologijos instituto (SMHI), yra sudėtinga hidrologinių procesų modeliavimo ir prognozavimo platforma. Integruodama hidrologinius duomenis, kritulių kiekį, temperatūrą ir kitus įvesties duomenis, HBV programinė įranga suteikia mokslininkams ir hidrologams galimybę modeliuoti ir numatyti būsimas hidrologines sausras. Kalibruojant sukurtus hidrologinius modelius, reikėjo pakoreguoti 16–19 pagrindinių parametrų. Tiek kalibravimo, tiek validavimo laikotarpiais koreliacijos koeficientai (r) tarp stebėtų ir apskaičiuotų skirtingų upių vandens debitų svyravo nuo 0,68 iki 0,88.

Hidrologinių sausrų prognozė pagal indeksą SDI-12

Remiantis sumodeliuotais upių nuotėkio duomenimis, artimos ateities laikotarpiui (2021–2060 m.) pagal du klimato scenarijus, nustatyta, kad Minijos upė (vakarų hidrologinis rajonas) yra jautresnė hidrologinėms sausroms, lyginant su Ventos (vidurio Lietuvos rajonas) ir Šventosios (pietvakarių rajonas) upėmis (9 pav.). Tolimoje ateityje (2061–2100 m.) Šventosios upėje, palyginti su Minijos ir Ventos upėmis, numatoma daugiau ekstremalių sausrų. Apskritai, pagal abu klimato scenarijus, visų upių atveju XXI a. antroje pusėje numatomas sausrų dažnėjimas.

Hidrologinių sausrų prognozė pagal indeksą SWLI

Hidrologinių sausrų analizė ateityje pagal indeksą SWLI rodo, kad dauguma sausrų numatoma tolimoje ateityje (3 lentelė). Pagal RCP4.5 scenarijų, išimtis nustatyta Šešuvio upei. Palyginus prognozuojamus ir istorinius duomenis paaiškėjo, kad tokiose upėse kaip Žeimena ir Šešuvis didėja didelių ir ekstremalių sausrų procentinė dalis. Tačiau Nemune nustatyta priešinga tendencija. Šį kontrastą gali lemti didesnis Nemuno baseino plotas ir mažėjantys vandens lygio svyravimai.



9 pav. Nuotėkio sausros indeksų SDI-12 pokyčiai ateityje: (a) pagal RCP 4.5 scenarijų artimoje ateityje; (b) RCP 8.5 artimoje ateityje; (c) RCP 4.5 tolimoje ateityje; (d) RCP 8.5 tolimoje ateityje

3 lentelė. Procentinis hidrologinių sausrų pasiskirstymas pagal indeksus SWLI artimoje ir tolimoje ateityje

	Periodas	Nemunas–Smalininkai	Žeimena–Pabradė	Šešuvis–Skirgailai
Istorinis periodas	1991–2020	5,94	5,80	3,80
RCP 4.5	2021–2060	2,98	3,65	5,10
	2061–2100	5,88	10,67	5,04
RCP 8.5	2021–2060	0,34	3,98	2,91
	2061–2100	9,52	10,34	6,55

Modeliuojant pasirinktų upių nuotėkį pagal ateities scenarijus, nustatyta, kad daugiausia hidrologinių sausrų prognozuojama tolimoje ateityje (2061–2100 m. laikotarpis).

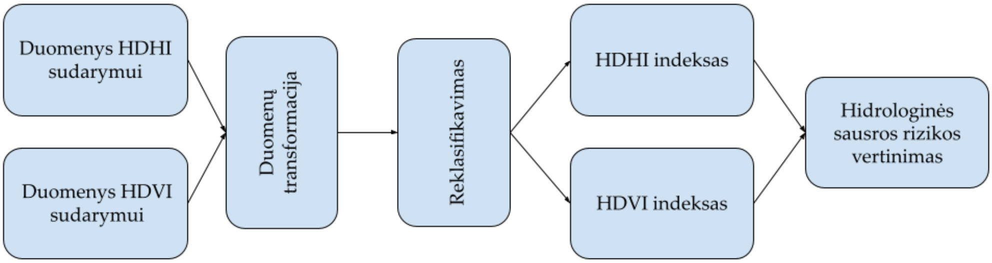
Pagal abu klimato scenarijus (RCP4.5 ir RCP8.5) padidės amplitudė tarp didžiausių ir mažiausių nuotėkio sausros indeksų reikšmių.

Priklausomai nuo RCP scenarijaus, hidrologinių sausrų tendencijos gali skirtis priklausomai nuo pasirinkto scenarijaus.

2.5. Hidrologinių sausrų rizikos žemėlapių sukūrimas bei labiausiai pažeidžiamų Lietuvos regionų identifikavimas.

Pastaraisiais metais sparčiai plėtojami ir taikomi įvairūs sausrų vertinimo metodai – nuo statistinės analizės iki sudėtingų modeliavimo metodų. Tačiau tais atvejais, kai ekstremalūs meteorologiniai reiškiniai, įskaitant sausras, dažnėja ir stiprėja, labai svarbu ne tik nustatyti sausrų atvejus, bet ir suprasti jų kilmę bei įvertinti pažeidžiamumą, kad būtų sumažintas sausrų būsimas poveikis. Strateginio planavimo metu ignoruojant sausrų problemą, gali kilti skaudžių padarinių, įskaitant vandens stygių, maisto trūkumą ir didelius ekonominius nuostolius. Todėl prisitaikymas prie hidrologinių sausrų turi būti paremtas išsamia sausros rizikos analize. Nepaisant didėjančio susidomėjimo sausrų tyrimais, Lietuvoje vis dar trūksta hidrologinio sausrų rizikos vertinimo tyrimų.

Hidrologinės sausros rizikos (HDR) vertinimą sudaro du pagrindiniai komponentai: sausros pavojus (HDHI) ir sausros pažeidžiamumas (HDVI). Bendra HDR skaičiavimo procedūra pavaizduota 10 paveiksle.



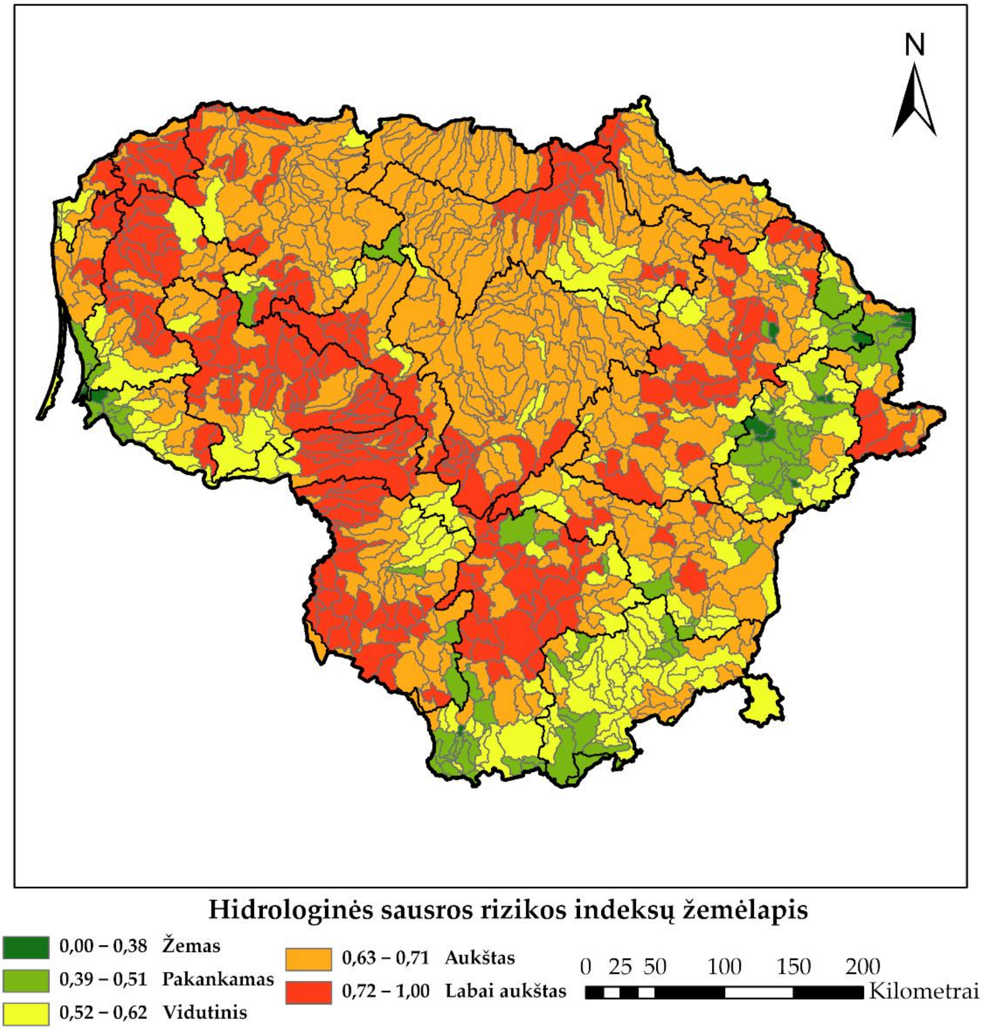
10 pav. Bendra hidrologinės sausros rizikos vertinimo schema

Hidrologinės sausros rizikai apskaičiuoti taikyta ši lygtis:

$$HDR=((WSD+WLD+R+RD)/4+(S+LULC+SL+L)/4)/2; \qquad (4)$$

čia WSD – 5–16 dienų trukmės hidrologines sausros, WLD – ilgiau nei 16 dienų trunkančios hidrologinės sausros, R – vidutinis kritulių kiekis, RD – upių nuotėkio priklausomybė nuo kritulių kiekio, S – upės nuolydis, LULC – žemės naudojimo ir (arba) žemės dangos sudėtis, SL – dirvožemio morfologinė sudėtis, L – ežerų tankis. Pirmieji keturi kintamieji atspindi sausros pavojaus komponentą, o paskutinieji keturi – pažeidžiamumą dėl sausros.

Hidrologinės sausros rizikos (HDR) žemėlapyje (11 pav.) matomos aiškios klasterių formacijos: didelės rizikos vertės šiaurinis regionas ir pailgas klasteris, kuriam būdingas mažas arba vidutinis rizikos lygis Lietuvos pietryčiuose. Tokie rezultatai pietryčiuose glaudžiai susiję su pietryčių hidrologiniu rajonu. Mažas sausros rizikos vertes šiame rajone galima paaiškinti dėl daugybės ežerų ir miškų, taip pat dėl aukštumų įtakos. Dideles hidrologinės sausros rizikos vertes šiaurėje galima paaiškinti ežerų ir miškų trūkumu, kritulių kiekiu ir iš dalies dirvožemio savybėmis. Sudarytas žemėlapis atskleidžia, kad nemaža dalis Lietuvos patenka į didelės ir labai didelės sausros rizikos kategorijas (49,8 %), o į mažos ir vidutinės rizikos kategorijas patenka tik apie 24,4 % teritorijos.



11 pav. Hidrologinės sausros rizikos indeksų žemėlapis

Iš 11 pav. matyti, kad mažiausia hidrologinės sausros rizika yra pietvakarių rajone, kuriame tik 10,4 % teritorijos priskirta didelės ir labai didelės rizikos sausrų kategorijoms. Priešingai, vakarų ir vidurio Lietuvos hidrologiniuose rajonuose nustatyti žymiai didesni plotai (atitinkamai, 61,1 % ir 72,7 %), kuriuose galima didelė hidrologinės sausros rizika.

Atlikti hidrologinės sausros pavojaus, pažeidžiamumo ir rizikos vertinimai leidžia daryti išvadas, kad daugiau nei 70 % Lietuvos teritorijos priskiriama didelio ir labai didelio pažeidžiamumo kategorijai, o maždaug 39 % teritorijos atitinka pavojingumo indekso kategorijas. Be to, beveik pusė šalies teritorijos patenka į didelės ir labai didelės hidrologinių sausrų rizikos kategorijas (49,8 %).

Pietvakarių hidrologinis rajonas išsiskiria iš kitų teritorijų dėl mažesnių hidrologinės sausros rizikos indeksų. Šiaurinėje vidurio Lietuvos rajono dalyje, konkrečiai Mūšos ir Lielupės upių baseinuose, yra nustatyti dideli sausrų rizikos indeksai.

3. IŠVADOS

Ištyrus upių nuosėkio ir hidrologinių sausrų pokyčius, įvertinus jų priklausomybę nuo klimato kaitos bei atlikus sausrų rizikos įvertinimą Lietuvos upėms praeityje ir ateityje, nustatyti šie dėsningumai:

1. Pagal hidrologinius vandens matavimo stočių duomenis, Lietuvoje identifikuotos 16 išdžiūstančių upių. Daugiausia išdžiūstančių upių yra vidurio Lietuvos hidrologiniame rajone. Upių išdžiūvimo trukmės rodikliai rodo reikšmingą koreliaciją su baseino plotu (r=0,74) ir upės nuolydžiu (r=0,77). Taip pat šie rodikliai tiesiogiai siejasi su klimato kaita, todėl ateityje daugės išdžiūstančių upių skaičius ir ilgės išdžiūvimo trukmė.
2. Lietuvoje upių nuosėkio (minimalių debitų) rodikliai pasiskirstę netolygiai. Didžiausios specifinio vidutinio minimalaus debito reikšmės stebimos pietvakarių hidrologiniame rajone (3,98 $l/s{\cdot}km^2$), o mažiausios – vidurio Lietuvos rajone (1,47 $l/s{\cdot}km^2$). Keičiantis klimatui, teigiama vidutinių minimalių debitų rodiklių didėjimo tendencija po 1973 m. išnyksta. Per pastaruosius 30 metų hidrologiniuose rajonuose nėra aiškių minimalių debitų kaitos tendencijų, išskyrus kelias atskiras upes, kuriose pastebimi reikšmingi neigiami arba teigiami pokyčių trendai.
3. Hidrologinių sausrų pasiskirstymas pagal trukmę ir stiprumą Lietuvos hidrologiniuose rajonuose nėra tolygus. Didžiausios hidrologinės sausros nustatytos 1961–1977 m., 2000–2007 m. ir 2018–2020 m. sausringais laikotarpiais. Ilgiausia hidrologinė sausra užfiksuota pietryčių hidrologiniame rajone (1971–1974 m. truko 42 mėnesius), tačiau daugiausia sausringų mėnesių, taip pat ir ekstremalių sausrų šiltuoju metų laikotarpiu nustatyta vakarų ir vidurio Lietuvos rajonuose.
4. Remiantis upių hidrologinių prognozių modeliais, pagrįstais RCP4.5 ir RCP8.5 klimato kaitos scenarijais, ateityje ekstremalios hidrologinės sausros dažnės, todėl upių vandens debito amplitudė tarp drėgnų ir sausringų laikotarpių padidės. Tolimoje ateityje (2061–2100 m.) hidrologinių sausrų dažnis bus didžiausias. Iš šešių upių prognozavimo modelių tik Ventos upėje, priklausančioje vidurio Lietuvos rajonui, nustatyta hidrologinių sausrų intensyvumo didėjimo tendencija pagal abu scenarijus, o kitų upių hidrologinių sausrų kaitos tendencijos kinta priklausomai nuo pasirinkto RCP scenarijaus.
5. Remiantis hidrologinės sausros rizikos vertinimu, maždaug pusė Lietuvos teritorijos patenka į didelės ir labai didelės sausrų rizikos intervalą, o į mažos ir vidutinės rizikos intervalą patenka tik 24,4 % baseinų ploto. Didžiausi sausrų rizikos indeksai nustatyti šiaurinėje vidurio Lietuvos rajono dalyje (Mūšos ir Lielupės upių baseinai). Mažiausi hidrologinių sausrų rizikos indeksai stebimi pietvakarių rajone. Tai galima paaiškinti dirvožemio

tipų, požeminio vandens maitinimo šaltinių, plataus ežerų ir miškų paplitimo, taip pat Baltijos aukštumų poveikio vietos klimatui įtaka.

6. Atlikus numatytus šiame darbe tyrimus, išryškėjo galimos Lietuvos upių nuosėkio tyrimų gairės ateityje: 1) šiuo metu trūksta vandens matavimo stočių duomenų apie išdžiūstančias upes (įprastai hidrologiniai matavimai atliekami didesnio ploto upių baseinuose, kur nėra užfiksuota upių išdžiūvimo atvejų), o tai apsunkina šio reiškinio tyrimus; 2) dėl vykstančių klimato pokyčių reikėtų nuolat analizuoti hidrologinę sausrą tiek trumpais, tiek ilgais vandens akumuliacijos laikotarpiais; 3) dėl klimato pokyčių būtina atlikti mokslinius tyrimus, kuriuose būtų nagrinėjamos upių bei jų ekosistemų prisitaikymo galimybės prie naujų sąlygų, sukeltų hidrologinių sausrų; 4) šiame tyrime daugiausia dėmesio skirta hidrologinių objektų sausros rizikai analizuoti. Tačiau norint įvertinti hidrologinės sausros rizikos poveikį visuomenei, reikalinga papildoma rizikos analizė, įtraukiant socialinius ir ekonominius rodiklius.

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IMPACT OF PHYSICO-GEOGRAPHICAL FACTORS AND CLIMATE VARIABILITY ON FLOW INTERMITTENCY IN THE RIVERS OF WATER SURPLUS ZONE

FLOW INTERMITTENCY IN RIVERS OF LITHUANIA

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Abstract

Climate change is inevitably altering the hydrological regime of water bodies. The interest in changing behaviour of intermittent rivers is increasing in many countries. This research was focused on intermittent rivers (rivers which naturally, periodically cease to flow) in Lithuania. The purpose of this research was to provide an overview of flow intermittency phenomena according to available data in a historical period and to evaluate the impact of catchment geographical features and climate variability on zero-flow events. The calculated indices of flow intermittency showed that the selected rivers had very different flow regimes. The threshold for the separation of typically intermittent rivers from only occasionally intermittent ones was suggested. Multiple linear regression analysis defined the crucial role of catchment size and watercourse slope on the river cessation process in Lithuania. The applied nonparametric Wilcoxon–Mann–Whitney test revealed the significance of the relationship between precipitation (in June–September) and zero-flow duration. Flow intermittency phenomena in Lithuanian rivers were linked to a low-frequency teleconnection pattern (SCAND index). A methodology of estimating the relation between river intermittency and large-scale atmospheric circulation pattern (based on SCAND index) was created. The generated regression equations between flow intermittency indices and catchment characteristics might be useful for the estimation of zero-flows in ungauged river catchments. The main aspect of future investigations might be related to forecasting flow intermittency using modern hydrological models and climate scenarios as well as the defined relationships between zero-flow indices and physico–geographical features of river catchments.

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KEYWORDS: river intermittency, flow indices, catchment features, precipitation, Wilcoxon–Mann–Whitney test, Scandinavian pattern.

INTRODUCTION

All over the world, climate change is inevitably altering the hydrological regime of water bodies. Due to rising air temperature and changed precipitation patterns, some territories are getting drier and experience more droughts, while others become wetter and suffer from floods. Some areas are periodically affected by both droughts and floods. There is a growing body of literature that focuses on the impact of climate change on perennial rivers. However, in recent years, the interest in the changing behaviour of temporal rivers is increasing as well (Gallart, Amaxidis, Botti, Canè, Castillo et al., 2008; Buttle, Boon, Peters, Spence, van Meerveld et al., 2012; Eng, Wolock, & Dettinger, 2015; Datry, Singer, Sauquet, Jorda-Capdevila, Von Schiller et al., 2017; Rutkowska, Kohnová, Banasik, & Szolgay, 2018). Failure to recognize, understand and manage these temporary waterways may lead to severe degradation of aquatic ecosystems and negative impacts on the societies that depend upon them (Acuña, Datry, Marshall, Barcelo, Dahm et al., 2014). After years of near-obscurity, research of intermittent rivers and ephemeral streams has been on an increase in the last decade, driven by climate change effects, increasing water scarcity issues and the recognition that such water bodies are prominently prevalent in river networks (Datry, Arscott, & Sabater, 2011).

Traditionally, two main indices describing temporal patterns of flow intermittency are used in intermittent river research: the frequency and duration of zero-flow events (Snelder, Datry, Lamouroux, Larned, Sauquet et al., 2013; Reynolds, Shafroth, & Poff, 2015; de Vries, van Hoeve, Sauquet, Leigh, Bonada et al., 2015). Other important variables include the beginning or timing of the zero-flow period (Rutkowska et al., 2018), the magnitude of the zero-flow event expressed by volume flowing through the gauging station (Delso, Magdaleno, & Fernández-Yuste, 2017) and others. Previous research established that in different parts of the world (e.g., in Slovakia (Rutkowska et al., 2018), in Switzerland (Paillex, Siebers, Ebi, Mesman, & Robinson, 2019), in southern Iberia (Delso et al., 2017), in the USA (Eng et al., 2015), in Australia (Bond & Cottingham, 2008), etc.) changes of flow intermittency currently take place or are expected in the future.

Drawing on an extensive range of sources, the authors have identified the different factors that might drive a phenomenon of flow intermittency. However, these factors are related to those that determine the runoff regime, i.e. natural features such as climate, local geology, relief, soils, vegetation cover, as well as anthropogenic factors. The study by Snelder et al. (2013) offers a comprehensive analysis which relates flow intermittency to several environmental characteristics. It has been established that regions with high probabilities of intermittent river segments are those with low annual rainfall, warm air temperatures and steep, small, elongated catchments. Climatic conditions, such as the amount and timing of precipitation and air temperature, are generally considered a first-order control on the occurrence of flow intermittency (Buttle et al., 2012; Snelder et al., 2013; Eng et al., 2015). As this phenomenon is usually observed in small-scale catchments, its intensity is strongly related to the interaction between local catchment characteristics and regional-scale climate patterns.

Even in Lithuania, which is considered a territory of relatively high availability of water resources, in light of recent extremely warm and dry summers, there is a rising problem of water scarcity. Climate change is generating significant alterations in river runoff dynamics. The summer of 2019 was the second summer in a row when a nationwide hydrological drought was declared in Lithuania. However, the problems related to hydrological droughts have not been properly addressed.

Both in Lithuania and the other Baltic States, there is still a lack of studies about intermittent rivers, which are particularly sensitive to any alterations of meteorological conditions or any anthropogenic disturbance. Many of such rivers remain ungauged and it is difficult to predict their state in climate change conditions. There is a probability that intermittent streams will disappear, while today's permanent rivers will become intermittent. This research was focused on intermittent rivers (rivers which naturally, periodically cease to flow) in Lithuania. The purpose of this research is to provide an overview of flow intermittency phenomena according to available data in a historical period and to evaluate the impact of catchment geographical features and climate variability on zero-flow events.

STUDY AREA, DATA AND METHODS

Study area and data

According to the Köppen–Geiger climate classification system, Lithuania belongs to a humid continental climate and falls within a water-surplus zone as the ratio between annual precipitation and evaporation reaches 1.47. It has over 22,000 rivers and streams with a total length of more than 76,000 km (Gailiušis, Jablonskis, & Kovalenkovienė, 2001). Although Lithuania is a relatively small country, its rivers differ in their hydrological behaviour. Due to different precipitation patterns, topography, catchment morphology and lithology as well as underground feeding peculiarities, the rivers are assigned to three hydrological regions: Western, Central and South-eastern (Figure 1). In Western Lithuania, rivers are mainly fed by precipitation (it comprises 40–70% of the annual runoff). The type of river feeding in Central Lithuania is mixed (snow and rain each contribute about 40% of the annual runoff). In western and central regions, the rivers are shallow, while their groundwater feeding is insignificant, therefore rivers with a smaller catchment area tend to dry out in summer. In rivers of South-eastern Lithuania, the runoff is generally formed by subsurface feeding (40–60% of the annual runoff). The dominant permeable sandy soils there efficiently absorb snowmelt and liquid precipitation into groundwater reserves and gradually release it later, supplying rivers during the low-flow period.

In Lithuania, river flow data of 183 water gauging stations (WGS) are available for the different time periods. Daily time series of all WGSs were screened looking for cessation events. The threshold of 0.001 m^3/s was applied for the indication of intermittent reach due to measurement resolution. Therefore, all data equal to or less than 0.001 m^3/s were considered as non-flows or zero-flows. Sixteen rivers were identified as intermittent rivers (or rivers prone to flow intermittency) because their observations showed at least three consecutive days of flow interruption in the warm period (May–September) during the entire observations. The majority of the selected rivers were located in lowlands of the Central Lithuania hydrological region, one river (the Akmena) was from Western Lithuania, and the other one (the Svyla) was from South-eastern region (Figure 1). The Central Lithuania hydrological region mostly coincides with the Middle Lithuanian Lowland pedological region. Here, the gleyic cambisols are the most dominant soil type according to pedological regionalization of Lithuania (Volungevičius & Kavaliauskas, 2009). The gleyic properties of the soils take a significant part of analysed river catchments (74.7%) and indicate weak infiltration characteristics with temporary or permanent saturation of moisture. These conditions do not allow free movement of surface water and groundwater of upper layers. Therefore, in frequent cases, the precipitation is stuck in the lowest forms of relief, evaporates and does not reach the river bed.

The hydrological database (Table 1) was created using the mean daily discharge data from 16 WGSs of the Lithuanian Hydrometeorological Service. The selected rivers have different length of the observation period, which ranges from 13 to 63 years.

Land use and soil data were provided by the National Land Service under the Ministry of Agriculture of the Republic of Lithuania. These data were processed and the percentages between the relevant groups were calculated using ArcGIS (Table 1).

Table 1 presents geographical features describing each gauging station catchment: mean annual discharge (Q), average area (A), average slope of a watercourse (S), percentage of forested (For) and agricultural lands (Agr) as well as the predominant soil types according to granulometric composition: sandy loam (SL), light clay loam (LCL), medium and heavy clay loam (MHCL) and peat (P). The majority of selected catchments are small and have a relatively small slope. They mostly consist of either forest or agricultural land. The largest areas of agricultural land are covered by light clay loam and sandy loam.

The meteorological database was created using the daily meteorological data (precipitation and air temperature) and decadal snow water equivalent data of six meteorological stations (MS) obtained from the Lithuanian Hydrometeorological Service for the periods of hydrological observations. The meteorological stations nearest to the catchments were selected for the analysis of meteorological drivers. For the relations between flow intermittency and Northern Hemisphere teleconnection patterns, the Scandinavian pattern (SCAND) was chosen. The monthly data of this index were downloaded from the NOAA (National Oceanic and Atmospheric Administration) National Weather Service, Climate Prediction Centre database (https://www.cpc.ncep.noaa.gov/). The maps of anomalies of 500 hPa geopotential height and sea level pressure during the years of different rate of flow intermittency were created according to the data provided by the NOAA/ESRL Physical Sciences Laboratory, Boulder, Colorado from their web site at https://psl.noaa.gov/.

Methods

As flow cessation in Lithuanian rivers usually occurs during the warm period of a year, the time series of the period from May 1 to September 30 were used to calculate the main indices of flow intermittency. The reach of each selected river was described by the mean duration of zero-flows (mDUR, days), which is the mean number of zero-flow days during the warm period of a year, and the mean annual frequency of zero-flow periods (FREQ, %), which is the percentage of years with zero-flows among the total number of years (the observation period). Additionally, the mean average flow (Q_P, m^3/s) of the warm period (May–September) and the timing of zero-flows (T_0), which is the mean Julian date of the first zero-flow event, were estimated.

All continuous hydrological time series and indices of flow intermittency as well as available catchment-scale data were analysed using statistical analysis methods (correlation and multiple linear regression analysis). First, the linear correlation matrix between indices of flow intermittency and geographical factors was created to identify the strongest relations and most significant variables. The geographical factors consisted of two groups: catchment characteristics (such as area, watercourse slope, percentage of forests and agricultural lands) and soil types based on their granulometric composition (Table 1). According to the most significant variables and relations of genetic origin, some of the geographical factors were selected for multiple linear regression analysis (MLRA). MLRA was used to create simple models to assess the relations between the main indices of flow intermittency (Q_P, mDUR, maxDUR and T_0) and geographical factors. In the created models, intermittency indices were selected as dependent variables (predictands), whereas geographical characteristics were used as independent variables (predictors). All characteristics of flow regime of intermittent rivers, as well as the geographical characteristics of catchments of those rivers, were selected according to a literature review of scientific publications related to the regions with similar physico-geographical conditions.

The daily precipitation amount was chosen as a meteorological parameter for the analysis of main meteorological drivers affecting flow intermittency. Nonparametric statistical analysis was applied using the Wilcoxon–Mann–Whitney test (Fay & Proschan, 2010). For the warm period (June–September) of each year, the number of zero-flow days was counted. If flow intermittency was absent in a particular year, the average discharge of the same period was estimated. Both characteristics were attributed as intermittency indices. The sum of precipitation amount was calculated for the analysed period as well. The observation years of each river were sorted according to the number of zero-flow days (from highest to lowest) or the average discharge (from lowest to highest), maintaining the link to the precipitation amount of a particular year. The methodology based on the ranking, i.e. Wilcoxon rank–sum test, is a nonparametric test of the null hypothesis that two populations are the same against an alternative hypothesis especially that a particular population tends to have larger values than the other and divides the data series into two equal populations respectively. In this research, one half of the years with the highest number of zero-flow days was assigned to a first rank population (dry year), whereas another half of the years having the lowest number of zero-flow days or the highest average discharge of the warm season (if flow intermittency was absent) was assigned to a second rank population (wet year). Afterwards, three-column data (intermittency index, precipitation amount and assigned rank) were sorted according to the precipitation amount of the warm period from the smallest to the largest and numbered from 1 (the lowest precipitation) to *n* (the highest precipitation), maintaining the link with intermittency index and assigned rank. The difference in the sum of the linked numbering (according to the precipitation sorting) between the groups of two separate ranks indicated the rejection of the null hypothesis at different levels of significance depending on the size of population.

In order to evaluate the atmospheric circulation and teleconnection patterns during the flow intermittency period, the Scandinavian (SCAND) pattern was used. The index is also known as Eurasia-1 (EU-1) and represents two centres of pressure. One of them is located over North Scandinavia (60°–70° N, 25°–50° E), while the second one with the opposite sign is located over Northwest China or West Mongolia at 30°–45° N and 80°–100° E (Barnston & Livezey, 1987). The index itself consists of positive and negative phases which are described by monthly positive or negative values respectively. The sum of the monthly SCAND index values was used to find out the relation with the duration of flow intermittency for the period of June–September. The sum of this index defines the tendency of index sign (positive or negative phase) for flow intermittency period. The estimated SCAND index was interrelated with flow intermittency using the Wilcoxon rank–sum test in the same manner as in the case of precipitation.

RESULTS

Variability of flow intermittency

The following characteristics describing flow intermittency in the warm period were estimated: the mean discharge of the warm period (Q_P in m^3/s), the mean number of zero-flow days (mDUR), the maximum number of zero-flow days (maxDUR), the mean annual frequency of zero-flow periods (FREQ, %) and the mean timing of the first zero-flow event (T_0; the mean Julian date) (Table 2).

The vast majority of the selected intermittent river catchments have small areas (10–200 km^2). The mean annual discharge of these rivers ranged from 0.07 m^3/s (in the Pedamė and Imsrė) to 2.56 m^3/s (in the Akmena), whereas the mean discharge during May–September was even 2–4 times lower (Table 2). The main indices of flow intermittency (duration and frequency of zero-flow periods) showed that the selected rivers (more precisely, river reaches) had a very different degree of intermittency. Among the analysed rivers, the shortest mean duration of flow intermittency (less than a day) as well as a more uniform runoff throughout the year were identified for the Agluona, Svyla and Akmena, the latter two being from different hydrological regions (South-eastern and Western Lithuania, respectively). The two smallest rivers (the Pedamė and Imsrė) can be considered as highly intermittent because during the observation period they ceased to flow for 77–85 days per year on average. The records of maximum duration of the period without flow belonged to the already mentioned Pedamė (152 days) and Imsrė (151 day) as well as to the Sidabra (142 days) and Milupė (129 days). The mean annual frequency of zero-flows indicated the periods of river flow absence in the Pedamė, Imsrė and Milupė for almost every observation year (89–93%), allowing to identify these rivers as regularly stopping to flow or extremely intermittent. Meanwhile, in the Svyla, Agluona, Akmena, Šušvė, Sidabra and Šešuva, the zero-flow events were observed only once or twice over their gauging history, indicating very low intermittency of the mentioned rivers or their sensitivity to environmental factors that drive this phenomenon. Over the observation period, the beginning of flow cessation was estimated as early as in the first decade of May (like in the Pedamė, Imsrė and Smilga) and as late as in the beginning of September (in the Daugyvenė and Smilga). According to the available data, the most zero-flow events took place at the end of the warm period, i.e. in August and September. A tendency for a longer duration of zero-flow period in case it starts earlier was estimated.

It is difficult to assess trends of stream intermittency in the studied rivers in the past because of the absence of a common observation frame. It can only be mentioned that during the last two decades (2000–2018), the greatest number of zero-flow days was recorded in 2006, 2015 and 2018.

Relations between flow intermittency and catchment geographical characteristics

Local factors such as catchment topography and geomorphology, land use, etc. determine the flow regime in rivers as well as intermittency phenomena.

In order to find out possible relations between intermittency indices (Q_p, mDUR, maxDUR, FREQ, T_0) and catchment features (catchment area (A), watercourse slope (S) as well as areas covered by forest (For), agricultural lands (Agr) and predominant soil types), a correlation analysis was performed. Soil types were described as sandy loam (SL), light clay loam (LCL), medium and heavy clay loam (MHCL) and peat (P). The analysis indicated how strongly or weakly these variables may be related to each other: only relations with moderate (0.50 to 0.70 or -0.50 to -0.70), high (0.70 to 0.90 or -0.70 to -0.90) and very high (0.90 to 1.00 or -0.90 to -1.00) correlation coefficients were analysed.

The primary analysis of linear correlation revealed that in the studied catchments, the mean discharge of the warm period was closely related to the catchment area (Figure 2a). Correlation coefficients showed the influence of the catchment area on the intermittency indices as well: as the catchment area increases, the likelihood of drying out decreases. The mean ($r = -0.52$) and maximum ($r = -0.53$) duration as well as the frequency of zero-flows ($r = -0.50$) were moderately related to the catchment area (Table 3). There was evidence of a positive relation between the catchment area and the timing of the zero-flow period (r = 0.53).

The influence of catchment topographic features on intermittency indices depends on the relief. As the majority of studied catchments are characterized by lowland terrain (the absolute height of WGSs is 18–129 m), the influence of surface topography is supposed to be insignificant. On the other hand, the slope of river watercourses seemed to have a much higher impact. In this analysis, watercourse slope presented itself as a catchment characteristic having the greatest influence on flow intermittency indices: the mean duration had a high positive relationship, both maximum duration and frequency had a moderate positive association, while timing was moderately negatively related to this characteristic, i.e. a greater watercourse slope determined earlier, more frequent and more prolonged zero-flow events.

The intermittency indices correlated neither to the percentage of forest area nor to the land used for agricultural activities in the catchments. However, the indices of zero-flow events were more or less dependent on the soil types such as sandy loam (SL), medium and heavy clay loam (MHCL) and peat (P). Sandy loam characteristic had a strong positive influence on the timing of the zero-flow period (r = 0.70) (Figure 2e) and a moderate negative influence on both mean and maximum durations of the zero-flows (r = -0.49 and r = -0.53, respectively). Therefore, there was evidence of a positive relation between medium and heavy clay loam (MHCL) and mean and maximum durations of the zero-flow period (r = 0.64 and r = 0.49, respectively) (Table 3). Opposite trends were found due to the influence of different soil composition (SL and MHCL) on the duration of zero-flow. The permeability of dominant soils in river catchment highly affects the fate of precipitation and conditions for groundwater storage, supplying rivers during the low water period. Therefore, soil composition is considered as one of the most important catchment characteristics influencing intermittency indices.

At the initial steps of this research, there was a challenge of determining the appropriate definition for intermittent rivers. For the primary analysis, 16 intermittently flowing rivers were selected by using a threshold of at least three consecutive days of flow interruption. However, later it was decided to use a stricter limit for values of intermittent indices to exclude the rivers and streams that only seldom cease to flow and can be considered as prone to intermittency or occasionally intermittent. Scientists specified a number of different ways to define intermittency phenomenon. Eng et al. (2015) described US rivers as intermittent if they had at least 15 days of zero-flow per year. Reynolds et al. (2015) categorized reaches in the Upper Colorado River basin as strongly intermittent if the average number of zero-flow days across the years was greater than 20 per year and weakly intermittent when this number was less than 20. According to De Vries et al.

(2015), on average, at least five zero-flow days per year in the gauging station records is enough to call as river intermittent. According to the results of this research, at least 15 days per year without flow and three years with recorded zero-flow events are sufficient to describe Lithuanian rivers as typically intermittent and separate those from a group of rivers that do not meet the threshold values (assigned to occasionally intermittent ones). The graphical illustration (Figure 2c) of the relationship between the intermittent catchment area and the mean duration of zero-flow periods supports the suggested classification; a cluster of only occasionally ceasing rivers (circled dots) reveals their dissimilarity from a group of typically intermittent rivers.

Such classification provided an opportunity to eliminate the hydrological 'noise', which originated from the other rivers and to highlight the consistent patterns of the dependence of the intermittency process on the geographical factors and meteorological drivers. Only one exception was made for the Daugyvenė. Despite its short hydrological observation period at a new WGS (from 2006) and only a few intermittency events, this river is the largest intermittent river of Lithuania according to previous historical records (Gailiušis et al., 2001). Therefore, the Daugyvenė was chosen as a river that represents the upper level of boundary conditions of a catchment area of an intermittent river. Based on the described criteria, the eight typically intermittent rivers were selected for further analysis. The major differences in the relations of some characteristics between 16 and 8 selected rivers are presented in Figure 2. The relation between the mean discharge of the warm period and the catchment area increased significantly in case of typically intermittent rivers compared with all analysed rivers. It was confirmed by the correlation coefficient, which increased from 0.73 to 0.97 (Figure 2a, b). For 8 rivers, the most clearly expressed relation was between the mean duration of zero-flow days and catchment area, in contrast with 16 rivers where the association was unclear. This relationship was described as a power function and reached 0.96 (Figure 2d). Such tendency confirms the dependence of one of the main indices of flow intermittency on the catchment area. All previously mentioned relations differed from each other in their strength and nature. To get a more complex evaluation, the multiple linear regression analysis (MLRA) was applied to combine the influence of several most significant geographical factors on intermittency indices. The correlations between geographical factors were done in order to estimate links between them and to eliminate those ones which are strongly interrelated (Table 3). This analysis highlighted the strong dependency between forest and agricultural land-use because the correlation between them reached 0.98. Therefore, it was decided to eliminate agriculture factor from independent variables for MLRA.

The MLRA showed that the combined effect of selected geographical factors strongly improved the relations between them and the indices of flow intermittency. The analysis was performed for

16 and 8 rivers. The created prediction models disclosed the assigned coefficients for the equations of MLRA (Table 4). They also presented the best combinations of geographical factors for all intermittency indices. The most common of them were catchment area, slope, peat, medium and heavy clay loam, sandy loam and forests. Depending on the analysed indices of flow intermittency (dependent variables), the coefficients of independent variables (geographical factors) ranged widely in both groups of the rivers. Based on 16 rivers, the determined combinations of geographical factors and their coefficients resulted in correlation coefficients from 0.74 (maxDUR) to 0.85 (T_0). When only typically intermittent rivers were used, the MLRA models showed better results and the correlation coefficients fluctuated from 0.96 to 0.99. The best results were obtained for Q_P and maxDUR. The mean discharge of the warm period was closely related to the catchment area, slope and percentage of peat. On the other hand, maxDUR was additionally dependent on sandy loam, the presence of which determines better infiltration properties and stronger groundwater supply. Therefore, the negative sandy loam coefficient indicates that maxDUR gets shorter with the increase of the percentage of sandy loam. The same interactions with the other indices of flow intermittency were obtained and genetic relations were confirmed. MLRA showed how strongly flow intermittency processes are interrelated with the physico-geographical characteristics of river catchment and that the catchment characteristics are the primary drivers of the formation of the intermittency phenomenon.

Relations between flow intermittency and climate variables

The variation and drivers of flow intermittency indices were analysed in the context of corresponding changes in climate variables. Flow intermittency takes part as a complex process in environmental hydrology therefore many different relations between meteorological parameters and indices of flow intermittency were tested. For the primary analysis, the simple correlation was applied and the average air temperature and the sum of precipitation of different seasons (the autumn of last year, and winter, spring and summer of current year) as well as average and maximum snow water equivalent of the cold season was used in order to assess the existence of the relations with zero flow days of typically intermittent rivers (Table 5). Several occasional relations of zero flow days were found with autumn and summer air temperatures in certain rivers. Also, the relation between zero flow days and average and maximum snow water equivalent was found in Pilvė River. Despite accidental relations, only precipitation of summer season showed a clearly expressed interrelation with zero-flow days of typically intermittent rivers. Therefore, the non-parametric Wilcoxon–Mann–Whitney test (Wilcoxon rank–sum test) was applied to evaluate the distribution patterns and their significance related to different drivers of further analysis (precipitation of the warm season and atmospheric circulation patterns). A greater concentration of years with the highest number of zero-flow days was obtained at a lower precipitation amount (Figure 3). Here, one bubble corresponds to one year and the rivers are listed according to the length of the data series. The years were assigned as a first rank year - dry year (outlined bubbles) or second rank year - wet year (bubbles without outline) depending on the hydrological conditions of intermittent rivers described in the methodology. Moreover, separate years of each river were sorted according to precipitation amount of those years (from lowest to highest) and indicate the number of zero flow days (Figure 3a). For example, in the Imsrė, all first rank years with the highest number of zero-flow days were located in the first half of the years with the lowest precipitation amount during June–September. Whereas, the second rank years (with the lowest number of zero-flow days) fell within the second half where precipitation was abundant. In the other rivers, the distributions of the years of the first and second ranks also showed similar patterns because only 1–3 years of the first rank were allocated on the side of higher precipitation. The statistical confidence of distributions was tested with the Wilcoxon rank-sum test. The results revealed a close dependence between flow intermittency and precipitation amount because the confidence level of 99% significance was estimated in all rivers except the Daugyvenė, where the significance was only 90%. Hence, the precipitation amount during the June–September season was the most important meteorological driver that influenced the rate of flow intermittency in Lithuanian rivers. In contrast, previously analysed geographical factors determined whether this phenomenon was possible in general.

Using the methodology of optimal sample size planning for the Wilcoxon-Mann-Whitney test, Happ, Bathke, & Brunner (2019) estimated that two data sample sizes ($n1 = n2 = 26$) are required to achieve at least 80% power. In this study, according to Wilcoxon–Mann–Whitney test, the confidence level of significance of the distributions (Figure 3) varied from 90 to 99% depending on the sample size of the investigated rivers. Therefore, the length of time series of flow intermittency and climate variables did not affect the reliability of the results.

Precipitation itself is closely related to large scale atmospheric circulation and different kinds of teleconnection patterns, which usually refer to a recurring and persistent, large-scale pattern of pressure and circulation anomalies. These anomalies are expressed as atmospheric circulation indices and represent changes in values between two centres of pressure. The Scandinavian pattern (SCAND index) was chosen to evaluate atmospheric circulation anomalies because the region of this index covers the study area. The SCAND index consists of negative and positive phase monthly values which fluctuate in the range from -2.69 to 3.15. The positive phase of the SCAND index is associated with positive anomalies of air pressure over Scandinavia and Northwest

Russia. Such conditions are favourable for formation of blocking anticyclones, which interrupt the westerly flow of the Northern Hemisphere. As a result, the positive phase is associated with below-average air temperatures and precipitation over Scandinavia, Baltic Sea region and Northwest Russia. On the contrary, the negative phase is associated with above-average values. Due to such feedback of climatic features, this teleconnection pattern was chosen for the evaluation of atmospheric circulation. A relation between the years of the first and second rank and SCAND index sum during the flow intermittency period of typically intermittent rivers was identified as well (Figure 3b). The results revealed a close interrelation between the phase of SCAND index and flow intermittency because the first rank years (hydrologically dry years) mostly concentrated at a positive SCAND index values, whereas the second rank years (hydrologically wet years) were denser at the negative SCAND index. However, depending on the SCAND phase, the distributions of the years of first and second ranks were scattered wider compared with the results of precipitation. Therefore, it was reflected on the statistical confidence level of the obtained distributions according to the Wilcoxon rank–sum test. The highest 99% statistical significance was estimated in the Smilga, while in other four rivers the significance reached 95%. The weakest distributions of 90% significance were determined in the Platonis and Milupė. Only in one river (Imsrė), the distribution was statistically insignificant. These results revealed the dependence and response of flow intermittency to changes in regional-scale teleconnection patterns.

The previously analysed Scandinavian pattern determines atmospheric circulation anomalies over the studied region, thus it was decided to compare the differences in anomalies of 500 hPa geopotential height (H500) and sea level pressure during the years with less river intermittency (wet years) and years with the highest rate of river intermittency (dry years) in typically intermittent rivers of Lithuania. For this purpose, two wettest and two driest years were selected for each of 8 rivers to create anomalies maps. Some of the selected years overlap each other, therefore they were considered as one year. 11 wet (1961, 1980, 1981, 1985, 1987, 1993, 1998, 2007, 2010, 2012 and 2017) and 11 dry (1964, 1970, 1971, 1975, 1992, 1994, 1995, 2002, 2006, 2015 and 2018) years have been selected and the anomaly (1981–2010) maps of 500 hPa geopotential height and sea level pressure were created for the period of June–September (Figure 4). During the wet years with the lowest number of zero-flow days, a strong negative anomaly of H500 was found over North-west Europe and South Scandinavia (Figure 4a). The epicentre of such a derivative of atmospheric circulation was located over the North Sea region. The negative anomaly of H500 covered a large region with the average values ranging from -10 to -30 metres. Such circulation indicated troughs and cyclones in the middle troposphere. Furthermore, it was revealed by anomalies in sea level pressure, because negative anomalies varied from -1.6 hPa in the epicentre to -1.2 hPa over the study area of intermittent rivers. However, during the years with the highest rate of flow intermittency, the positive anomalies of H500 were detected over the southern part of the Baltic Sea region and neighbouring countries (Figure 4b). The location of the epicentre coincided with the southern and south-eastern parts of the Baltic Sea, where the area of this study is located. The values of positive anomaly fluctuated in the range from 10 to 25 metres and resulted in high H500 values, which indicate atmospheric circulation ridges and anticyclones. The determined positive anomalies of sea level pressure defined a more specific area where higher pressure was dominant. This area of a 1 hPa anomaly covered the southern part of the Baltic Sea as well as Latvia and Estonia. The studied intermittent rivers of Lithuania fell within the zone of a positive 0.8 hPa anomaly, which covered much more extensive areas including Denmark, South Sweden, North Belarus and previously mentioned Latvia and Estonia. Such circulation patterns caused the most prolonged intermittency processes in the analysed river catchments. Therefore, a similar analysis could be done in the region within the detected anomalies in order to find out the behaviour of intermittent rivers in the other Baltic Sea countries.

DISCUSSION

The main purpose of the paper was to draw attention to intermittent rivers as the most sensitive segment of the river network and an object, which has not been investigated in Lithuania. The results revealed that flow intermittency is a relevant hydrological topic not only in Mediterranean region, Australia or arid and semiarid areas of the western USA, but in relatively humid countries of north-eastern Europe as well.

The flow intermittency characteristics of the selected rivers showed that they had a very different flow regime. However, as in the cases of other countries (Delso et al., 2017), there was a strong relationship between intermittency frequency and its mean duration.

The performed correlation analysis between the intermittency indices and catchment characteristics indicated that the occurrence of zero-lows is very dependent on catchment size. High correlation coefficients between this feature and the mean discharges during the warm period as well as moderate relationships between the studied intermittency indices and catchment size were determined. These results show that the flow regime of small river catchments is more sensitive to intermittency drivers. As the catchment area increases, the influence of local factors tends to disappear. However, the correlation coefficients revealed that a critical catchment factor controlling the studied phenomenon was watercourse slope: a steeper river watercourse determined earlier, more frequent and more prolonged zero-flow events.

Contrary to expectations, the zero-flow indices did not correlate with the proportion of agricultural land or forest. Only a moderate relationship between the characteristics of flow intermittency and the catchment soil texture was established.

Based on graphical analysis of the mentioned relationships and highly variable degree of flow intermittency among the selected 16 rivers, a threshold was suggested for the separation of typically intermittent rivers from only occasionally intermittent ones. The repeated correlation analysis for the selected 8 rivers determined much stronger relationships between their intermittent behaviour and catchment features, indicating that typically intermittent rivers have a uniform hydrological regime.

As intermittency is a complex phenomenon and it might be driven by multiple physical factors, each of which has a moderate influence (Snelder et al., 2013), the analysis continued on the set of the most critical catchment-scale environmental characteristics whose interactions might lead to the highest probability of river drying. The multiple linear regression analysis (MLRA) confirmed the crucial role of catchment size and watercourse slope. It also revealed that three soil types (peat, medium and heavy clay loam and sandy loam together with the relative area of forest) should also be considered significant drivers of zero-flow phenomena in rivers. Mean discharge of the warm period was identified as the most closely linked to catchment size, slope and area of the peat soils. The maximum duration of the zero-flow period was found to be negatively related to the catchment area covered by sandy loam. These results are in accord with other studies indicating that catchment area and slope (Snelder et al., 2013; Oueslati, De Girolamo, Abouabdillah, Kjeldsen, & Lo Porto, 2015) as well as the presence of forests or other natural vegetation (Kirkby, Gallart, Kjeldsen, Irvine, Froebrich et al., 2011; Reynolds et al., 2015) are among local-scale drivers of flow intermittency. The listed key factors control baseflow as well as flow intermittency through their influence on infiltration, rates of water removal from the catchment and subsurface storage properties (Miller, 1994; Price, 2011). However, the percentage of agricultural land was found to be a poor predictor of river cessation. A likely explanation of this might be different agricultural activities that give dissimilar infiltration rates.

Climatic conditions, such as the amount and timing of precipitation and energy inputs, are generally considered a first-order control on the occurrence of intermittently flowing rivers (Buttle et al., 2012). A number of previous studies (e.g. Gallart et al., 2008; Snelder et al., 2013; Eng et al., 2015) support the existing strong dependence of zero-flow events on climate characteristics. However, in this study no strong correlation was detected between intermittency indices and particular climate variables (the average air temperature and the sum of precipitation of different seasons, and average and maximum snow water equivalent of the cold season), except for precipitation in June–September, which showed a clearly expressed association with zero-flow duration in typically intermittent rivers. This study confirms the findings of De Vries et al. (2015), who stated that relations between climate variability and intermittency are not straightforward. Local-scale catchment peculiarities determine if a particular river or stream is prone to intermittency, whereas combinations of unfavourable climate parameters control how often zero-flow will occur. The results of this study are also in line with those of Reynolds et al. (2015), who indicated that individual climate variables are poor predictors of inter-annual variation of zero-flow days on intermittent streams and instead proposed the composite precipitation and temperature index, Palmer Drought Severity Index, which highly correlated with the degree of stream intermittency.

In this study, the Scandinavian (SCAND) pattern was used. It is a low-frequency teleconnection pattern over the North Atlantic–Eurasian sector and is considered to be able to induce significant climate anomalies over Eurasia and the continent's surroundings (Wang & Tan, 2020); therefore, it should be linked to flow intermittency phenomena in Lithuanian rivers. The methodology of estimating the relation between river intermittency and large-scale atmospheric circulation pattern based on the SCAND index was created. First of all, two driest and two wettest years were selected according to the number of zero-flow days during the warm period. These years were used for the creation of anomaly maps of 500 hPa geopotential height and sea level pressure during the years with the highest rate of flow intermittency (selected dry years) and the years with less intermittency (selected wet years) for the period of June–September. Using the created methodology, the circulation patterns related to river intermittency could be determined for each country of the Baltic Sea region where such phenomena can be found and local meteorological parameters are under the influence of the Scandinavian pattern. For this task, only the information related to dry and wet years for target rivers of each country is necessary. The positive or negative anomalies can be determined during the years with less or high flow intermittency, only the numerical value of the anomaly can slightly differ from anomalies estimated in the Lithuanian case.

The main limitation of the studies like this, however, is a problem that existing river monitoring programs poorly represent intermittent streams and rivers (Bond & Cottingham, 2008; Oueslati et al., 2015; Gallart et al., 2016; Datry et al., 2017). The identified relationships and drivers of flow intermittency would have been more reliable if complete long-term data covering a common specific observation period was available. The analysis did not allow determining any trends or cycles of wetting and drying or at least a common year when the highest flow intermittency occurred, which is a usual problem in such studies (Sefton, Parry, England, & Angell, 2018). Lack of hydrological data does not allow estimating intermittency indices in ungauged rivers, whereas the created regression equations between flow intermittency indices and catchment characteristics could be useful for approximate estimation of zero-flow parameters in the ungauged river reaches of the studied area.

The identified relationships between the response of intermittently flowing rivers and environmental factors highlight a threat of more severe conditions of flow regime due to potential anthropogenic pressures and projected climate changes in the future. Previous studies demonstrated an increase of climate aridity (Stonevičius, Rimkus, Kažys, Bukantis, Kriaučiūnienė et al., 2018) as well as a significant decrease of low flows in Lithuanian rivers (Šarauskienė, Akstinas, Kriaučiūnienė, Jakimavičius, Bukantis et al., 2018) in the summer season at the end of the 21st century. All rivers in the studied Central Lithuanian hydrological region are at a high risk of increasing drying up in response to climate change. Other scientists also point out that climate change is likely to have substantial effects on the hydrological regime of temporal rivers (Cipriani, Tilmant, Branger, Sauquet, & Datry, 2014; Pumo, Caracciolo, Viola, & Noto, 2016). Some perennial rivers will likely shift to intermittent flow under climate-driven changes in timing and magnitude of precipitation and runoff, combined with increases in temperature (van Vliet, Franssen, Yearsley, Ludwig, Haddeland et al., 2013; Reynolds et al., 2015). The expected changes in intermittent flow behaviour may be more pronounced due to the impact of anthropogenic activities (Buttle et al., 2012; Eng et al., 2015). However, the findings of some scientists concerning measures that could mitigate or exacerbate climate change effects (Pumo et al., 2016) sound quite promising and need to be continued. The main aspect of future investigations could be related to forecasting of flow intermittency using both modern hydrological models and climate scenarios as well as the defined relationships between zero-flow indices and physico–geographical features of river catchments.

CONCLUSIONS

The study showed that flow intermittency in the rivers of water surplus zone may be a relevant hydrological topic as well.

Almost all identified intermittent rivers are located in the Central Lithuania hydrological region that has specific physico-geographical conditions: gleyic properties of the soils, slight slopes of river watercourses and a small underground runoff. It was estimated that river intermittency indices can vary widely: mean duration from 0.1 to 85 days, maximum duration from 6 to 152 days, frequency from 2 to 92.9% and timing from 12 May to 31 August. The variability of intermittency indices depends on the physico-geographical characteristics of river catchments, the most important of which are the catchment area and slope. The flow cessation process is not correlated with the proportion of agricultural land or forest and only moderately correlated with the catchment soil texture.

The close relationship of intermittency indices with precipitation amount and large-scale atmospheric circulation pattern based on the SCAND index confirms that atmospheric circulation patterns have a decisive effect on river drying. The methodology of estimating the relation between river intermittency and the SCAND index was created. This methodology can be applied to determine the circulation patterns related to river intermittency for any country of the Baltic Sea region.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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Table 1. Main characteristics of the studied gauging station catchments

River	WGS	Period	Q, m³/s	A, km²	S, m/km	For, %	Agr, %	Soils, %			
								SL	LCL	MHCL	P
Šešuva	Kalnėnai	1952–1965	0.82	130	1.21	74.2	23.5	22.5	4.39	1.38	5.81
Dotnuvėlė	Dotnuva	1947–1969	0.78	166	0.89	16.1	79.1	26.3	52.9	1.01	4.83
Smilga	Pasmilgys	1973–1999	1.17	206	1.52	31.4	66.7	19.8	46.6	0.78	5.29
Šušvė	Šiaulėnai	1956–2018	1.22	162	0.72	33.4	48.2	19.6	22.8	0.01	39.7
Alsa	Paalsys	1961–1999	0.36	49.0	2.21	35.0	63.8	28.6	43.8	1.79	4.46
Pedamė	Antkalniai	1970–1990	0.07	10.2	3.19	97.5	2.50	0.43	0.32	1.11	0.00
Imsrė	Jakaičiai	1970–1983	0.07	10.1	3.78	14.0	86.0	2.81	31.9	51.2	0.13
Pilvė	Papilvis	1978–1999	0.79	123	0.96	33.3	64.7	55.5	4.50	0.15	7.54
Milupė	Stoškai	1957–1993	0.21	37.4	1.27	2.50	96.0	26.8	64.3	8.51	0.26
Svyla	Guntauninkai	1966–2018	0.91	148	0.91	22.0	74.2	29.2	39.9	5.64	14.2
Agluona	Dirvonakiai	1960–1999	0.45	63.0	0.66	13.3	84.4	63.8	19.4	0.01	14.0
Daugyvenė	Rimšoniai	2006–2018	2.39	487	0.85	20.9	74.3	41.8	34.3	0.54	6.00
Yslykis	Kyburiai	1971–2018	0.35	71.2	1.05	5.10	91.5	6.48	51.3	34.0	6.77
Platonis	Vaineikiai	2006–2018	0.55	133	1.89	13.1	84.8	12.3	68.5	6.06	1.23
Sidabra	Šarkiai	2006–2018	0.32	79.7	1.67	5.90	84.2	11.3	70.2	7.06	1.11
Akmena	Tūbausiai	1949–1991	2.56	193	1.76	47.2	50.1	12.4	52.9	1.13	6.15

Table 2. The main characteristics of flow intermittency in the warm period

River	WGS	Q_P	mDUR	maxDUR	FREQ	T_0
Šešuva	Kalnėnai	0.47	3.00	24	14.3	195
Dotnuvėlė	Dotnuva	0.23	1.26	23	13.0	231
Smilga	Pasmilgys	0.32	15.2	100	25.9	190
Šušvė	Šiaulėnai	0.54	1.70	54	3.17	221
Alsa	Paalsys	0.13	7.68	81	28.9	208
Pedamė	Antkalniai	0.03	77.1	152	90.5	156
Imsrė	Jakaičiai	0.02	85.4	151	92.9	144
Pilvė	Papilvis	0.27	19.9	79	50.0	206
Milupė	Stoškai	0.05	53.6	129	88.9	157
Svyla	Guntauninkai	0.40	0.11	6	1.89	241
Agluona	Dirvonakiai	0.16	0.73	29	2.50	242
Daugyvenė	Rimšoniai	0.67	4.15	30	15.4	244
Yslykis	Kyburiai	0.10	33.6	116	58.3	181
Platonis	Vaineikiai	0.11	18.2	122	23.1	182
Sidabra	Šarkiai	0.08	10.9	142	7.69	133
Akmena	Tūbausiai	0.84	0.26	11	2.33	174

Table 3. Coefficients of linear correlation between flow intermittency indices and catchment characteristics for 16 intermittent rivers

Indices	A, km²	S, m/km	For, %	Agr, %	Soils, %			
					SL	LCL	MHCL	P
Q_P	0.74	-0.42	0.23	-0.29	0.18	-0.13	-0.42	0.43
mDUR	-0.52	0.77	0.14	-0.07	-0.49	-0.14	0.64	-0.44
maxDUR	-0.53	0.65	-0.09	0.12	-0.53	0.20	0.49	-0.44
FREQ	-0.50	0.63	0.10	-0.02	-0.36	-0.14	0.56	-0.47
T_0	0.53	-0.68	-0.07	0.04	0.70	-0.27	-0.46	0.52
A, km²		-0.46	-0.07	0.03	0.29	0.05	-0.37	0.23
S, m/km			0.32	-0.24	-0.63	-0.06	0.51	-0.55
For, %				-0.98	-0.21	-0.69	-0.35	-0.15
Agr, %					0.22	0.68	0.40	0.14
Soils, % SL						-0.30	-0.47	0.65
Soils, % LCL							0.15	-0.13
Soils, % MHCL								-0.25
Soils, % P								

Table 4. Results of MLRA of flow intermittency indices according to catchment characteristics

No.	Dependent variable	Coefficients for independent variables							Correlation coefficients
		Intercept	Area	Slope	P	MHCL	SL	For	
16 rivers	Q_P	-0.021	0.002	0.022	0.009	-	-	-	0.80
	mDUR	14.110	-0.057	-	-0.707	1.173	-	0.359	0.81
	maxDUR	99.221	-0.146	14.837	-1.143	-	-0.699	-	0.74
	T_0	153.334	0.096	-2.628	1.184	-	0.998	-	0.85
8 rivers	Q_P	-0.049	0.001	0.015	0.014	-	-	-	0.99
	mDUR	35.586	-0.046	-	-3.803	0.835	-	0.415	0.96
	maxDUR	150.056	-0.161	1.455	-2.586	-	-0.595	-	0.99
	T_0	151.678	0.134	-1.160	2.807	-	0.256	-	0.98

Table 5. Correlation between meteorological parameters and zero flow days

Meteorological parameter	River							
	Yslykis	Milupė	Smilga	Pilvė	Pedamė	Imsrė	Platonis	Daugyvenė
T_{autumn}	-0.10	0.28	-0.35	-0.18	0.19	**0.61**	0.08	-0.04
T_{winter}	0.03	0.18	0.14	0.43	0.45	0.17	-0.12	0.26
T_{spring}	0.08	0.22	0.13	0.14	0.49	0.49	-0.42	0.20

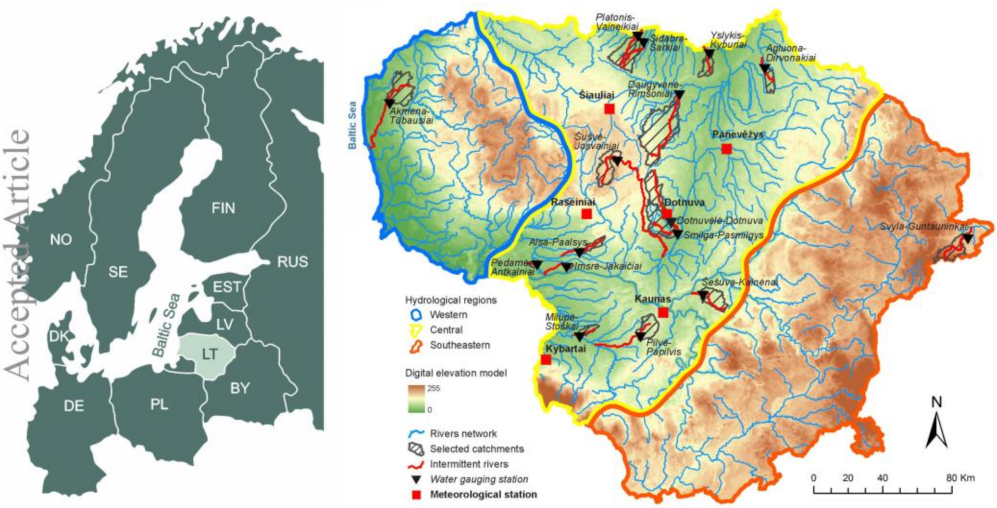
T_{summer}	0.17	0.43	0.34	**0.76**	0.29	0.35	0.20	0.06
P_{autumn}	-0.09	0.12	-0.02	-0.38	0.03	0.14	**-0.56**	0.11
P_{winter}	0.11	0.16	0.09	0.31	0.17	-0.01	-0.36	0.33
P_{spring}	-0.21	0.08	0.01	0.44	-0.07	0.08	-0.21	0.06
P_{summer}	**-0.59**	**-0.69**	**-0.61**	**-0.74**	**-0.67**	**-0.80**	**-0.51**	**-0.58**
SWE_{mean}	-0.02	-0.19	-0.04	**-0.53**	-0.03	0.16	-0.17	0.03
SWE_{max}	0.02	-0.30	0.04	**-0.62**	-0.09	0.08	-0.23	0.12

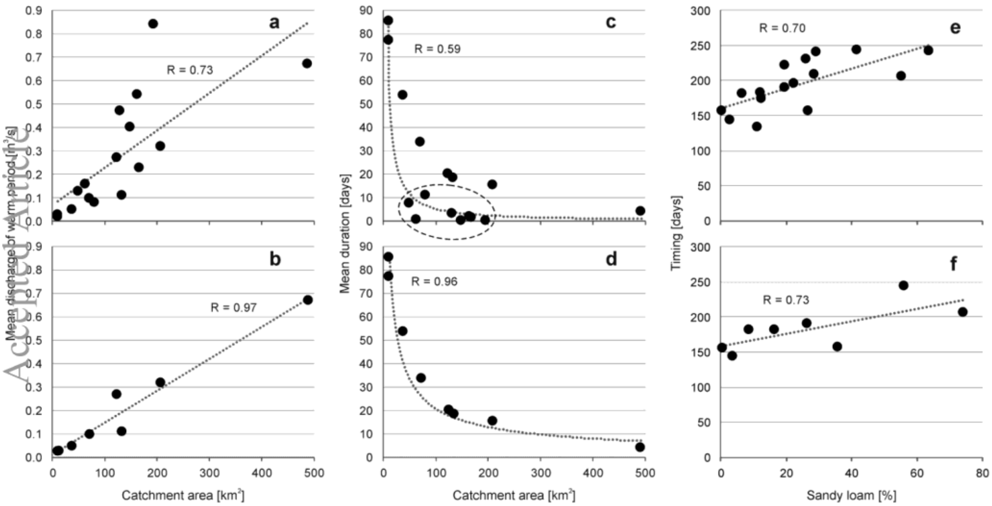
Figure 1. Study area (meteorological and water gauging stations, intermittent river catchments and three hydrological regions of Lithuania)

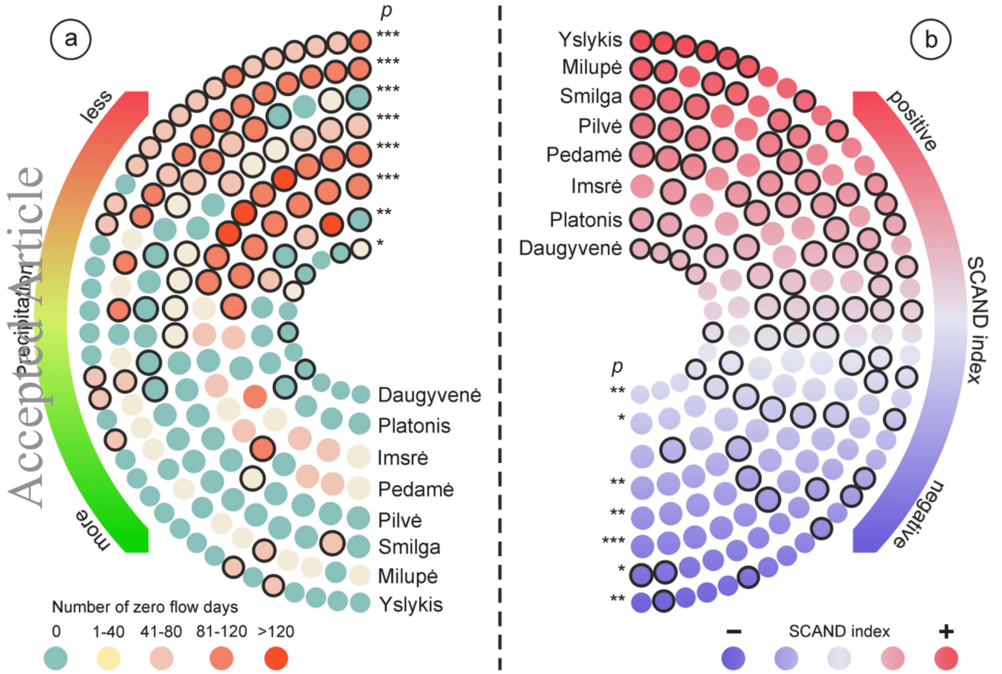
Figure 2. Relationships between flow intermittency indices and catchment characteristics: a - b) Q_P – A, for 16 and 8 rivers, respectively, c - d) mDur – A, for 16 and 8 rivers, respectively, e - f) T_0 – SL, for 16 and 8 rivers, respectively.

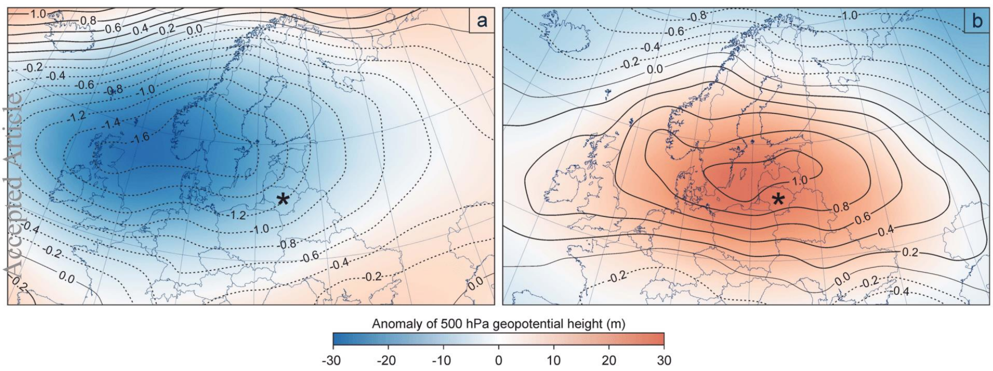
Figure 3. Distribution of years with the highest number of zero-flow days (first rank years - outlined bubbles) and years with the lowest number of zero-flow days or without it (second rank years - bubbles without outline) sorted according to precipitation amount (a) and SCAND index value (b) during the period of June–September, and statistical significance of their distributions according to Wilcoxon–Mann–Whitney test (* - 90%, ** - 95%, *** - 99%) in typically intermittent rivers

Figure 4. Anomaly of 500 hPa geopotential height in metres (gradient colour) and sea level pressure in hPa (isolines – negative dotted) during the years with less river intermittency (a) and years with the highest rate of river intermittency (b) for the period of June–September over the Europe and study area (*)


NO
SE
FIN
RUS
EST
LV
LT
DK
DE
PL
BY
Baltic Sea
Akmena-Tūbausiai
Platonis-Vaineikiai
Sidabra-Šarkiai
Yslykis-Kybunai
Agluona-Dirvonakiai
Daugyvenė-Rimšoniai
Šiauliai
Panevėžys
Šušvė-Josvainiai
Raseiniai
Dotnuva
Dotnuvėlė-Dotnuva
Smilga-Pašmilgys
Alsa-Paalsys
Pėdamė-Antkalniai
Imsrė-Jakaičiai
Šešuva-Kalnėnai
Svyla-Guntauninkai
Kaunas
Milupė-Stoškai
Pilvė-Papilvis
Kybartai
Hydrological regions
Western
Central
Southeastern
Digital elevation model
255
0
Rivers network
Selected catchments
Intermittent rivers
Water gauging station
Meteorological station
N
0 20 40 80 Km


a
R = 0.73
b
R = 0.97
Mean discharge of warm period [m³/s]
Catchment area [km²]
c
R = 0.59
d
R = 0.96
Mean duration [days]
Catchment area [km²]
e
R = 0.70
f
R = 0.73
Timing [days]
Sandy loam [%]


a
b
p
less
more
Precipitation
Daugyvenė
Platonis
Imsrė
Pedamė
Pilvė
Smilga
Milupė
Yslykis
Number of zero flow days
0
1-40
41-80
81-120
>120
positive
negative
SCAND index
−
+


a
b
Anomaly of 500 hPa geopotential height (m)
-30
-20
-10
0
10
20
30

water

Article

Spatial and Temporal Patterns of Low-Flow Changes in Lowland Rivers

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Abstract: At the beginning of the 21st century, ongoing climate change led to research into extreme streamflow phenomena. This study aimed to assess the patterns of low-flow changes in different hydrological regions of Lithuania using selected hydrological indices (the annual minimum 30-day flow (m^3 s^{-1}) of the warm period—30Q), its duration, and deficit volume (below the 80th and 95th percentile flow: 30Q80 and 30Q95). Differences in low-flow indices in separate hydrological regions and over different periods (1961–2020, 1961–1990, 1991–2020) were analyzed, applying the HydroOffice tool, the TREND software package, and mapping using the Kriging interpolation. The highest specific indices of 30Q were estimated in the Southeastern hydrological region (3.97 L/s·km^2) and the lowest in the Central hydrological region (1.47 L/s·km^2). In general, the 30Q values in the periods 1961–2020 and 1991–2020 had no trends. In 1961–1990, trends in 30Q data were significantly positive, and positive in most investigated rivers of the Western and Central hydrological regions. The average number of dry days at both thresholds decreased in the Western and Southeastern hydrological regions and increased in the Central hydrological region comparing two subperiods.

Keywords: hydrological regions; low-flow indices; dry days; deficit of discharge; mapping; spatial and temporal patterns

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1. Introduction

Low flow is a seasonal phenomenon and a basic component of the river flow regime [1]. Low flows occur after periods of low rainfall or when precipitation falls as snow [2]. Since one or both situations occur annually in many regions, by the season of occurrence, low flows are described as summer low flow and winter low flow. Low flow is a compulsory component in the ecological integrity of most river systems; low-flow timing and duration are critical features regarding aquatic ecosystem viability, as well as sufficient water quality and supply [3]. Under extreme and prolonged low-flow conditions, instream habitats are reduced, become fragmented or lost, aquatic species lack the ability to disperse due to the altered environment, alteration of food resources occurs, changes in the strength and structure of interspecific interactions are observed, etc. [4–7]. Water scarcity threatens the ecosystem, businesses, and the community. The Communication on Water Scarcity and Drought [8], adopted by the European Commission in 2007, highlights the emerging challenge of basic needs so that every human being and most economic activities have access to sufficient good quality water. A recent report of IPCC [9] warns of a continuing rise in global surface temperature until at least the mid-century, with all emissions scenarios considered. As a result, the seasonal flow regime of the river is going to experience significant alterations through a variety of (potentially interfering) mechanisms, including shifts in the temporal and spatial precipitation pattern, changes in snow-melt timing due to rising temperature, or increasing evaporation demand [10–12].

Low-flow patterns depend on geographical, climatic, and anthropogenic factors [13]. A study of seasonal timing and the main drivers of low flows across 1860 European and US catchments [13] revealed that low flows tend to occur in either late summer/autumn or winter across these study regions. In Europe, winter low flows occur mainly in the Alps and northern Scandinavia; in the rest of the European sites, annual low flows are observed almost exclusively in late summer (August and September) and are primarily associated with periods of high excess potential evapotranspiration. The records of near-natural streamflow from 441 small catchments in 15 countries across Europe showed that low flows have increased in most winter low-flow regimes and decreased in most summer low-flow regimes [10]. However, on a finer scale, the authors found that decreasing trends are often weak in the areas with summer low-flow regimes and patterns of directionality are mixed; positive trends predominate around the Baltic Sea and are found locally elsewhere. A study based on thousands of time series of river flows and hydrological extremes across the globe [14] found that the observed trends can only be explained if the effects of climate change are considered.

To describe and analyze low-flow regimes, researchers often use a variety of hydrological indices, such as mean minimum monthly flows, low-flow index, low-flow pulse count and duration, annual minima of 1-/3-/7-/30-/90-day means of daily discharge, low exceedance flows, etc. [15]. Since maintaining a certain low flow in a river is related to defining environmental flow standards, such indices are widely used and, in some countries, are officially adopted. Trends in low flows of German rivers were analyzed using annual minimum low flows (for 1-/7-/14-/21-/30-/60-/90-days), discharge deficits (below Q90 and Q95 by calendar year), and low-flow durations (below Q90 and Q95 by calendar year) [16]. Although each index is applied for different purposes in water management applications, the authors found similar spatial patterns for all used indices. The study of trend detection in river flow indices [17] stated that, in Poland, in general, decreases of low flow, expressed as the annual minima of 7-day averaged daily flows, were observed in areas where the mean river flow was low. The applied mean summer minimum discharge did not indicate an expected significant decrease in low flows in the most studied Central European headwaters [18]. In contrast, results based on the 7-day annual minimum streamflow and the 10th percentile of the annual flow duration curve showed a general decline in low flows throughout the rivers in Spain [19]. In Ireland, statistically significant trends in the 7-day sustained low-flow time series of mixed direction were identified only at a part of studied gauging stations [20]. No clearly pronounced decrease in low flows was detected using annual minimum 30-day flow (m^3 s^{-1}) and prevalence of low flows (number of days below the 90th percentile flow) based on 120 near-natural catchments in the UK [21]. Statistical analysis of average low flow and minimum monthly summer and winter discharges showed significant positive trends in all parameters of the low-water period in the rivers of the European part of Russia [22]. Analysis of the Latvian river discharge regime revealed that, in most cases, there were no statistically significant overall long-term changes in low-flow discharges of the warm period (defined as a series of the 30-day minimum discharge in May–October); however, a statistically significant upward trend in low flow during the cold period was found [23].

In Lithuania, low flows typically occur during extended dry periods in the late summer and early autumn. For many years, only a limited number of studies have been related to this critical component of a river flow regime. However, at the beginning of the 21st century, research into extreme streamflow phenomena has intensified with the growing evidence of climate change. Low-flow changes in Lithuanian rivers in the 20th century (more precisely—till 2003) were investigated [24]. The authors identified the cyclic variations in the 30-day minimum discharge series, but no significant trends of this characteristic were detected. The meteorological and hydrological drought patterns were analyzed in the Lithuanian permanent rivers [25]. It has been established that climate change predicted at the end of the 21st century may increase the likelihood of more intense and frequent meteorological droughts in Lithuania [26]. Summer flows projections in the studied rivers showed a decreasing tendency [27,28]. The ongoing signs of climate change led to the investigation of intermittent rivers, which are particularly sensitive to any alterations in meteorological conditions or any anthropogenic disturbances [29].

Although the summer low-flow period is a critical time for water users and aquatic ecosystems, the spatial and temporal behavior of low flows in Lithuanian catchments is not fully understood. This study, therefore, set out to assess the patterns of low-flow changes in different hydrological regions of Lithuania using selected hydrological indices. The paper analyzed the annual minimum 30-day flow (m^3 s^{-1}) of the warm period (30Q), its duration, and deficit volume (below the 80th and 95th percentile flow: 30Q80 and 30Q95). The defined differences in low-flow indices in different hydrological regions and over different periods (1961–2020, 1961–1990, 1991–2020) provide a better understanding of low-flow behavior in lowland river catchments.

2. Materials and Methods

2.1. Study Area and Data

Lithuania (total area of 65,200 km^2) has over 22,000 rivers with a total length exceeding 37,000 km. The annual river runoff varies from 4.2 to 14.0 L/(s·km^2). The Nemunas River is a major Lithuanian river. Its total length is 937 km, while the basin area covers 98,200 km^2, of which 46,600 km^2 belong to Lithuania (comprising 72% of Lithuanian territory). Climatic factors, soil structure, geology, geomorphology, and anthropogenic activities affect the hydrological regime of the Lithuanian rivers [29]. According to the hydrological regime and the river feeding type, the territory of Lithuania is divided into three hydrological regions (Figure 1): Western (W-LT), Central (C-LT), and Southeastern (SE-LT). In the W-LT region, the main source of river feeding is precipitation. In the SE-LT region, subsurface feeding dominates: widespread permeable sandy soils effectively absorb snowmelt water and gradually release it later, supplying rivers during the low-water period. The type of river feeding in the C-LT region is mixed; the rivers here obtain water mostly from two main sources: rainfall and snowmelt. Very irregular distribution of discharges throughout the year is the main feature of the rivers in this region.

Daily discharge data (1961–2020) from 17 water gauging stations (WGS) in different hydrological regions were used for this study (Table 1). These data sets were obtained from the Lithuanian Hydrometeorological Service. In this study, low flows were defined as the 30-day minimum discharge (30Q, m^3/s) and were calculated for each year (average of 30Q in the period 1961–2020 was defined from $30Q_{av}$); this definition in Lithuanian hydrology was formed historically due to the frequent violation of low flow stability by rain floods in summer. Thus, 30Q is less prone to critical deviations that show values over a shorter period (e.g., 1, 3, 5, 7 days) and eliminates deviations caused by precipitation. The 30Q95 and 30Q80 flow quantiles were estimated from the 30Q time series. The homogeneity of used daily discharge data for 1961–2002 was checked by the Standard Normal Homogeneity Test (SNHT) and the Pettitt Test.

2.2. Methods

There are two types of low flows in Lithuania—winter and summer–autumn. This study focused on the summer low-flow events observed from 1 May to 31 October. A typical hydrograph of a river in the SE-LT region and selected low-flow indices are presented in Figure 2.

Low flows were calculated for the periods of 1961–2020, 1961–1990, and 1991–2020. Generally, in Lithuanian catchments, the period of 30Q is observed in summer and autumn, and it differs depending on the hydrological region. In addition, two more indices of low flow were estimated: 30Q95 and 30Q80. For calculation of mentioned indices, the data set of 30Q, which was equal to or exceeding 95% and 80% of all values, was used. These indices were used as a threshold for estimating the duration of low flow and deficit volume. To facilitate the comparison of the low-flow indices on various spatial scales, a specific low-flow q (30q, 30q95, and 30q80) was calculated, which should be defined as $q = Q/A \cdot 1000$ (where Q is 30Q/30Q95/30Q80 low flow discharge in m^3/s, A—the catchment area in km^2).

Modular coefficients for the low-flow period $K = 30Q_i/30Q_{av}$ ($30Q_i$ is the discharge in year i, and $30Q_{av}$ is the average discharge for the entire period of observation) were used to estimate the regularities and to examine how low flows differed by decades (1961–2020) in the rivers from the different hydrological regions. This relative coefficient K enables a comparison of the rivers with different runoff values.

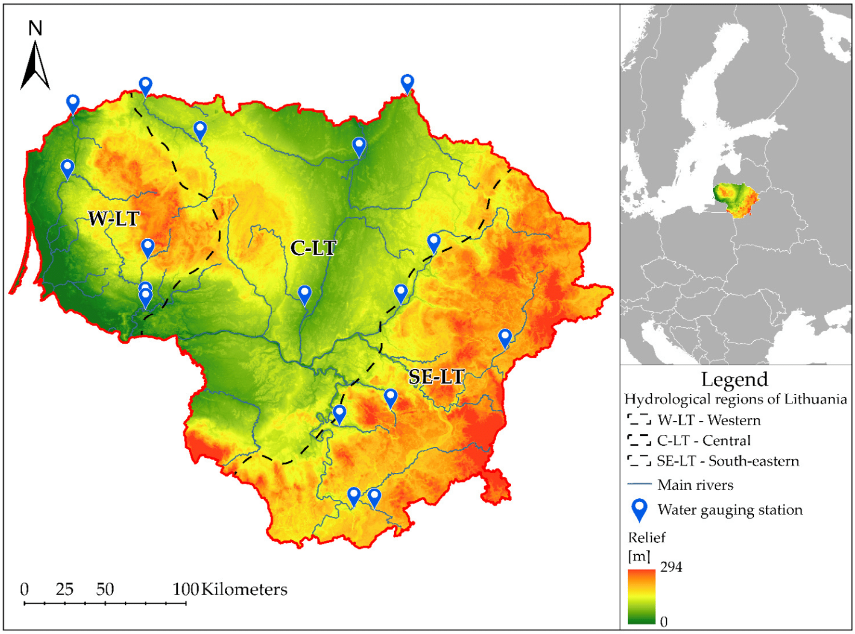

Figure 1. Geographical position (**left**) and water gauging stations of three hydrological regions of Lithuania (**right**).

To quantify the information incorporated in hydrographs, the HydroOffice software package [30] was applied. The HydroOffice tool FDC (flow duration curves; version 2.1) is often used to assess low flows. It was selected to calculate 30Q95 and 30Q80. FDC can be created from the entire imported time series or defined parts, such as annual or monthly segments. The HydroOffice tool TLM (threshold level or sequence peak algorithm methods; version 2.1) can be used to evaluate extreme flow conditions. Segments with extreme conditions can be statistically processed and visualized. TLM is designed to assess hydrological drought and flood events. Daily discharge and threshold values were used as input data for calculation with TLM, while drought period (duration), maximum deviation, and deficit volume were obtained as output data (Figure 3).

Table 1. Characteristics of selected water gauging stations (1961–2020).

№	River	WGS	Abbreviation	A, km^2	Q_{av}, m^3/s	$30Q_{av}$, m^3/s	30Q95, m^3/s	30Q80, m^3/s
				Western hydrological region				
1.	Jūra	Tauragė	JUR	1690	22.05	3.72	1.62	2.43
2.	Akmena	Paakmenis	AKM	314	4.29	0.69	0.30	0.45
3.	Minija	Kartena	MIN	1230	16.56	2.93	1.32	1.77
4.	Bartuva	Skuodas	BAR	612	7.55	0.76	0.30	0.50
				Central hydrological region				
5.	Šušvė	Josvainiai	SUS	1100	5.62	0.62	0.22	0.33
6.	Šešuvis	Skirgailai	SES	1880	15.20	2.47	1.19	1.72
7.	Nemunėlis	Tabokinė	NEM	2690	19.63	3.12	1.19	1.81
8.	Mūša	Ustukiai	MUS	2280	10.40	1.37	0.53	0.70
9.	Venta	Papilė	VEN1	1570	9.81	1.67	0.73	1.08
10.	Venta	Leckava	VEN2	4060	29.91	5.24	2.32	3.10
				Southeastern hydrological region				
11.	Merkys	Puvočiai	MER	4300	31.92	21.79	16.20	18.43
12.	Ūla	Zervynos	ULA	679	4.88	2.93	1.94	2.42
13.	Verknė	Verbyliškės	VER	694	5.05	2.16	1.46	1.78
14.	Strėva	Semeliškės	STR	234	1.65	1.00	0.69	0.82
15.	Žeimena	Pabradė	ZEI	2580	20.46	12.14	8.09	10.15
16.	Šventoji	Anykščiai	SVE1	3600	26.46	10.32	3.96	7.41
17.	Šventoji	Ukmergė	SVE2	5440	39.05	14.51	6.48	10.05

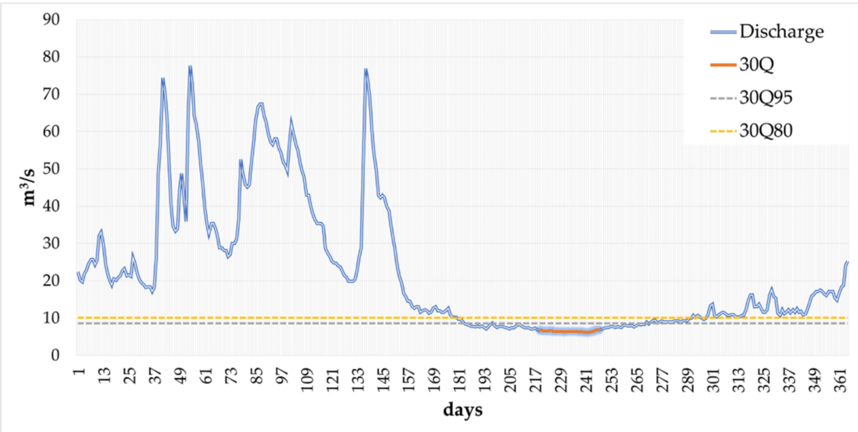

Figure 2. Low flow indices (example of the Šventoji at Ukmergė WGS in 1973).

Maps were created in ArcGIS 10.4 using the Kriging interpolation method (Spatial Analyst toolbox). Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface. The Kriging tool fits a mathematical function to a specified number of points, or all within a specified radius, to determine the output value for each location. The general formula for both interpolators is formed as a weighted sum of the data:

$$\hat{Z}(s_0) = \sum_{i=0}^{N} \lambda_i Z(s_i)$$

where $Z(s_i)$ is the measured value at the ith location, λ_i—an unknown weight for the measured value at the ith location, s_0—the prediction location, N—the number of measured values. The weight, λ_i, depends solely on the distance to the prediction location. However, with the Kriging method, the weights are based not only on the distance between the measured points and the prediction location, but also on the overall spatial arrangement of the measured points.

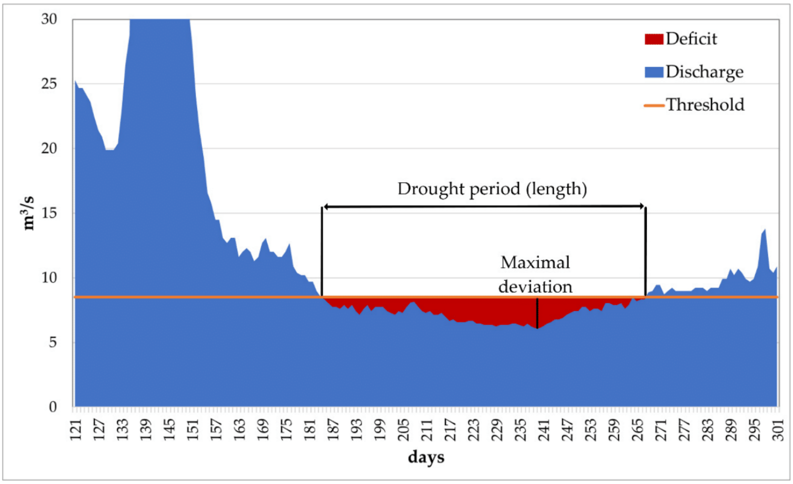

Figure 3. Principal scheme of TLM tool.

The TREND software package (V.1.0.2.) is a standalone product of the CRC for Catchment Hydrology's (CRCCH) Climate Variability Program designed to facilitate statistical testing of trend, change, and randomness in hydrological time series data [31]. It contains 12 statistical tests based on the WMO/UNESCO Expert Workshop on Trend/Change Detection. This software was used to detect and examine the statistical significance of trends by the Mann–Kendall (MK) and Spearman's Rho (SR) nonparametric tests. The MK nonparametric test was developed by Mann [32] and Kendall [33] to detect linear or non-linear trends. The SR test is applied to identify the absence of trends [34,35]. The presence and direction of monotonic trends in the data series of 30Q were tested at significance levels α = 0.1 or 0.05 (positive/negative or significant positive/negative, respectively).

3. Results

3.1. Spatial Variability of the Low-Flow Indices

Low flows may occur at any time of the year, depending on the climatic conditions and hydrological processes taking place in the catchment. Regional patterns in low-flow behavior were analyzed using specific low-flow indices (30q, 30q95, and 30q80 (L/s·km^2))

for the two selected periods (1961–1990 and 1991–2020) (Table 2). In the Southeastern hydrological region (SE-LT), the increase in lower values of all low-flow indices was established by comparing the 1961–1990 and 1991–2020 periods. In the Western hydrological region (W-LT) and the Central hydrological region (C-LT), a different allocation of lower values between selected periods was established, e.g., lower values of 30q decreased, and meanwhile, no clear tendencies in the changes of other indices were identified.

Table 2. Low-flow indices by the different regions and periods.

	1961–1990			1991–2020		
	30q	**30q95**	**30q80**	**30q**	**30q95**	**30q80**
W-LT	1.28–2.63	0.45–1.13	0.75–1.56	1.04–2.32	0.49–1.23	0.74–1.69
C-LT	0.63–3.31	0.15–2.38	0.32–2.71	0.46–3.39	0.18–2.42	0.24–2.91
SE-LT	2.24–5.07	1.20–3.77	1.66–4.84	2.62–5.06	1.51–3.77	1.87–4.25

The analysis of the distribution of low-flow indices showed that, in the W-LT region, the 30q average was 2.07 L/s·km^2 in 1961–1990 and 1.83 L/s·km^2 in 1991–2020 (Figure 4). There were no pronounced differences between 30q of the selected periods in the C-LT region (1.49 and 1.46 L/s·km^2, respectively, in two periods) and the SE-LT region (3.97 L/s·km^2 in both periods). The biggest 30q average was found in the SE-LT region in both periods. The same tendencies were estimated by the other two indices (30q95 and 30q80). Meanwhile, the lowest average values of all three indices in both periods were detected in the C-LT region.

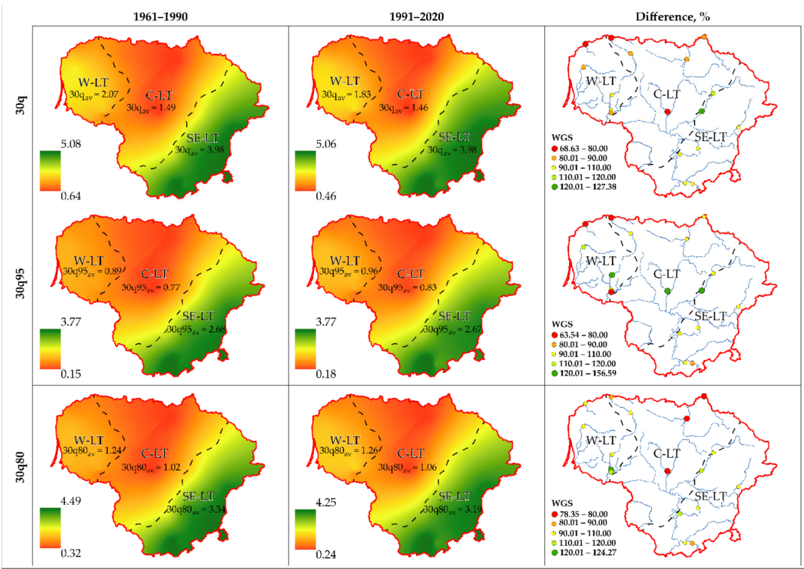

Figure 4. Distribution of low-flow indices (30q, 30q95, 30q80) in the different hydrological regions in 1961–1990 and 1991–2020, and the difference between low-flow indices in the two periods.

Further details on the established differences of low-flow indices in 17 WGSs in 3 hydrological regions are provided in Figure 5. The figure shows differences in the indices both over time and across regions. The highest indices were estimated in the SE-LT region, and the lowest were in the C-LT region.

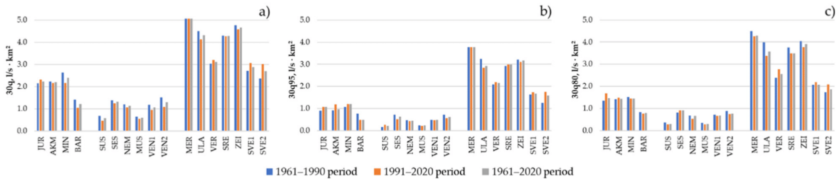

Figure 5. Temporal changes of low-flow indices in three periods: (**a**) 30q, (**b**) 30q95, and (**c**) 30q80.

In Figure 4, the differences of the low-flow indices between the two periods (1961–1990 and 1991–2020) and three hydrological regions are given as percentages. Only differences greater than 20% were taken into account in the analysis.

In the W-LT region, a significant decrease in 30q (by 27%) over the last thirty years was estimated for BAR. In the C-LT region, for SUS and VEN2, a considerable difference in the decrease in 30q (32% and 29%, respectively) was found. Meanwhile, in the SE-LT region, the most pronounced increase in 30q was detected for SVE2 (27%).

The changes in 30q95 values over time and across different hydrological regions revealed substantial differences between the two periods. In the W-LT region, in AKM, 30q95 increased by 28%; meanwhile, in BAR, it decreased by 37%. In the C-LT region, three WGSs showed significant differences, i.e., in SUS, 30q95 increased by 56%, and in two other WGSs, it decreased (SES (27%) and VEN2 (21%)). In the SE-LT region, 30q95 significantly increased at one WGS (SVE2 by 38%).

Differences in the 30q80 values were also significant. The C-LT region should be singled out as the one where, in almost all WGSs, the 30q80 values decreased (in three of them significantly, i.e., by more than 20%).

In summary, it should be highlighted that the low-flow indices changed the most significantly in the rivers of the C-LT region. For example, in SUS, 30q decreased by 32% and 30q80 decreased by 22%, whereas 30q95 increased by 56%.

To compare the low flows of different rivers, a modular coefficient K of 30Q was calculated for three hydrological regions in different decades (Table 3). This analysis showed that the modular coefficient varied differently: in the W-LT region, its values were 0.80–1.42; in the C-LT region, they were 0.83–1.37; and in the SE-LT region they were 0.97–1.05. The smallest deviation was detected in the SE-LT region. In all hydrological regions, the highest *K* was determined in 1981–1990, whereas the lowest values were established in the W-LT region in 1961–1970, in the C-LT region in 2011–2020, and in the SE-LT region in 1971–1980.

Table 3. Distribution of *K* by decades for hydrological regions.

	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	2011–2020
W-LT	0.80	1.14	1.42	1.04	0.91	0.89
C-LT	0.87	1.08	1.37	0.91	0.93	0.83
SE-LT	0.97	0.92	1.05	0.97	1.07	1.02

3.2. *Temporal Analysis of Low Flow Indices*

The analysis of 30Q changes in the individual rivers from different hydrological regions (MIN from the W-LT region, MUS from the C-LT region, and MER from the SE-LT region) confirmed the presence of different low-flow patterns in the period 1961–2020

(Figure 6). In the W-LT region, 30Q tended to decrease; on the contrary, 30Q had tendency to increase in the SE-LT region. There was no trend detected in 30Q of MUS from the C-LT region.

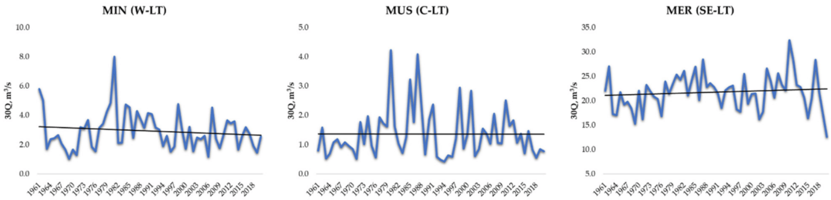

Figure 6. 30Q variation in different hydrological regions.

The general behavior of the low-flow (30Q) trend characteristics was assessed for all 17 WGSs using the Mann–Kendall (MK) and Spearman's Rho (SR) tests over 3 periods (1961–2020, 1961–1990, and 1991–2020). Both tests revealed very similar results (Figure 7). This analysis indicated different trends in different WGSs during the same observation period and in the same hydrological region. It is important to note that no zero-flow values in any low-flow sequence of 30Q were found.

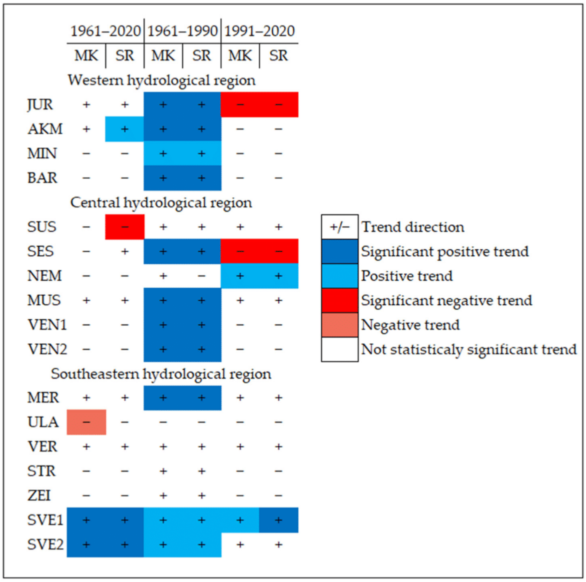

Figure 7. The significance of trends (30Q) by the three periods applying MK and SR tests (red/blue color means that the trend is very significant (α ≤ 0.05), light red/light blue color means that the trend is significant (α ≤ 0.1), no color means that there is no significant trend (α > 0.1)).

Different tendencies in data of 30Q were detected during the entire observation period and two thirty-year periods. The 30Q values of the longest period (1961–2020) had no trends in the W-LT and C-LT regions (Figure 7). Only in the SE-LT region, significant positive trends of 30Q were identified in two WGSs located on the same river (SVE1 and SVE2). On the opposite, in 1961–1990, trends in 30Q data were significantly positive, and were positive in most rivers, except for a few WGSs, which had no trend (mainly from the SE-LT region). Both tests showed, mostly, no significant trends for the period of 1991–2020, except for one WGS with a significant negative trend in the W-LT region, two WGSs with trends of different significance in the C- LT region, and one WGS in the SE-LT region with a significant negative trend.

Thirty-year moving averages of 30Q data sets of 17 WGSs were estimated for the period 1961–2020 using the Mann–Kendal test (Figure 8). This approach allows for examining the evolution and dynamics of low flows in a more detailed resolution. In all WGSs, positive or significant positive trends were estimated until 1973, except for one WGS in the SE-LT region with an opposite direction. After 1973, all WGSs in two hydrological regions (W-LT and C-LT) showed negative or significant negative trends. WGSs in the SE-LT region usually did not have significant trends. Moreover, one river with two WGSs had positive or significant positive trends in this region. In contrast, the values of 30Q were significantly increasing in SVE2 (the SE-LT region) until 1976, making it the only WGS with significant increases throughout the whole observation period.

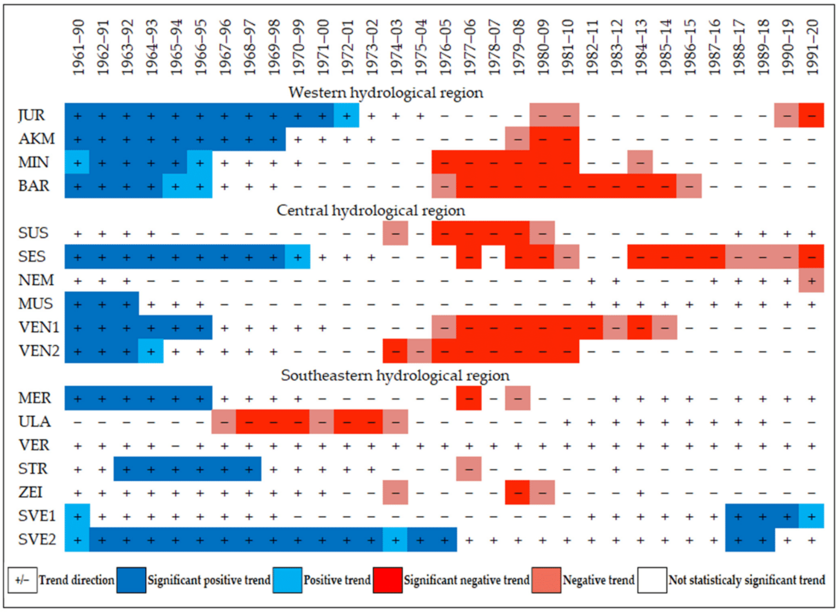

Figure 8. The results of the MK test for 30-year moving averages for 1961–2020 (red/blue color means that the trend is very significant ($\alpha \leq 0.05$), light red/ light blue color means that the trend is significant ($\alpha \leq 0.1$), no color means that there is no significant trend ($\alpha > 0.1$)).

In general, statistically significant positive trends prevailed during the first half of the observation period in the W-LT and C-LT regions, while the negative trends were more concentrated in the middle and at the end of the 1973–2020 period. Meanwhile, WGSs showed different trend directions in the SE-LT region, mainly for the entire observation period.

3.3. Alternations of Duration and Volume of Low Flow

During the analysis of low flow, attention was paid to hydrological droughts, which were determined by two threshold values, namely the indices 30Q95 and 30Q80. For a more detailed analysis of the extreme conditions, drought probability curves were constructed depending on each threshold value for each river (Figure 9a,b). From the obtained graphs, it can be concluded that the duration of droughts increased from the W-LT region to the SE-LT region. This trend can be explained by the impact of different feeding sources in each hydrological region. The rivers of the W-LT region with primary rain feeding were more resistant to prolonged droughts. In the calculations with the threshold value of 30Q95, the highest probability of short droughts (1–2 days) was established in the C-LT region. The longest droughts at the 30Q80 threshold were observed in these rivers: SVE1 was 151 days, SVE2 was 111 and 121 days, ULA was 103 days. With a threshold value of 30Q95, the longest-lasting droughts were observed in these rivers: SVE2 was 72 and 85 days, MER was 61 days.

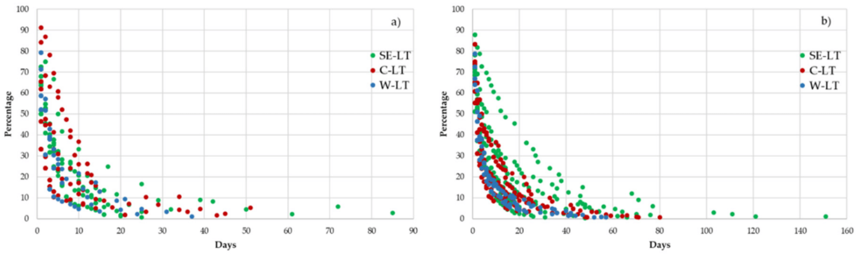

Figure 9. The average number of drought days for the three regions: (**a**) at threshold 30Q95, (**b**) at threshold 30Q80.

The distribution of dry days over time (Figure 10) showed that, at both thresholds, the average number of dry days per year per river tended to decrease in the W-LT and SE-LT regions, and to increase in the C-LT region. The driest years in Lithuania were 1969 and 1971 (for both thresholds), 1976 (for the 30Q80 threshold), and 2006 (for the 30Q95 threshold). In general, the highest concentration of dry days was observed in the periods 1963–1976, 1992–2006, and 2015–2020. The driest years in the W-LT region were 1969 (33 days for 30Q95, 76.5 days for 30Q80); in the C-LT region, 1971 (47.3 days for 30Q80) and 2006 (21.5 days for 30Q95); in the SE-LT region, 1971 (33.7 days for 30Q95, 64.4 days for 30Q80).

Analysis of annual trends of the deficit of discharge and the number of dry days in each river showed no clear patterns (Figures 11 and 12). In some cases, there was a positive trend towards increasing droughts and a negative trend towards decreasing discharge deficit. For example, in the case of JUR for a threshold value of 30Q95, the mentioned tendencies can indicate a decrease in the deficit of discharge and an increase in dry days. The trends obtained using the two thresholds generally coincided. An exception was ZEI, in which, at the 30Q95 threshold, the duration of droughts and discharge deficits tended to decline, while, at the 30Q80 threshold, the opposite trend was observed.

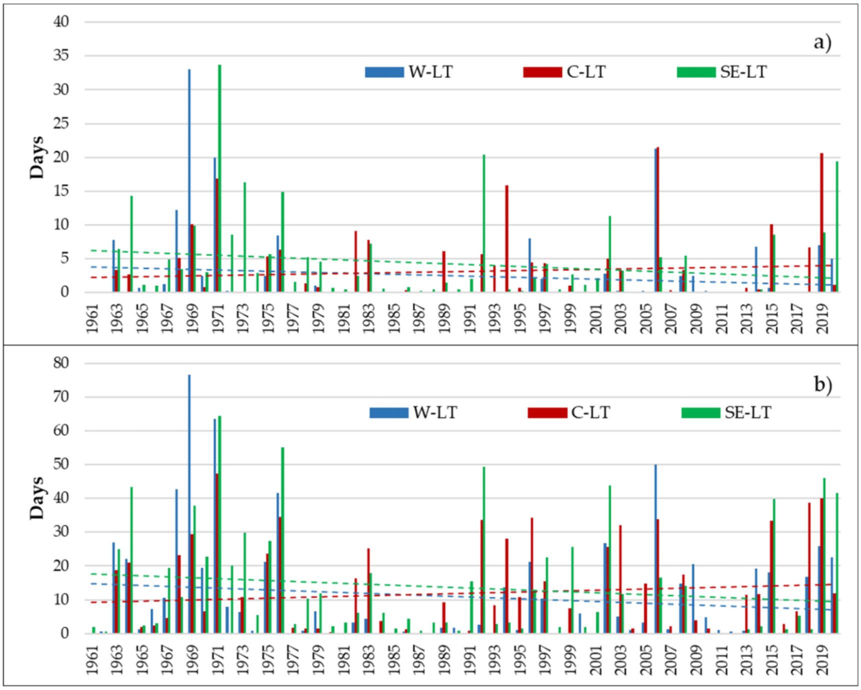

Figure 10. The average number of drought days in the three regions: (**a**) at threshold 30Q95, (**b**) at threshold 30Q80.

More detailed information on each river is provided in Tables 4 and 5 (for thresholds 30Q95 and 30Q80, respectively). These results confirmed previous findings in the C-LT region—the number of dry days and discharge deficit is higher in the second period—but it should be noted that the depth of droughts (maximum deviation) for some rivers decreased compared to the first period. In the W-LT region, only general trends in the decline of dry days were detected in the second period; all other data were heterogeneous. Only in the case of MIN, the consistency in all drought indices and downward trends in the deficit of discharge and the duration of the drought in the second period at both thresholds were identified. In the rivers of the SE-LT region, no tendencies of decline in the duration or depth of droughts were found.

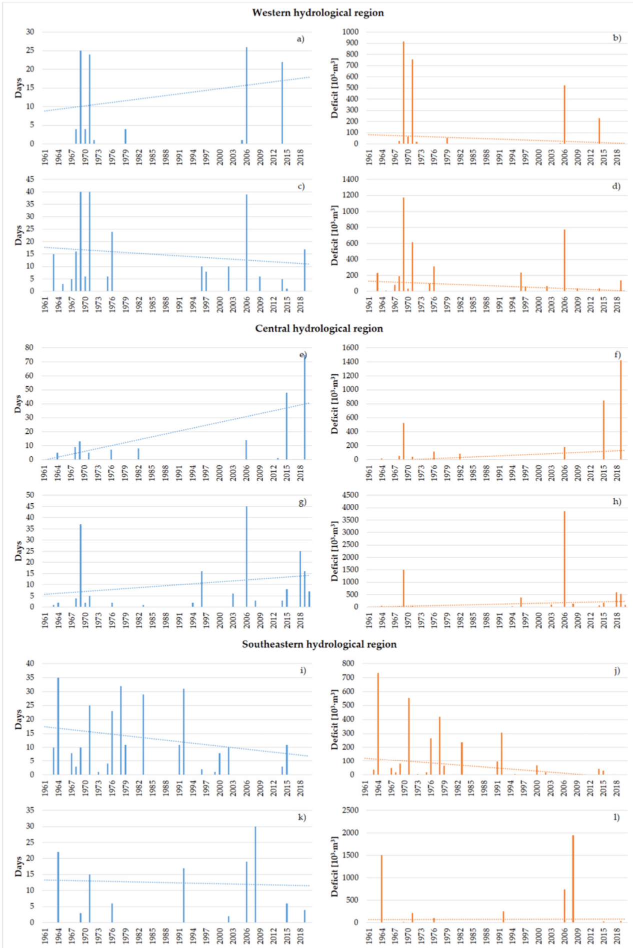

Figure 11. Examples of drought changes for 30Q95 threshold over time: (**a**) days with drought in JUR river, (**b**) deficit volume in JUR river, (**c**) days with drought in MIN river, (**d**) deficit volume in MIN river, (**e**) days with drought in SES river, (**f**) deficit volume in SES river, (**g**) days with drought in VEN2 river, (**h**) deficit volume in VEN2 river, (**i**) days with drought in VER river, (**j**) deficit volume in VER river, (**k**) days with drought in ZEI river, (**l**) deficit volume in ZEI river.

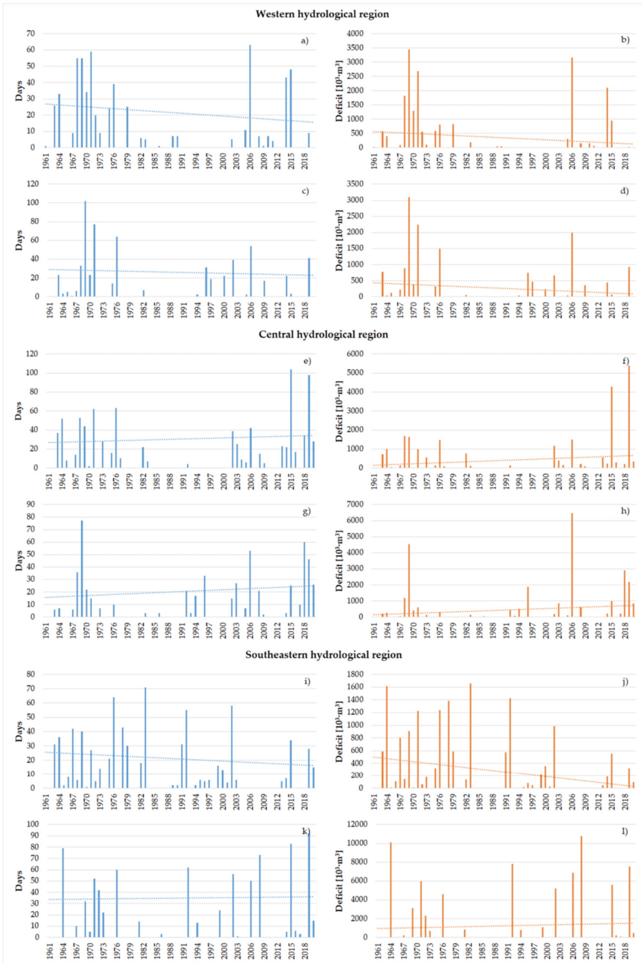

Figure 12. Examples of drought changes for 30Q80 threshold over time: (**a**) days with drought in JUR river, (**b**) deficit volume in JUR river, (**c**) days with drought in MIN river, (**d**) deficit volume in MIN river, (**e**) days with drought in SES river, (**f**) deficit volume in SES river, (**g**) days with drought in VEN2 river, (**h**) deficit volume in VEN2 river, (**i**) days with drought in VER river, (**j**) deficit volume in VER river, (**k**) days with drought in ZEI river, (**l**) deficit volume in ZEI river.

Table 4. Changes for 30Q95.

River	Average Deficit during 1961–1990 ($10^3 \cdot m^3$/day)	Average Deficit during 1991–2020 ($10^3 \cdot m^3$/day)	Days with Drought (1961–1990)	Days with Drought (1991–2020)	Flow Deficit during 1961–1990 ($10^3 \cdot m^3$)	Flow Deficit during 1991–2020 ($10^3 \cdot m^3$)	The Lowest Deviation in 1961–1990	The Lowest Deviation in 1991–2020
Western hydrological region								
JUR	29.6	15.5	62	49	1834.3	760.3	−1.18	−0.44
AKM	3.9	5.6	117	13	457.9	72.6	−0.14	−0.30
MIN	17.7	14.1	155	96	2751.0	1351.3	−0.74	−0.37
BAR	3.5	5.4	25	79	87.3	426.8	−0.10	−0.28
Central hydrological region								
SUS	6.0	5.3	120	59	718.9	312.8	−0.23	−0.12
SES	17.9	17.8	47	138	838.9	2450.3	−0.61	−0.41
NEM	19.2	17.8	99	132	1899.9	2343.2	−0.52	−0.56
MUS	6.9	5.6	69	113	477.8	630.7	−0.29	−0.14
VEN1	11.5	8.5	70	84	805.3	710.2	−0.33	−0.30
VEN2	30.8	45.6	54	131	1660.6	5975.4	−1.05	−1.96
Southeastern hydrological region								
MER	53.7	122.6	82	140	4399.5	17,159.0	−2.11	−4.41
ULA	3.0	5.2	4	116	12.1	597.0	−0.05	−0.15
VER	13.0	7.4	191	77	2479.7	570.2	−0.76	−0.24
SRE	12.2	7.3	362	196	4430.6	1435.1	−0.42	−0.41
ZEI	40.0	38.6	46	78	1840.3	3012.8	−1.33	−1.24
SVE1	90.3	48.8	103	58	9295.8	2830.5	−2.34	−1.56
SVE2	79.3	22.3	281	27	22,284.3	603.1	−2.40	−0.64

Table 5. Changes for 30Q80.

River	Average Deficit during 1961–1990 ($10^3 \cdot m^3$/day)	Average Deficit during 1991–2020 ($10^3 \cdot m^3$/day)	Days with Drought (1961–1990)	Days with Drought (1991–2020)	Flow Deficit during 1961–1990 ($10^3 \cdot m^3$)	Flow Deficit during 1991–2020 ($10^3 \cdot m^3$)	The Lowest Deviation in 1961–1990	The Lowest Deviation in 1991–2020
Western hydrological region								
JUR	16.7	68.2	415	198	6946.6	13,515.6	−1.82	−1.08
AKM	8.7	5.7	491	249	4243.1	1423.9	−0.29	−0.45
MIN	26.8	23.5	358	252	9594.7	5932.2	−1.05	−0.68
BAR	6.9	9.9	207	447	1436.0	4436.6	−0.30	−0.48
Central hydrological region								
SUS	10.9	4.9	199	449	2172.1	2202.4	−0.33	−0.22
SES	22.5	31.8	418	471	9409.0	14,982.6	−1.13	−0.93
NEM	33.6	34.9	375	502	12,585.0	17,511.6	−1.10	−1.14
MUS	11.3	11.9	239	381	2702.6	4549.0	−0.46	−0.31
VEN1	18.6	18.7	286	396	5322.2	7420.0	−0.65	−0.62
VEN2	41.0	50.3	192	369	7869.3	18,552.7	−1.67	−2.58
Southeastern hydrological region								
MER	126.4	164.0	359	378	45,374.7	61,986.8	−4.33	−6.63
ULA	12.6	21.7	154	586	1941.4	12,694.8	−0.49	−0.59
VER	23.8	17.0	463	291	11,013.4	4952.5	−1.05	−0.53
SRE	15.5	10.4	627	479	9684.6	4996.5	−0.54	−0.53
ZEI	87.3	96.2	319	483	27,841.5	46,453.8	-3.22	−3.13
SVE1	93.2	83.1	448	217	41,760.6	18,030.8	−3.78	−3.00
SVE2	114.1	81.5	733	132	83,650.8	10,752.5	−3.93	−2.17

4. Discussion

The abundant and indisputable scientific evidence that significant climate change is taking place leaves no doubt that low flow is undergoing substantial changes. Therefore, this study intended to provide fresh insight into this phenomenon in Lithuanian rivers, using a long series of available data and more sophisticated methods than previously used.

Two features determine the hydrological regime of Lithuanian rivers. They are all lowland rivers. It is well-known that low-flow formation processes differ in the highlands and lowlands [13,36,37]. Therefore, the Lithuanian river network is expected to have a homogeneous flow behavior. Besides that, catchments in this relatively small country exhibit different hydrological characteristics depending on physico-geographical and climatic (mainly on the distance from the Baltic Sea) conditions. This is the second important feature of Lithuanian river catchments: based on the listed conditions, they are classified into three distinct hydrological regions: Western (W-LT), Central (C-LT), and Southeastern (SE-LT). It is important to mention that since the 1970s, when the first attempt to classify Lithuanian river catchments into regions was made [38], the regional boundaries shifted only slightly [39], and this shift occurred due to climate changes.

For the above reasons, in this study, the regularities of low flow using specific low-flow indices, 30q, 30q95, and 30q80 in rivers in different hydrological regions and over two subperiods (1961–1990 and 1991–2020), were compared and analyzed. The highest indices were estimated throughout the entire observations period in the SE-LT region (30q = 3.97 L/s·km^2), and the lowest in the C-LT region (1.47 L/s·km^2). In the SE-LT region, the lowest values of indices became less extreme compared to the first subperiod. There were no clearly expressed changes in the river indices of the W-LT and C-LT regions over time.

The trend analysis of 30Q data in rivers from different hydrological regions confirmed the presence of different low-flow patterns in the selected periods, as well. In general, the 30Q values over the entire period (1961–2020) had no trends in all hydrological regions. An exception was one river (from the SE-LT region) having two WGSs (SVE1 and SVE2), where both tests estimated significant positive trends in 1961–2020. In the subperiods, values of the low-flow indices in SVE1 and SVE2 also demonstrated a more or less significant increase. On the opposite, in the first subperiod (1961–1990), trends in 30Q data were significantly positive and positive in most rivers of the W-LT and C-LT regions. Whereas, in the SE-LT region, only a few significant trends were found. The most recent subperiod (1991–2020) can be characterized as having the least pronounced tendencies in the low-flow changes. With some exceptions of more or less significant trends of mixed direction, in the bigger part of WGSs, only a downward direction was identified.

Contrary to expectations, this analysis did not find a significant difference in low-flow characteristics between the regions. Explaining the estimated regularities is a rather complicated task. The fact that no significant changes were observed in the SE-LT region may be related to the runoff fed specifics of the rivers there. Since these rivers are mainly groundwater-fed, it can be argued that despite the ongoing climate change, the low-flow regime of the rivers remains the least affected. The significant positive trends in the first subperiod and slight tendencies of decrease in the second thirty-year period in rivers from other regions might be attributed to climate change, as the river runoff in the W-LT and C-LT regions is more dependent on rain variability [39]. In these regions, estimated thirty-year moving averages in 30Q data in 1961–2020 also showed a decrease in low-flow discharge.

No trends in the annual variation of 30Q over the more extended periods of 1922–2003 and 1941–2003 were detected in the earlier study by Kriaučiūnienė et al. [24]. The identified positive trends in rivers in the W-LT region in 1961–2003 were explained by a very wet period of 1977–1991 in this territory. A similar study of Latvian rivers revealed no statistically significant long-term trends in 30Q of the warm period [23]. The findings of trend analysis of flow indices in Polish rivers [17] demonstrated the existence of some complex spatial gradient. The distance of the catchment centroid from the coast was found to be a very good predictor of trend slopes for most studied indices. In the pan-European study, Stahl et al. [10] found dominant positive trends of low-flow indices around the Baltic Sea.

Over time, the average number of dry days (at both thresholds: 30Q95 and 30Q80) decreased in the W-LT and SE-LT regions and increased in the C-LT region. The identified changes (and the already mentioned lowest specific low-flow indices) in the C-LT region may explain the presence of intermittent rivers. However, the trends in the number of dry days and flow deficit of individual Lithuanian rivers did not help distinguish clear tendencies (e.g., in the study of Bormann and Pinter [16]). In most cases, changes in these two indices went in the same direction; however, the trend of low-flow indices in some rivers was the opposite. The absence of a direct relationship between the two indices shows that low-flow behavior is complex and often catchment-specific.

The most obvious finding to emerge from this study is that the low-flow regime in Lithuanian rivers has changed over time. Similar changes in 30Q in the W-LT and C-LT regions may be related to the predominant surface feeding type of river runoff. In recent decades, the observed decreasing precipitation amount [40] could cause a decrease in low-flow discharges. The estimated increase in the number of dry days in the rivers of the C-LT region may be explained by the decrease in humidity (as the climate becomes less humid moving away from the sea). It has been found that weak infiltration characteristics and high dependence on surface feeding sources (mainly rain and snow) are related to zero-flow phenomena in this region [29]. The differences of low-flow characteristics among the rivers inside the hydrological regions may point to various complex local catchment-specific features that are difficult to include in the investigation. Meanwhile, the absence of a direct link between climatic variables and low-flow events does not indicate that the impact of climate change can be dismissed [36]. Therefore, the present findings showed that it is difficult to establish clear tendencies in the observed low-flow changes over time, and such results are consistent with those obtained in other adjacent and geographically similar catchments. Although in the present study, analyzed river catchments were semi-natural, the potential impact of anthropogenic nature on the identified regularities should not be neglected as well [16,41].

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water

Article

Patterns of Past and Future Droughts in Permanent Lowland Rivers

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Abstract: The problem of droughts is acute due to climate change. The study aims to assess the temporal and spatial drought patterns in Lithuanian lowland rivers in the past and to project these phenomena according to climate scenarios and models. Drought analysis was based on Standardized Precipitation Index (SPI), Reconnaissance Drought Index (RDI) and Streamflow Drought Index (SDI). To evaluate the past patterns, the hydrometeorological data of 17 rivers were used from 1961–2020. Future drought changes were analyzed in 2021–2100 according to the selected RCPs (Representative Concentration Pathways) using the hydrological model HBV. There were different patterns of droughts in three hydrological regions of Lithuania (Western, Central and Southeastern). The Southeastern region was more prone to extreme summer hydrological droughts, and they had a shorter accumulation period compared to the other two regions. SPI and RDI indices showed that the number of dry months and the minimum value of the index increased, extending the accumulation period. The highest correlation was recorded between RDI-12/SPI-12 and SDI-12. The amplitude between extremely wet and dry values of river runoff will increase according to RCP8.5. The projections indicated that hydrological drought intensity in the Central region is expected to increase under both analyzed RCPs.

Keywords: meteorological drought; SPI and RDI indices; hydrological drought; SDI index; historical droughts; droughts projections; lowland rivers

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1. Introduction

Drought is a recurring phenomenon that has plagued civilization throughout history [1]. Droughts are among the costliest natural hazards that influence various economic sectors and ecosystems in many different ways. This slowly moving hazard can affect virtually all climatic regimes [2]. It can occur in any part of Europe, in both high and low rainfall areas, and at any time of the year. In recent decades the most severe drought in Europe in 2003 was followed by droughts in 2007, 2011, 2013, 2015, 2017, and 2018 that affected large parts of Southern, Western and even Northern Europe [3]. Pan-European studies [4] show a statistically significant tendency towards less frequent and severe drought events over North-Eastern Europe, especially in winter and spring, and a moderate or more remarkable opposite tendency over Southern and Eastern Europe, especially in summer. The rise of compound warm-season droughts in Europe is a dynamic, developing phenomenon [5]. The most comprehensive climate change analysis in the Sixth Assessment Report published by the IPCC (Intergovernmental Panel on Climate Change) [6] warns that there will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming. It means that this phenomenon may intensify further. Many scientists and decision-makers are concerned about the diversity and complexity of drought impacts and the low level of preparedness for future events [7]. U.S. researchers [8] projected that under the most pessimistic scenario, at the end of the 21st century, 43% of the world's land area would suffer from increased drought. According to Naumann et al. [9], in the absence of climate action (4 °C in 2100 and no adaptation), the combined annual drought losses in the European Union and the United Kingdom are projected to rise to more than €65 billion per year compared with €9 billion per year currently.

There is a growing need to understand the potential impact of this extreme weather-related hydrological phenomenon to reduce or mitigate its threats. According to Encyclopedia Britannica, drought is generally defined as a lack or insufficiency of rain for an extended period that causes a considerable hydrologic (water) imbalance and, consequently, water shortages, crop damage, streamflow reduction, and depletion of groundwater and soil moisture. The drought type generally reflects the compartment of the hydrological cycle or sector of human activity that is affected; deficits typically propagate through the hydrological cycle, affecting different ecosystems and human activities accordingly [10]. The following types/categories/phases of drought can be found in the literature: meteorological, soil moisture/agricultural/vegetation, hydrological, groundwater, environmental and socio-economic drought. Drought indicators or indices are often used to help track droughts, and these tools vary depending on the region and the season [11,12]. Indicators are variables or parameters used to describe drought conditions (e.g., precipitation, temperature, streamflow, groundwater level and soil moisture). Indices are typically computed numerical representations of drought severity, assessed using climatic or/and hydrometeorological inputs, including the indicators listed above. They combine meteorological and hydrological parameters into a single numerical value or formula and provide a comprehensive decision-making picture [13–17]. Among the most frequently used drought indices are the Palmer Drought Severity Index (PDSI) [18], Rainfall Deciles [19], Crop Moisture Index (CMI) [20], Surface Water Supply Index (SWSI) [21], Standardized Precipitation Index (SPI) [22], Reconnaissance Drought Index (RDI) [23] and Drought Frequency Index (DFI) [24]. The National Meteorological and Hydrological Services worldwide are encouraged to use the SPI to describe meteorological drought; however, scientists seem to agree that there is still no "best" hydrological and agricultural drought index, so further discussion is needed on this topic [2]. Each index currently in use is appropriate to meet the expectations of a particular type of drought, while pre-knowledge about each case is crucial. However, the aim should be to develop a composite drought index to integrate all relevant data and drought definitions regarding the dominant types of monthly droughts in time and space, along with climate change scenarios [25].

Even though Lithuania belongs to the humid climate zone and is rich in rivers and lakes, drought is not uncommon. As evidence of climate change increases, research into drought events in this Baltic country intensifies. However, the analysis of dryness dynamics in the Baltic Sea region discovered a decline, shown by the increase in SPI values over the last fifty years in most studied areas [26]. The dynamics of meteorological and hydrological droughts in Lithuania did not reveal clear signs that extreme droughts have also increased. Still, in some sub-basins of the Nemunas River (which basin covers almost 72% of the Lithuanian territory), a statistically significant rise in SPI values was observed [27]. Whereas, at the end of the century, the climate changes are likely to lead to more intense and possibly more frequent meteorological droughts (especially in June–August), and the meteorological conditions will significantly impact river runoff [28,29]. Besides the SPI, for drought investigation, [30] used Hydro-thermal Coefficient of Selyaninov, HTC; [27] applied the Streamflow Drought Index, SDI. Rimkus et al. [31] used the normalized difference vegetation index (NDVI) and Vegetation Condition Index (VCI) to determine drought effect on vegetation. Rimkus et al. [32] analyzed widely used drought detection indices: Standardized Precipitation Evapotranspiration Index, SPEI; Effective Drought Index, EDI; Percent of Normal Precipitation, PNP; Aridity Index, AI. These scientists proposed a new Temperature-Precipitation Index (TPI) to identify agricultural drought in Lithuania. Kugytė and Valiuškevičius [33] analyzed hydrological droughts and suggested a new hydrological drought index SWLI (Standardized Water Level Index) to identify drought in Lithuanian rivers. Research over the last decades has provided important information on drought detection, dynamics, recent trends and projections in Lithuania. So far, however, the main focus of Lithuanian scientists has been on meteorological and agricultural droughts. Less attention was paid to the study of hydrological droughts. There is no research in Lithuania and the Baltic States related to forecasting hydrological droughts in future.

The main objective of our research is to assess the temporal and spatial patterns of hydrological droughts in Lithuanian rivers using multiannual hydrometeorological data, to study how meteorological and hydrological droughts are related and project these phenomena according to new regional climate models. Drought analysis will be based on the Standardized Precipitation Index (SPI), Reconnaissance Drought Index (RDI) and Streamflow Drought Index (SDI).

2. Materials and Methods

2.1. Study Area and Data

This study focuses on the entire territory of Lithuania, the area of which is 65,200 km^2. The whole territory of the country belongs entirely to the plains, with the highest point 294 m above sea level. Lithuania belongs to the humid zone, with annual precipitation in the Western hydrological region (W-LT) 735–810 mm, in the Central hydrological region (C-LT) 600–680 mm and in the Southeastern hydrological region (SE-LT) 600–670 mm [34]. There are about 22,000 rivers in Lithuania with a total length of more than 37,000 km. All Lithuanian rivers belong to the Baltic Sea River Basin. Depending on climatic conditions and types of river feeding, Lithuania is divided into three hydrological regions: the Western, Central and Southeastern regions. During the driest 30-day summer period, the runoff of the rivers in the Western region of Lithuania is 0.4–2.5$\cdot 10^{-3}$ m^3/s$\cdot$km^2, in the Center region—0.1–1.7 $\times$ 10^{-3} m^3/s$\cdot$km^2 and in the Southeastern region—1.7–4.7 $\times$ 10^{-3} m^3/s$\cdot$km^2 [35]. In the Western hydrological region, the main feeding source is precipitation. In the Central hydrological region, there is no dominant type of river feeding; runoff is formed mainly from snowmelt and rainfall. Groundwater generates runoff in the Southeastern hydrological region [36].

The long-term hydrological and meteorological data sets for this study were obtained from the Lithuanian Hydrometeorological Service. Meteorological data from 12 meteorological stations (MS) from 1961 to 2020 were used. Hydrological data from 17 water gauging stations (WGS) with observation data covering at least 59 years from 1961 to 2020 were applied (Table 1). The selected WGSs are located in different hydrological regions: four WGSs in the Western, six WGSs in the Central and seven WGSs in the Southeastern hydrological region. All hydrological stations describe typically small and medium-sized rivers (catchment area varies from 162 km^2 to 5440 km^2). The location of the studied basins, WGSs and MSs are shown in Figure 1, and additional information is provided in Table 1.

Three rivers were selected for modeling of hydrological drought index SDI in future. These rivers are located in different hydrological regions of Lithuania: the Minija River in the Western, the Venta in the Central and the Šventoji in the Southeastern hydrological region. Hydrological data from water measurement stations (WMS) and meteorological stations (MS) on these rivers were used for calibration and validation to create hydrological models and project water discharges in future.

Since the network of meteorological stations in Lithuania is sparse, the point data from the meteorological stations were transformed into averages for each basin, using the weighted coefficients of the influence of approximate stations on a given basin. The weighted coefficients were calculated using Thiessen polygons. Polygons were created in ArcGIS 10.8 software using the Create Thiessen Polygons tool. First, all entry points (meteorological stations) were used to create a triangulated irregular network according to Delaunay criteria. The perpendicular bisectors for each triangle edge were generated to form the edges of the Thiessen polygons. The points of bisectors intersection determine the location of the vertices of the future polygons, which are connected around each meteorological station using ArcGIS Pro help archive. The Thiessen polygons method has already been successfully used to calculate climatic parameters [37–39]. Further calculation of the percentage of the river basins area belonging to each meteorological station and the creation of maps also took place in ArcGIS 10.8.

Table 1. List of the studied gauging station catchments with the main characteristics (observation period 1961–2020).

No	River	WGS	A, km^2	$Q_{average}$, m^3/s	Q_{max}, m^3·s^{-1} (Year)	Q_{min}, m^3·s^{-1} (Year)
Southeastern hydrological region						
1.	Merkys	Puvočiai	4300	31.6	43.3 (1994)	20.9 (2020)
2.	Ūla	Zervynos	679	4.82	6.95 (1994)	2.84 (2020)
3.	Verknė	Verbyliškės	694	5.00	8.33 (1994)	3.27 (1969)
4.	Strėva	Semeliškės	234	1.64	2.43 (1994)	1.16 (2003)
5.	Žeimena	Pabradė	2580	20.3	31.1 (1990)	14.1 (2003)
6.	Šventoji	Anykščiai	3600	26.5	50.9 (2017)	14.9 (1971)
7.	Šventoji	Ukmergė	5440	38.9	73.0 (2017)	20.2 (1976)
Central hydrological region						
8.	Nevėžis	Panevėžys	1090	7.25	19.7 (1972)	2.11 (2003)
9.	Šušvė	Šiaulėnai	162	1.18	2.11 (1980)	0.43 (2020)
10.	Nemunėlis	Tabokinė	2690	19.5	37.1 (1962)	9.19 (2006)
11.	Mūša	Ustukiai	2280	10.2	19.7 (1998)	2.89 (1976)
12.	Venta	Papilė	1570	9.66	18.8 (1980)	3.88 (1976)
13.	Venta	Leckava	4060	29.5	60.8 (1980)	13.8 (1963)
Western hydrological region						
14.	Jūra	Tauragė	1690	21.9	37.7 (1974)	10.6 (1964)
15.	Akmena	Paakmenis	314	4.26	6.87 (1998)	1.96 (1964)
16.	Minija	Kartena	1230	16.5	26.3 (2007)	7.47 (1969)
17.	Bartuva	Skuodas	612	7.50	13.6 (1981)	3.17 (1969)

Figure 1. Location of hydrological regions and selected WGSs and MSs.

2.2. Methodology

Research of past and future droughts was carried out in the following steps:

1. Estimating past changes in meteorological and hydrological drought indices (SPI, RDI and SDI) using statistical analysis methods (Sections 3.1 and 3.2).
2. Preparation of data (T, P and Q) for future drought index calculations (in the 21st century) in three Lithuanian river basins according to the selected climate models and scenarios:
   (a) preparation of daily air temperature and precipitation series based on the database (Section 3.3);
   (b) projection of the daily discharges of three selected rivers according to the selected climate models and scenarios using the HBV hydrological model (Section 3.3).
3. Projection of meteorological and hydrological drought indices (SPI, RDI and SDI) and their analysis in the three selected river catchments in the 21st century.

2.2.1. Calculation of Drought Indices

One hydrological (Streamflow Drought Index) and two meteorological indices (Standardized Precipitation Index and Reconnaissance Drought Index) were chosen to identify and characterize droughts in Lithuania. The indices were selected considering their widespread use, the simplicity of the calculations, the availability of the necessary meteorological and hydrological data, and the possibility of the regional analysis. All drought indices were calculated for five different time series, i.e., 1, 3, 6, 9, and 12 months in each river basin.

DrinC software (Drought Indices Calculator) developed by the Center for the Assessment of Natural Hazards and Proactive Planning and the Laboratory of Reclamation Works and Water Resources Management of the National Technical University of Athens was used to calculate the indices [40]. In recent years, this tool was successfully applied to drought analysis [41,42].

Standardized Precipitation Index (SPI) was developed and introduced by McKee et al. [22]. It is now widely used to detect and describe meteorological drought and recommended by World Meteorological Organization (WMO) as the standard drought index [43]. SPI determines precipitation anomalies by comparing the observed total precipitation amounts over the accumulation period of interest (e.g., 1, 6, 12 months) with the long-term historical rainfall record, which is fitted to a probability distribution using the gamma function [44]. Precipitation is transformed into normalized numerical values. The SPI is the number of standard deviations by which the observed precipitation deviates from the long-term mean of a normally distributed random variable [45].

SPI is calculated as follows:

$$SPI = \frac{x_i - \overline{x}}{\sigma}, \quad (1)$$

where x_i is the precipitation of the selected period during the year i, $\overline{x}$ is long term mean precipitation, and σ is the standard deviation for the selected period. Further details on the SPI index calculation can be found in the work of McKee et al. [22].

The obtained positive SPI index values reflect wet conditions when the total precipitation over a specific period is greater than the median. The negative SPI values describe dry conditions when the total precipitation over a specific period is lower than the median precipitation. The classification of drought conditions according to SPI index values is described in [46–48]. Moderately dry drought conditions will be when $-1.49 < SPI < -1.0$; severely dry conditions—$-1.99 < SPI < -1.5$; and extremely dry conditions — $SPI < -2.0$.

The widespread use of the SPI index can be explained by advantages such as the ability to use it in any geographic location and any number of time scales, the possibility of regional analysis and the need for only one input parameter (precipitation accumulation). However, this index does not consider other important meteorological parameters, such as the effect of high temperature and evaporation [44,45]; therefore, for more accurate identification of meteorological droughts in Lithuania, another meteorological index was additionally calculated.

According to McKee et al. [22], at least 30 years of precipitation data without gaps are required to calculate the SPI. Guttman [49] and Wu et al. [50] argue that a data series should be 40–60 years for stable distribution in the central part. A 70–80 year record is needed for stability in tails. It should be noted that for gamma distribution these periods can be longer [50]. In this article, 60 years of data records were used.

Reconnaissance Drought Index (RDI) was presented by Tsakiris and Vangelis [23] and successfully used by many scientists [47,51–53]. RDI involves two main parameters such as precipitation (P) and potential evapotranspiration (PET). PET is calculated from temperature data using the Thornthwaite method [54]. RDI can be expressed in three formulas. The first expression, the initial value (α_0), is usually calculated for the year i on an annual basis as follows [23]:

$$\alpha_n^{(i)} = \frac{\sum_{j=1}^{12} P_{ij}}{\sum_{j=1}^{12} PET_{ij}},\ i = 1 \text{ to } N,\ \text{and } j = 1 \text{ to } 12 \tag{2}$$

in which P_{ij} and PET_{ij} are precipitation and potential evapotranspiration of the month j of the year i, starting usually from October as it is customary for Mediterranean countries, N is the total number of years of the available data.

The second expression, the Normalized RDI (RDI_n), is computed using the following equation for each year, in which the parameter $\overline{\alpha}_0$ is the arithmetic mean of α_0 values calculated for the N years of data.

$$RDI_n^{(i)} = \frac{a_0^{(i)}}{\overline{\alpha}_0} - 1 \tag{3}$$

The standardized form of the index (RDI_{st}) is calculated as:

$$RDI_{st}^{(i)} = \frac{y^{(i)} - \overline{y}}{\hat{\sigma}_y} \tag{4}$$

in which y_i is the $\ln\left(\alpha_0^{(1)}\right)$, $\overline{y}$ is its arithmetic mean and $\hat{a}_y$ is its standard deviation.

In this study, the standardized form of the index (RDI_{st}) was used. The calculation of the RDI_{st} was performed by fitting the gamma probability density function (pdf) to the given frequency distribution of the $\alpha_{k,}$ as in most cases, the gamma distribution is more successful than lognormal [55]. The RDI values were classified similarly to the SPI index values.

Streamflow Drought Index (SDI) was developed by Nalbantis and Tsakiris [56] and is based on the concept of the SPI index. The SDI index is a simple and effective index to monitor hydrological droughts using cumulative streamflow discharge [57,58]. The cumulative streamflow discharge $V_{i,k}$ for the i-th hydrological year and the k-th reference period can be calculated using the following equation:

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j}\quad i = 1, 2, \ldots\quad j = 1, 2, \ldots, 12\quad k = 1, 2, 3, 4 \tag{5}$$

where $V_{i,k}$ is the cumulative streamflow volume for the i-th hydrological year and the k-th reference period, k = 1 for October–December, k = 2 for October–March, k = 3 for October–June, and k = 4 for October–September.

Then, the SDI is defined for each reference period k of the i-th hydrological year by the following equation:

$$SDI_{i,k} = \frac{V_{i,k} - \overline{V}_k}{s_k} \quad i = 1,\ 2, \ldots \quad j = 1,\ 2, \ldots, 12 \quad k = 1,\ 2,\ 3,\ 4 \tag{6}$$

where $\overline{V}_k$ and s_k are the mean and standard deviation of the cumulative streamflow volumes of the reference period *k*, respectively.

Like to SPI and RDI, the streamflow probability distribution was normalized using a gamma distribution. An SDI value below zero indicates hydrological drought [48]. Moderate droughts will be when $-1.49 < SDI < -1.0$; severe droughts—$-1.99 < SDI < -1.5$; and extreme droughts — $SDI < -2.0$.

2.2.2. Selection and Preparation of Models

For projection of drought changes in the future, 13 regional climate models were considered that would have data for the two most commonly used RCP scenarios (RCP4.5 and RCP8.5). Monthly temperature and precipitation changes of observed historical data and historical simulated data were analyzed and compared. The correlation method was used for the statistical comparison of simulated and observed data. Additionally, the Wilcoxon test (for data with non-normal distribution) and the Pared t-test (for data with normal distribution) were used to determine whether the simulated data of each specific regional climate models (RCMs) differed from the observation data in a statistically significant manner. The whole analysis was based on data comparison for three meteorological stations (one from each hydrological region): Panevėžys, Vilnius and Telšiai. As a result, three regional climate models were selected: CNRM-CERFACS-CNRM-CM5, ICHEC-EC-EARTH and MPI-M-MPI-ESM-LR.

Daily air temperature (T, °C) and precipitation (P, mm) data of regional climate models were extracted from the EURO-CORDEX database (www.euro-cordex.net (accessed on 14 March 2021)). To adapt mentioned data to the Lithuanian conditions, the quantile mapping method was used [59,60]:

$$St^{Obs} = h\left(St^{CM\ RP}\right) = ECDF^{Obs-1}\left(ECDF^{CM\ RP}\left(St^{CM\ Fut}\right)\right) \tag{7}$$

where St^{Obs}—observed meteorological parameter, $S^{\ CM\ RP}$—climate model output for the reference period, $ECDF^{Obs}$—empirical cumulative distribution function for the observation period, $ECDF^{CM\ RP}$– empirical cumulative distribution function for climate model reference period, and $S^{CM\ Fut}$—meteorological parameter, which is modelled by climate model for the future period. All estimated results were compared with the values of the reference period (1986–2005).

2.2.3. Discharge Projections in the Selected River Catchments Using HBV Hydrological Model

The drought projections in the 21st were calculated for three rivers from the different hydrological regions of Lithuania using the HBV model. HBV is a technique of rainfall-runoff modelling used to calculate the total water balance in a catchment. HBV is based on the water balance equation [61]:

$$P - E - Q = \frac{d}{dt}[SP + SM + UZ + LZ + V] \tag{8}$$

where P—precipitation, E—evaporation, Q—discharge, SM—soil moisture SP—snow pack, UZ—upper groundwater zone, LZ—lower groundwater zone, and V—lake or dam volume.

Model computations were performed in three steps: 1. Estimation of precipitation amount that falls to the ground; 2. Estimation of the slope runoff; 3. Evaluation of runoff in watercourse and runoff transformation. A considerable amount of geographical information is necessary to create hydrological models (Table 2).

Table 2. Main characteristics of the selected river catchments.

River-WGS	Hydrological Characteristic		Geographical Characteristic		
	Average Discharge, $m^3\ s^{-1}$	Basin Area, km^2	Lakes, %	Wetland, %	Woods, %
Šventoji-Ukmergė	38.9	5440	3.8	9.0	12.0
Minija-Kartena	16.5	1230	1.4	8.0	20.0
Venta-Leckava	29.5	4060	1.0	9.0	22.0

Calibration of developed hydrological models was performed using 16 main parameters. The correlation coefficients r between measured and calculated water discharges varied from 0.68 to 0.88 in calibration and validation periods (Table 3). High r values enabled to use hydrological models to project selected rivers runoff in climate change conditions. More information on the application of the HBV model to project Lithuanian river runoff is presented in our previous research [36,62].

Table 3. Results of calibration and validation of hydrological models (where NSE is Nash–Sutcliffe model efficiency coefficient: RE is a difference between observed and modeled runoff in %).

River-WGS	Calibration			Validation		
	r	NSE	RE, %	r	NSE	RE, %
Šventoji-Ukmergė	0.75	0.64	2.6	0.68	0.64	12.9
Minija-Kartena	0.88	0.77	3.8	0.83	0.70	−1.1
Venta-Leckava	0.88	0.77	−2.6	0.81	0.75	3.5

3. Results

Seventeen rivers with the complete data set (1961–2020) were selected for the temporal and spatial analysis of meteorological and hydrological droughts. In addition, one river (in total, three rivers) from each hydrological region was selected for more detailed analysis and drought projections in the near (2021–2060) and far future (2061–2100) periods.

3.1. Variation of Precipitation and Runoff in the River Catchments in the Past

As already mentioned in the methodology, the value of meteorological indicators (precipitation and temperature) was calculated for each catchment area, considering their affiliation with a particular meteorological station. This section analyzed the annual indicators (sum of annual precipitation and average annual runoff) from 1961 to 2020. Based on the calculated annual averages, the average values for the entire observation period were calculated, and the years with the highest average and lowest average were selected.

The average annual precipitation in the studied catchments from the Southeastern hydrological region (SE-LT) ranged from 599 mm to 665 mm per year. The Central hydrological region (C-LT) had a wider range of the average annual values, from 598 mm to 762 mm. While the Western hydrological region (W-LT) was characterized by the highest precipitation and minor fluctuations in the mean annual values between the catchment areas, ranging from 744 mm to 798 mm.

The presented data of the annual amount of precipitation in the WGS catchments indicate a significant spatial variation within the territory of Lithuania. At the same time, most catchment areas within one hydrological region had the same years with the highest and lowest rainfall. For example, in six out of seven catchments within the SE-LT, the highest amount of precipitation was observed in 2010 and 2017, and the lowest in 1964 and 1971. The catchments of the C-LT did not have pronounced coincidences of years with minimum and maximum values, which may reflect the transitional position of this region between the other two hydrological regions. For the W-LT, 1981 had the highest precipitation amount in all catchments.

In addition to the average annual discharge for each catchment over the studied period (1961–2020), extreme values of the average annual data were calculated. It should be noted that the years with the maximum and minimum annual precipitation in a particular catchment practically did not coincide with the years of maximum and minimum average annual runoff in this catchment. According to precipitation and water discharge, only six catchments out of 17 had the same wettest year. For only one river, the Mūša, the years with the lowest and highest annual precipitation coincided with the years with minimum and maximum values of water discharge. The small number of coincidences of dry years can be explained by the significant impact of groundwater supply and direct human impact.

In addition, three representative rivers were selected (one from each hydrological region) to calculate the deviations of annual precipitation and average annual runoff from the average values for the entire study period. The results are presented in Figure 2.

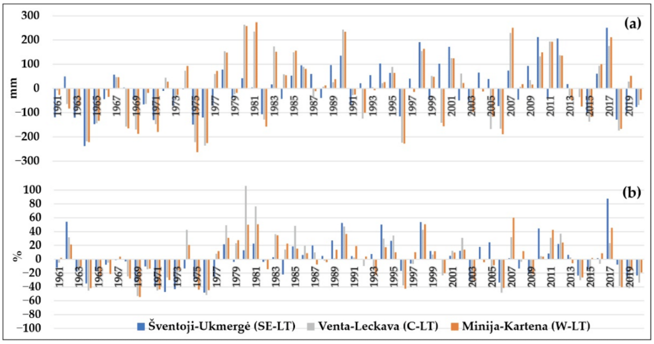

Figure 2. (**a**) Deviations from the average amount of precipitation (in mm); (**b**) Deviations from the average amount of discharge (in %).

The amount of precipitation in the C-LT was similar to the amount of precipitation in the W-CL and had the same trends. The SE-LT differed significantly in the amount of precipitation from the other two regions and sometimes had opposite trends (as an example, a slight increase compared to the average in the SE-LT with a decrease in precipitation in the other two regions (1962, 1992, 2000 and some other years)). Despite the similarities in precipitation, the C-LT and W-LT had significant differences in river runoff. The peak values of both graphs had some differences. Such a situation indicates the dependence of river runoff on precipitation; however, the critical minimum and maximum discharges are due to other factors.

3.2. Analysis of the Dry Periods Using the Drought Indices

Hydrological and meteorological droughts (or dry periods) were analyzed by the SPI, RDI and SDI indices. The two main parameters, the number of dry months and index minimum value, were calculated for the 1, 3, 6, 9 and 12-month accumulation periods and presented in Appendix A. The distribution of the parameter values by hydrological regions for each index was shown using box plots (Figure 3).

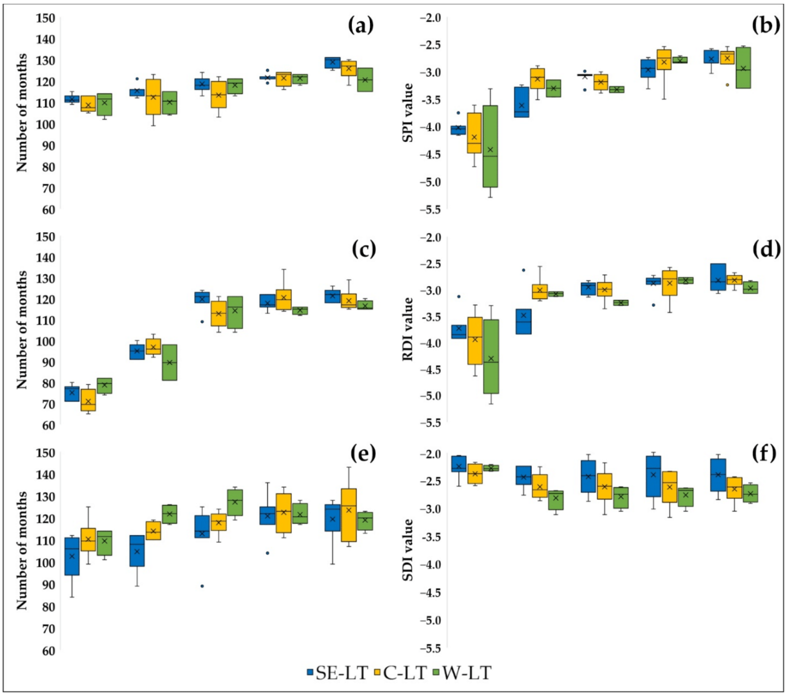

Figure 3. Distribution of drought values in the different hydrological regions (the accumulation period increases from left to right: 1, 3, 6, 9 and 12, respectively): (**a**) number of dry months for SPI-index; (**b**) distribution of minimum values by region for SPI-index; (**c**) number of dry months for RDI-index; (**d**) distribution of minimum values by region for RDI-index; (**e**) number of dry months for SDI-index; (**f**) distribution of minimum values by region for SDI-index.

As shown in the tables (Appendix A, Tables A1–A3), dry periods are those when the index value is ≤ -1. The analysis of the obtained SPI parameters showed that, in most cases, the number of dry months and the minimum value of the index increased with the extension of the accumulation period. In addition, during the 12-month accumulation period, the difference in the number of dry months between hydrological regions was more pronounced (125–131 in the SE-LT, 118–130 in the C-LT and 115–126 in the W-LT). At the same time, there were no significant differences in the minimum values of the index between the hydrological regions. As an example, for a 6-month accumulation period, the following distributions were estimated: -3.33 –(-2.99) for the SE-LT, -3.39–(-3.00) for the C-LT and -3.38–(-3.27) for the W-LT (Figure 3b).

The values of the RDI parameters also increased with a longer accumulation period (9 and 12 months). It should be noted that the number of dry months with RDI values ≤ -1 for almost all rivers and periods of accumulation was less than the number of dry months with SPI values ≤ -1. At the same time, with longer periods of accumulation, the difference in the number of dry months between the indices practically disappeared. The difference in minimum values between the RDI and SPI indices was not as evident as in the number of dry months. In addition, no patterns in the distribution of minimum values of meteorological indices according to the different hydrological regions were noted. For example, the lowest values of SPI-1 (−5.29) and RDI-1 (−5.16) were recorded in the W-LT, SPI-3 (−3.83) and RDI-3 (−3.84) in the SE-LT, SPI-6 (−3.39) and RDI-6 (−3.36) in the C-LT, SPI-9 (−3.50) and RDI-9 (−3.43) in the C-LT, and SPI-12 (−3.30) in the W-LT and RDI-12 (−3.07) in the SE-LT and W-LT.

As with meteorological indices, the number of dry months with SDI values ≤ -1 was higher for longer accumulation periods; however, the minimum values of SDI, as opposed to SPI and RDI, did not increase. Therefore, the minimum SDI values for the 3, 6, 9 and 12-month accumulation periods reflected the difference between hydrological regions. The SE-LT was characterized by a wider range (the largest range was noted for SDI-9 from −3.01 to −2.06) and higher minimum values of the SDI index. The W-LT had the lowest average minimum SDI values for the accumulation periods of 3, 6, 9 and 12 months (Figure 3f).

3.3. Distribution of Index Values According to Drought Condition Classes

Table 4 shows the percentage distribution of all months (60 observation years) according to drought condition classes of three indices in the three Lithuanian rivers, each of which represents one of the hydrological regions. The percentage of Extremely Dry months for meteorological indices decreased with the extension of the accumulation period, while the percentage of Moderately Dry and Severely Dry months increased. This might indicate the presence of short but extremely strong dry periods, which became less pronounced as the accumulation period lengthened. According to the hydrological index, the percentage of Moderately Dry months decreased in the rivers from the Central region (Venta) and the Western region (Minija) with an extension of the accumulation period. While in the Šventoji River (SE-LT), there were no regularities for this class. According to the hydrological index, the percentage of Severely Dry and Extremely Dry months increased as the accumulation period lengthened. The increase in the number of extremely dry periods for SDI might be due to the synergistic effect of less significant deviations from normal conditions, which could not be noticed in the smaller accumulation periods. According to meteorological and hydrological indices, the percentage of Extremely Dry and Moderated Dry months had opposite trends with an extension of the accumulation period. The explanation for this may be the different nature of the two processes, namely precipitation, which is not constant and may have significant interruptions, and the runoff formation process, which depends not only on precipitation but also on many different factors.

3.4. Relations between Meteorological and Hydrological Droughts

Pearson's correlation was used to investigate the relationships between meteorological and hydrological droughts in more detail. Six months of the warm season (May–October) were taken for correlation analysis, as the presented work concentrates on summer droughts. The example of the results of the correlation analysis is presented in Appendix B (Tables A4 and A5). Only two (Verknė and Strėva) of the seventeen rivers had no strong ($\geq$0.7) correlation between meteorological and hydrological indices for any accumulation period.

The correlation analysis between SPI and RDI indices with different lengths of accumulation periods (SPI-1 vs. RDI-1, SPI-3 vs. RDI-3, etc.) showed high correlation coefficients, which often approached 1. In most cases, the correlation between SDI and RDI was stronger than between SDI and SPI. Therefore, it was decided to present only the RDI index, as its differences from the SPI were insignificant, and the correlation of RDI with SDI was more pronounced. The general correlation matrix is shown in Figure 4.

Table 4. Percentage distribution of index values by drought condition classes.

Index	Extremely Wet Index > 2.0	Severely Wet 2.0 > Index > 1.5	Moderately Wet 1.5 > Index > 1.0	Normal 1.0 > Index > −1.0	Moderately Dry −1.0 < Index < −1.5	Severely Dry −1.5 > Index > −2.0	Extremely Dry Index < −2.0
Šventoji–Ukmergė							
SPI-1	1.39	3.33	9.45	70.14	7.64	3.61	4.44
SPI-3	1.11	5.85	9.75	66.44	9.61	4.04	3.20
SPI-6	1.82	5.17	9.23	67.97	9.37	4.20	2.24
SPI-9	1.69	5.34	8.71	66.71	10.81	4.77	1.97
SPI-12	2.40	4.65	8.60	66.29	11.43	5.08	1.55
RDI-1	2.79	2.61	8.38	71.32	8.38	3.73	2.79
RDI-3	2.47	5.56	7.25	69.29	10.03	3.24	2.16
RDI-6	2.10	6.29	8.39	67.97	8.81	4.62	1.82
RDI-9	2.11	5.34	9.55	67.13	9.27	4.63	1.97
RDI-12	1.83	4.8	10.72	65.87	9.59	5.22	1.97
SDI-1	4.19	3.49	7.54	69.97	10.90	3.77	0.14
SDI-3	3.66	3.66	9.02	68.87	9.44	4.79	0.56
SDI-6	2.42	4.28	9.70	67.76	9.42	5.28	1.14
SDI-9	1.73	5.78	8.81	65.61	11.13	5.35	1.59
SDI-12	1.32	6.00	10.1	64.28	10.98	4.83	2.49
Venta–Leckava							
SPI-1	1.11	4.03	9.03	70.83	7.22	4.31	3.41
SPI-3	1.67	4.46	8.63	71.45	6.13	4.60	3.06
SPI-6	1.82	5.31	9.23	67.97	9.09	3.92	2.66
SPI-9	1.97	4.35	10.25	66.85	8.57	5.48	2.53
SPI-12	1.13	4.94	11.14	64.88	9.87	5.92	2.12
RDI-1	1.65	3.30	9.16	71.98	7.87	3.84	2.20
RDI-3	2.60	3.06	9.48	70.80	7.49	4.43	2.14
RDI-6	2.38	3.50	10.91	67.69	8.81	4.75	1.96
RDI-9	1.55	4.49	10.67	67.28	7.44	6.04	2.53
RDI-12	1.83	3.25	11.28	67.42	7.62	7.19	1.41
SDI-1	3.47	3.75	9.31	68.33	11.11	3.61	0.42
SDI-3	2.65	4.87	8.64	67.27	11.42	4.04	1.11
SDI-6	2.52	4.19	8.39	68.39	10.21	4.06	2.24
SDI-9	1.68	4.92	7.86	69.52	8.57	5.34	2.11
SDI-12	1.83	4.09	9.45	69.53	6.35	6.77	1.97
Minija–Kartena							
SPI-1	0.97	3.89	9.44	71.53	6.53	3.61	4.03
SPI-3	1.67	4.32	8.50	71.03	6.96	4.04	3.48
SPI-6	1.82	5.03	9.93	66.85	9.37	4.34	2.66
SPI-9	1.54	5.06	10.53	66.29	8.57	5.06	2.95
SPI-12	1.27	5.50	10.16	65.30	9.59	6.35	1.83
RDI-1	1.78	4.10	9.09	71.84	7.67	2.85	2.67
RDI-3	2.55	3.00	8.56	73.73	6.31	3.90	1.95
RDI-6	2.38	3.91	10.35	67.83	9.51	3.64	2.38
RDI-9	1.69	4.35	11.10	66.85	8.99	4.49	2.53
RDI-12	2.26	2.40	13.12	65.30	9.45	5.78	1.69
SDI-1	3.33	4.03	8.89	67.92	10.97	3.89	0.97
SDI-3	2.23	3.90	10.58	65.88	11.56	3.48	2.37
SDI-6	1.12	4.19	10.91	66.01	9.79	4.90	3.08
SDI-9	0.28	4.36	11.80	66.85	7.02	6.18	3.51
SDI-12	0.99	3.53	11.14	66.99	7.19	6.63	3.53

Drought Index	V	VI	VII	VII	IX	X
SPI_3m vs. SDI_1m		3	3	7	13	12
SPI_3m vs. SDI_3m				2	8	4
SPI_6m vs. SDI_1m			1	4	10	12
SPI_6m vs. SDI_3m				6	12	12
SPI_6m vs. SDI_6m	4	3				9
SPI_9m vs. SDI_1m				3	3	9
SPI_9m vs. SDI_3m				1	5	10
SPI_9m vs. SDI_6m	9					9
SPI_9m vs. SDI_9m	7	3	1	2	1	3
SPI_9m vs. SDI_12m	5					
SPI_12m vs. SDI_1m				2	2	6
SPI_12m vs. SDI_3m				1	4	5
SPI_12m vs. SDI_6m	11	7				1
SPI_12m vs. SDI_9m	13	13	10	2		4
SPI_12m vs. SDI_12m	13	13	6	5	2	4

Drought Index	V	VI	VII	VII	IX	X
RDI_3m vs. SDI_1m	1	2	7	9	12	11
RDI_3m vs. SDI_3m						
RDI_6m vs. SDI_1m		2	2	9	10	12
RDI_6m vs. SDI_3m				11	12	12
RDI_6m vs. SDI_6m						
RDI_9m vs. SDI_1m				5	8	12
RDI_9m vs. SDI_3m			1	7	8	12
RDI_9m vs. SDI_6m	1					11
RDI_9m vs. SDI_9m	1	2	1	1		
RDI_9m vs. SDI_12m		1	1	1	1	
RDI_12m vs. SDI_1m			1	2	3	13
RDI_12m vs. SDI_3m	1			2	4	13
RDI_12m vs. SDI_6m	9	4				12
RDI_12m vs. SDI_9m	15	13	10	1	1	6
RDI_12m vs. SDI_12m	14	14	14	13	13	8

Figure 4. The number of strong correlations among all rivers for each summer month (numbers indicate the number of rivers that had a strong correlation in a particular month, color displays data in ascending order from red (1) to green (15), months without any strong correlation are not colored).

The highest number of strong correlations was estimated between RDI-12 and SDI-12, RDI-12 and SDI-9, SPI-12 and SDI-12. For almost all rivers (15 out of 17), a strong correlation was determined between RDI-12 and SDI-9 in May; the correlation coefficient (r) ranged from 0.70 to 0.91, except for the rivers Verknė (r = 0.66) and Strėva (r = 0.52). The strongest correlation was found for the Venta River between the RDI-12 and SDI-12 indices for May (0.907). The highest number of strong correlations ($r \geq 0.7$) was in October, followed by September and May (Figure 4).

It is also extremely important to analyze the distribution of correlations in the matrices. The highest number of cases of a strong correlation between the hydrological index with short accumulation periods (one and three months) and the meteorological index with different accumulation periods was determined in October and September. At that time, with long accumulation periods (9 and 12 months) of the hydrological index, most cases of strong correlations were found in May and June. Such a distribution indicates a significant impact on the river runoff of meteorological phenomena that occurred in the winter or summer–autumn period of the year before observation. In addition, a considerable number of strong correlations estimated in September and October indicate the decisive effects of meteorological phenomena on hydrological drought, as the relationship was present not only between short accumulation periods, but also between short accumulation periods of the hydrological index and long accumulation periods of the meteorological index (as an example of RDI-12 and SDI-1).

Figure 4 shows the highest correlations between meteorological and hydrological indices with 12 month accumulation periods. Three rivers from different hydrological regions were selected for a detailed analysis of the relationship between RDI and SDI indices (Figure 5). On average, hydrological drought followed the meteorological drought with a delay of three months, but this period may vary depending on the conditions preceding these events.

As seen in Figure 5, there was no significant difference between trends in the hydrological and meteorological indices. The Minija and Venta had almost identical plots of index values and a greater dependence on meteorological conditions, since variations in the hydrological index practically repeated the meteorological index. The Šventoji River had a larger difference between the values of hydrological and meteorological indices, but the trends were almost identical. The dry period in the Minija and Venta rivers dated from the end of 1964 to the second half of 1977, with peaks observed in 1969, 1972 and 1976–1977. The Šventoji had a similar dry period, but the extreme values were concentrated at the end of the dry period with peaks in 1972, 1974 and 1976–1977. No significant droughts were observed between 1977 and 1996 in the Minija and Venta rivers, and from 1977 to 2003 in the Šventoji River. In 1996, there was an extreme drought in the Minija, a moderated drought in the Venta and no drought in the Šventoji. There was also a difference in the wettest months: in the Minija and Venta rivers they were in 1981, and in the Šventoji river—in 2017–2018, also in some rivers of the Southeastern hydrological region in 1994 (Figure 6). From 1996 to 2006 in the Minija and Venta rivers, and from 2003 to 2009 in the Šventoji River there were a number of droughts with the extreme in 2006, especially in the rivers of the Central hydrological region (Figure 6). Further, by the end of 2018, the wet periods with short and moderated droughts predominated, and from 2019, droughts appeared throughout Lithuania, with a slight delay in the Southeastern hydrological region (Figures 5 and 6). The values of the indices remained negative until the end of 2020, except for four months in the Bartuva River (Figure 6).

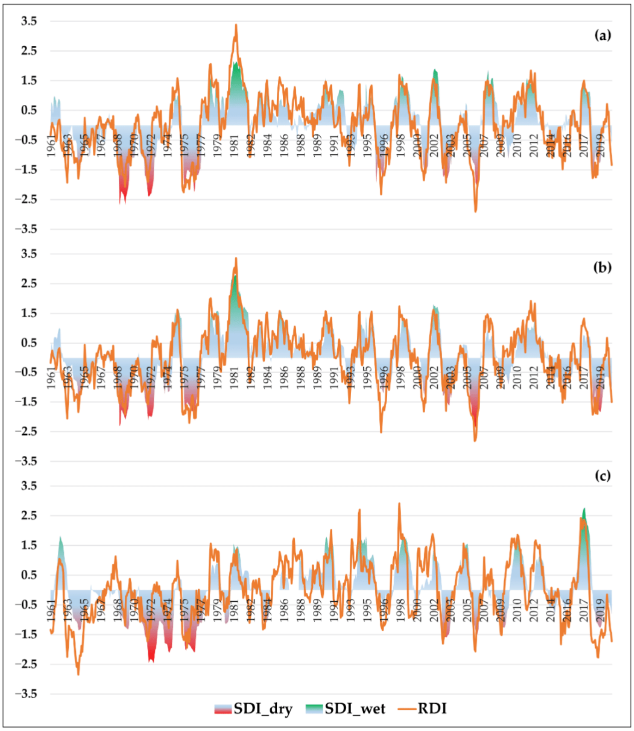

Figure 5. Values of meteorological (SPI-12) and hydrological (SDI-12) indices during the period from 1961 to 2020, in: (**a**) Minija-Kartena; (**b**) Venta-Leckava; (**c**) Šventoji-Ukmergė.

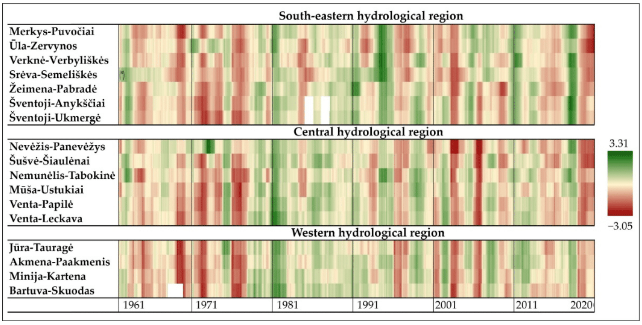

Figure 6. Graphical representation of the SDI-12 index calculation results in 1961–2020, where green indicates wet months and red indicates dry months, white—no data, the magnitude of the events depends on the brightness of the color.

3.5. Analysis of the Hydrological Drought Duration

Duration is one of the main characteristics of droughts. The drought period was considered the period from the month when the SDI value was ≤ -1. The duration of the maximum drought increased with the extension of the accumulation period (Figure 7). On average, the duration of hydrological droughts in the W-LT was shorter compared to the SE-LT and C-LT. The maximum duration of the drought was recorded for a 12-month accumulation period in the SE-LT (the Šventoji catchment). The drought lasted 42 months from 05.1971 to 10.1974. The extreme values of SDI-12 for this river (-2.46) were also observed in this period (10.1972). The maximum duration of drought in the C-LT was noted with a 12-month accumulation period in the Nemunėlis River—27 months from 12.1975 to 02.1978. The W-LT had the shortest maximum drought duration among regions based on SDI-12—23 months. This duration was recorded in two rivers of the region: the Akmena and Minija from 12.1975 to 10.1977. Most of the longest droughts were estimated in 1963–1977, which was the driest in the entire analyzed period [34]; almost all extreme droughts were from this period.

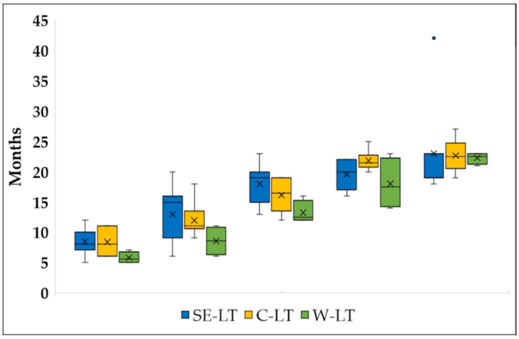

Figure 7. Box plot based on hydrological drought duration in months (the accumulation period increases from left to right: 1, 3, 6, 9 and 12, respectively).

3.6. Distribution of Droughts by Summer Months and Their Number

When analyzing the months with the highest number of droughts (Figure 8), it was concluded that there was no clear distribution pattern of rivers related to the driest months in Lithuania. SDI-1 was characterized by the greatest similarity between rivers in terms of the driest months. In most cases with a 1-month accumulation period, most drought events occurred in the first two months of the warm season (May and June). Still, there were also three rivers in northwestern Lithuania, where the greatest number of drought events occurred in October. For SDI-3, the dominance of droughts in the first half of the warm period continued. No patterns were distinguished for SDI-6 and SDI-9. SDI-12 also did not have a clear distribution related to dry months, but there was an increase in the number of droughts in the second half of the warm season.

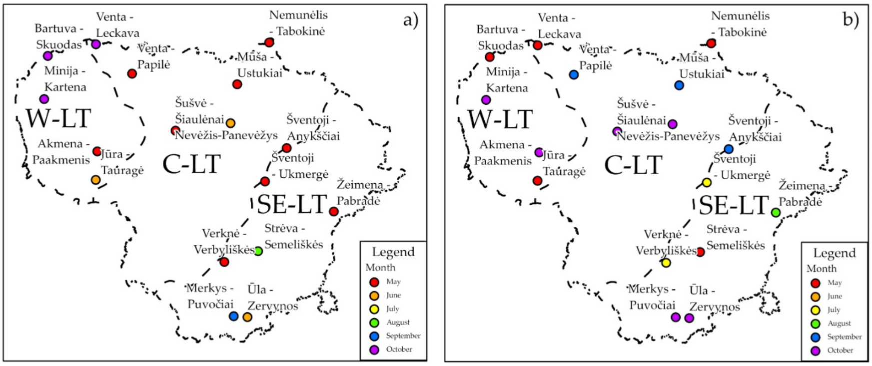

Figure 8. Distribution of rivers according to the driest months in the warm period: (**a**) SDI index with 1-month accumulation period; (**b**) SDI index with 12-month accumulation period.

For comparative analysis, it was decided to calculate the total number of Severely Dry and Extremely Dry months during the warm periods.

According to SDI-1 (Figure 9), the Western hydrological region had the lowest number of Severely Dry and Extremely Dry months, while the Southeastern hydrological region had the highest number. SDI-3 showed similar but less pronounced differences between regions. The analysis of SDI-6 revealed no significant differences between regions. According to SDI-9 and SDI-12, prolonged droughts were more prevalent in the W-LT and C-LT, while the catchments from the SE-LT had fewer dry months. From the above, it can be concluded that the SE-LT is more prone to the extreme summer droughts, which have a shorter period compared to the C-LT and W-LT. However, with a longer accumulation period, the runoff deficit decreased in the SE-LT due to its leveling by wet months. While in the W-LT and C-LT, longer periods with runoff deficit led to more prolonged droughts.

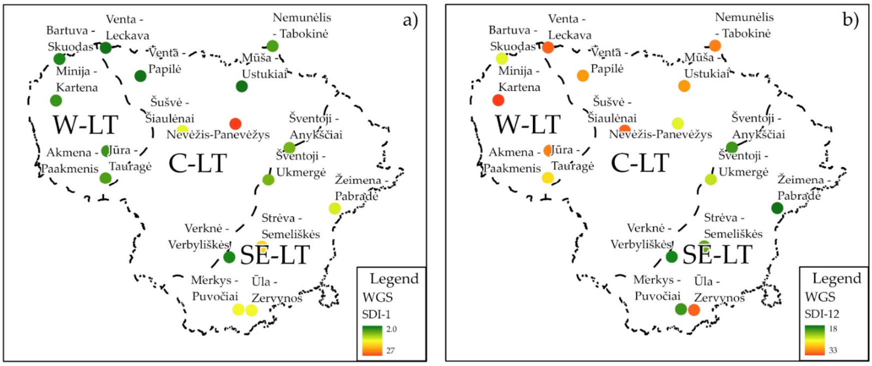

Figure 9. Distribution of rivers according to the number of driest months in the warm period for: (**a**) SDI index with 1-month accumulation period; (**b**) SDI index with 12-month accumulation period.

3.7. Analysis of Trends in Future Droughts

It was decided to use a 12-month accumulation period to analyze the projected data, as it sufficiently shows the trends in the occurrence of droughts. Moreover, due to the "smoothing", it is possible to obtain data closer to the real ones and eliminate extraordinary values.

Meteorological and hydrological indices were calculated for the period from 2021 to 2100 (in total, 80 years). The comparison was made separately for the first subperiod (the near future or the first 50% of the calculated index values) and the second subperiod (the far future or the last 50% of the calculated index values).

3.7.1. Analysis of Future Meteorological Droughts

Meteorological indices (SPI and RDI) were calculated according to two scenarios RCP 4.5 and RCP 8.5. The distribution of the SPI index values obtained based on RCP 4.5 is similar to the historical distribution of SPI index values (Figure 10a–c). In all catchments, the number of months with normal conditions decreases in the far future (Table 5). The prognosed percentage of extremely dry months (SPI-12 < -2 according to the RCP 4.5 scenario) increases in the Šventoji and Venta rivers compared to the historical period (most are concentrated in the far future), and opposite trends are observed in the Minija (Table 5).

The distribution of the SPI index values according to RCP 8.5 had more significant deviations than the historical distribution. (Figure 10d–f). As in the case of the RCP 4.5 scenario, all catchments were characterized by increasing deviations from the historical values in the far future (Table 6). Under scenario RCP 8.5, more droughts are expected in the near future, while more wet events are expected to occur in the far future.

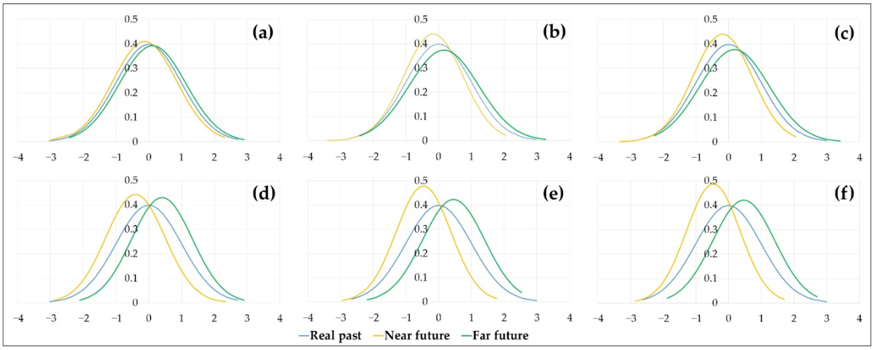

Figure 10. Deviation of SPI index with 12-month accumulation period in: (**a**) Šventoji—Ukmergė under RCP 4.5; (**b**) Venta—under RCP 4.5; (**c**) Minija—Kartena under RCP 4.5; (**d**) Šventoji—Ukmergė under RCP 8.5; (**e**) Venta—Leckava under RCP 8.5; (**f**) Minija—Kartena under RCP 8.5.

Table 5. Changes of SPI (x in Table) according to RCP 4.5.

Condition Classes	Šventoji–Ukmergė			Venta–Leckava			Minija–Kartena		
	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)
x > 2.0	2.40	1.15	1.25	1.13	0.10	1.67	1.27	0.10	1.56
1.5 < x < 2.0	4.65	1.15	1.88	4.94	1.25	2.40	5.50	1.04	3.75
1.0 < x < 1.5	8.60	4.69	6.67	11.14	3.02	7.50	10.16	3.44	6.67
−1.0 < x < 1.0	66.29	33.54	32.08	64.88	35.94	31.14	65.30	35.42	31.04
−1.0 > x > −1.5	11.43	5.41	4.69	9.87	6.15	4.06	9.59	6.77	3.96
−1.5 > x > −2.0	5.08	3.12	2.08	5.92	2.60	1.77	6.35	2.19	2.50
x < −2.0	1.55	0.94	1.35	2.12	0.94	1.46	1.83	1.04	0.52
SUM	100	50	50	100	50	50	100	50	50

The distribution of RDI index values in both RCP 4.5 and RCP 8.5 scenarios was close to the historical distribution of the data (Figure 11). The percentage of extreme droughts (RDI < −2 according to the RCP 4.5 scenario) is projected to increase compared to the historical period in all rivers (Table 7). Most months with extreme droughts are expected in the distant future.

Table 6. Changes of SPI (x in Table) according to RCP 8.5.

Condition Classes	Šventoji–Ukmergė			Venta–Leckava			Minija–Kartena		
	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)
x > 2.0	2.40	0.31	1.98	1.13	0.00	2.71	1.27	0.00	3.23
1.5 < x <2.0	4.65	0.83	2.50	4.94	0.52	5.31	5.50	0.31	4.58
1.0 < x < 1.5	8.60	1.46	9.38	11.14	1.88	6.88	10.16	2.29	7.39
−1.0 < x < 1.0	66.29	35.1	31.77	64.88	35.10	32.60	65.30	34.90	31.88
−1.0 > x > −1.5	11.43	6.67	3.54	9.87	8.75	1.77	9.59	8.65	2.50
−1.5 > x > −2.0	5.08	3.65	0.73	5.92	2.29	0.42	6.35	2.81	0.42
x < −2.0	1.55	1.98	0.10	2.12	1.46	0.31	1.83	1.04	0.00
SUM	100	50	50	100	50	50	100	50	50

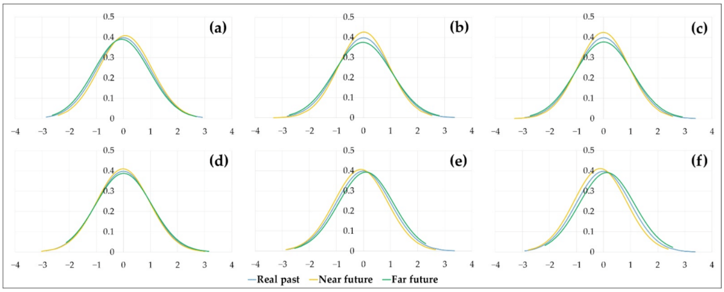

Figure 11. Deviation of RDI index with 12-month accumulation period: (**a**) Šventoji—Ukmergė under RCP 4.5; (**b**) Venta—Leckava under RCP 4.5; (**c**) Minija—Kartena RCP under 4.5; (**d**) Šventoji—Ukmergė RCP under 8.5; (**e**) Venta—Leckava under RCP 8.5; (**f**) Minija—Kartena under RCP 8.5.

Table 7. Changes of RDI (x in Table) according to RCP 4.5.

Condition Classes	Šventoji–Ukmergė			Venta–Leckava			Minija–Kartena		
	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)
x > 2.0	1.83	1.25	0.42	1.83	0.41	1.67	2.26	0.42	1.77
1.5 < x < 2.0	4.80	2.71	2.71	3.25	1.56	0.83	2.40	1.67	1.04
1.0 < x < 1.5	10.72	5.00	4.58	11.28	5.21	6.35	13.12	5.21	6.56
−1.0 < x < 1.0	65.87	34.16	33.13	67.42	36.04	31.98	62.30	35.62	31.56
−1.0 > x > −1.5	9.59	4.27	4.06	7.62	4.17	4.28	9.45	4.06	5.42
−1.5 > x > −2.0	5.22	2.40	2.81	7.19	1.88	2.92	5.78	1.98	2.50
x < −2.0	1.97	0.21	2.29	1.41	0.73	1.67	1.69	1.04	1.15
SUM	100	50	50	100	50	50	100	50	50

According to the RDI index calculated under scenario RCP 8.5, an increase in extremely wet months and a decrease in extremely dry months are expected in the Šventoji, and Minija catchments, with most extreme months concentrated in the near future (Table 8).

Table 8. Changes of RDI (x in Table) according to RCP 8.5 for three rivers.

Condition Classes	Šventoji–Ukmergė			Venta–Leckava			Minija–Kartena		
	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)
x > 2.0	1.83	1.35	2.29	1.83	0.63	1.25	2.26	0.52	1.77
1.5 < x < 2.0	4.80	1.46	1.36	3.25	2.40	4.58	2.40	2.61	3.75
1.0 < x < 1.5	10.72	4.89	3.33	11.28	4.58	4.37	13.12	4.58	5.00
−1.0 < x < 1.0	65.87	35.42	35.1	67.42	33.85	31.88	62.30	33.54	31.46
−1.0 > x > −1.5	9.59	4.17	5.00	7.62	5.73	6.15	9.45	5.73	6.25
−1.5 > x > −2.0	5.22	1.67	2.29	7.19	1.46	1.15	5.78	1.98	1.56
x < −2.0	1.97	1.04	0.63	1.41	1.35	0.62	1.69	1.04	0.21
SUM	100	50	50	100	50	50	100	50	50

As can be seen from Figures 10 and 11, the SPI and RDI meteorological indices had significant differences in data distribution, especially under the RCP 8.5 scenario. Such differences may be due to the data used to calculate these indices. In general, historical modelled precipitation data significantly differed from real observation data, while the temperature was more accurate for forecasting. Despite the quantile mapping method, these differences remained. Thus, the SPI index based solely on precipitation gave much more significant differences in data distribution. The RDI index eliminated significant precipitation deviations due to evaporation data (calculated from the temperature) and gave a more even distribution of values.

3.7.2. Analysis of Future Hydrological Droughts

According to the SDI index, calculated using the RCP 4.5 scenario, the percentage of severely and extremely dry months are projected to remain similar to the historical period in the Venta, decrease in the Šventoji and increase in the Minija (Table 9 and Figure 12a–c). In general, the number of dry months is expected to be higher in the far future. Basically, the percentage of extremely wet months should decrease in the future, compared to historical data, with the exception of the Minija (Table 9).

SDI index values calculated using RCP 8.5 scenario showed similar trends as for scenario RCP 4.5 (Figure 12). An increase in the percentage of extremely wet months compared to the historical period was estimated in the far future, while the percentage of severely and extremely dry months decreased (Table 10). It should be noted that most dry months according to the hydrological index are projected at the end of the century.

Table 9. Changes of SDI (x in Table) according to RCP 4.5.

Condition Classes	Šventoji–Ukmergė			Venta–Leckava			Minija–Kartena		
	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)
x > 2.0	1.32	0.94	0.21	1.83	0.00	0.63	0.99	0.00	1.35
1.5 < x < 2.0	6.00	3.75	2.08	4.09	3.23	2.60	3.53	2.40	2.29
1.0 < x < 1.5	10.10	7.08	3.75	9.45	5.21	3.54	11.14	5.31	4.69
−1.0 < x < 1.0	64.28	31.46	34.27	69.53	34.58	31.88	66.99	34.27	31.04
−1.0 > x > −1.5	10.98	4.38	5.52	6.35	4.48	5.10	7.19	4.27	5.42
−1.5 > x > −2.0	4.83	1.56	2.61	6.77	2.29	4.27	6.63	2.71	4.06
x < −2.0	2.49	0.83	1.56	1.97	0.21	1.98	3.53	1.04	1.15
SUM	100	50	50	100	50	50	100	50	50

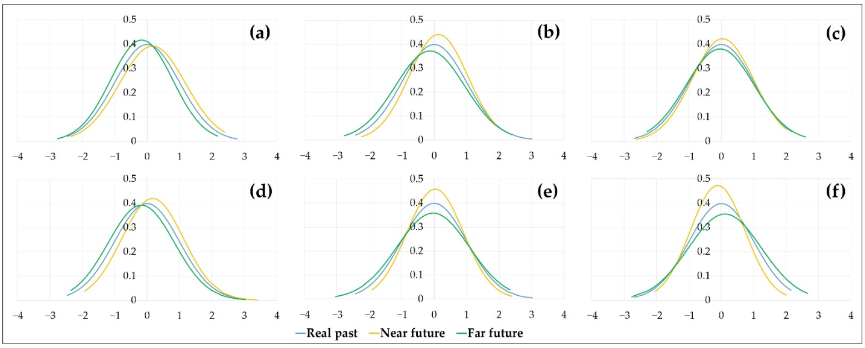

Figure 12. Deviation of SDI index with 12-month accumulation period: (**a**) Šventoji—Ukmergė under RCP 4.5; (**b**) Venta—Leckava under RCP 4.5; (**c**) Minija—Kartena under RCP 4.5; (**d**) Šventoji—Ukmergė under RCP 8.5; (**e**) Venta—Leckava under RCP 8.5; (**f**) Minija—Kartena under RCP 8.5.

3.7.3. Comparison of Rivers, According to Meteorological and Hydrological Drought Indices in Future

As noted in Section 3.7.2, most hydrological droughts are expected in the far future period. Depending on the climate scenario, each river has its unique characteristics. For example, the SDI index in the Šventoji is characterized by more extreme droughts under the RCP 4.5 scenario, as well as more extreme wet events under the RCP 8.5 scenario (Figure 13). The SDI index, based on the RCP 4.5 scenario, in the Šventoji is characterized by a higher number of severe and extreme dry months. In addition, the opposite extreme values are changing sharper too. While the RCP 8.5 scenario gives a much smaller amplitude of fluctuations most of the time.

Table 10. Changes of SDI (x in Table) according to RCP 8.5.

Condition Classes	Šventoji–Ukmergė			Venta–Leckava			Minija–Kartena		
	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)	Historical Data (1961–2020)	Near Future (2021–2060)	Far Future (2061–2100)
x > 2.0	1.32	1.35	2.08	1.83	0.94	1.99	0.99	0.10	1.98
1.5 < x < 2.0	6.00	2.08	0.83	4.09	2.81	3.23	3.53	2.08	6.04
1.0 < x < 1.5	10.10	5.00	2.50	9.45	3.86	6.04	11.14	3.44	4.69
−1.0 < x < 1.0	64.28	35.63	34.79	69.53	38.02	27.50	66.99	37.08	28.33
−1.0 > x > −1.5	10.98	5.21	5.94	6.35	3.85	6.98	7.19	5.73	6.46
−1.5 > x > −2.0	4.83	0.73	3.13	6.77	0.52	3.44	6.63	1.46	1.56
x < −2.0	2.49	0.00	0.73	1.97	0.00	0.83	3.53	0.11	0.94
SUM	100	50	50	100	50	50	100	50	50

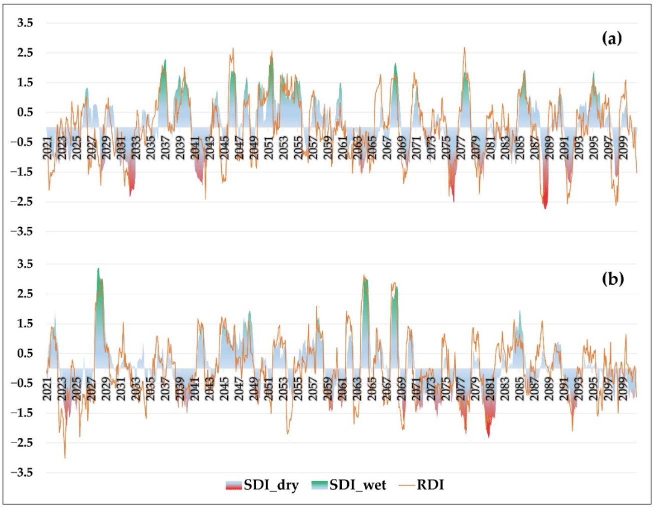

Figure 13. The Šventoji River, accumulation period 12 months: (**a**) RCP 4.5; (**b**) RCP 8.5.

The Venta is characterized by similar amplitudes of the hydrological index values of both climate scenarios (Figure 14). According to both climate scenarios, the number of hydrological droughts and the amplitude of the values will increase in the far future. As in the Šventoji, there will be more extreme droughts under the RCP 4.5 scenario.

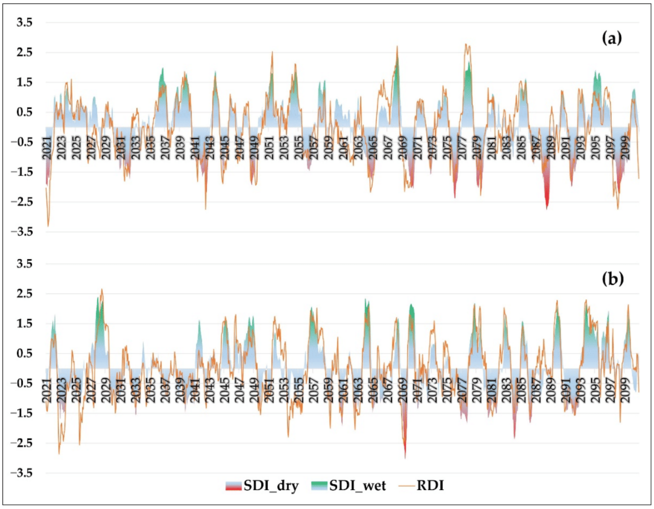

Figure 14. The Venta River, accumulation period 12 months: (**a**) RCP 4.5; (**b**) RCP 8.5.

The Minija is characterized by considerable changes in the extreme values of the hydrological index under both climate scenarios, which can be explained by the significant impact of precipitation (Figure 15). The amplitude of the values is expected to increase in the far future period. While for other rivers, under the RCP 4.5 scenario, more severe and extremely dry months are projected. In the Minija, under different scenarios, there is no significant difference in the amplitudes of the values of the hydrological index.

In general, in the near future under both climate scenarios, the Minija is more prone to droughts compared to the Venta and Šventoji, while the Šventoji is characterized by stronger wet events (Figure 16). The Šventoji will have more dry events in the far future than the Minija and Venta. An increase in the percentage of extreme droughts is projected in all rivers at the end of the century.

Comparison of the projection results with historical data (Figure 5) showed that spatial differentiation of hydrological regions will be maintained in the future. The Minija and Venta are expected to remain similar in terms of meteorological and hydrological indices. The delay of hydrological droughts from the beginning of meteorological disappears in the future or lasts no more than three months in the Minija and Venta and up to six months in the Šventoji. The wettest month SDI values for the Šventoji and Venta rivers will decrease under the RCP 4.5 climate scenario and the driest month values will become even more critical, and the opposite trend will occur for the Minija River. The amplitude between the extremely wet and dry values projections based on the RCP 8.5 climate scenario will increase compared to the historical period. According to the climate scenario RCP 8.5, the SDI values of the wettest month are expected to increase in the Šventoji River, and the values of the driest month will become less extreme. No significant changes are projected for the Minija River, except for expanding the range of maximum and minimum values. The Venta River will distinguish by a decrease in the value of the wettest month and an increase in the value of the driest month.

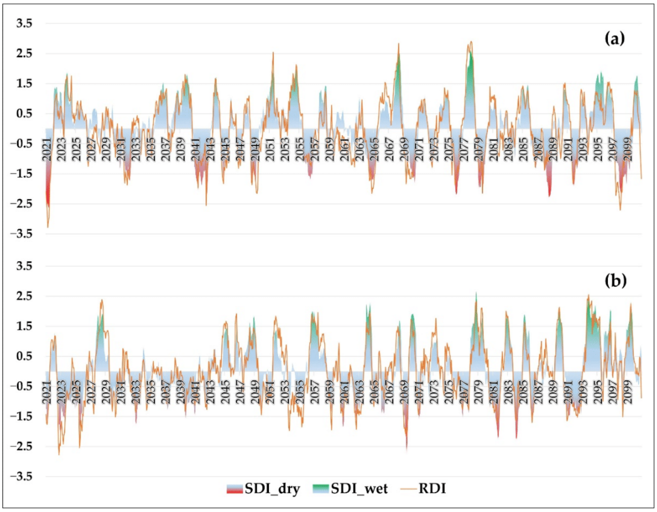

Figure 15. The Minija River, accumulation period 12 months: (**a**) RCP 4.5; (**b**) RCP 8.5.

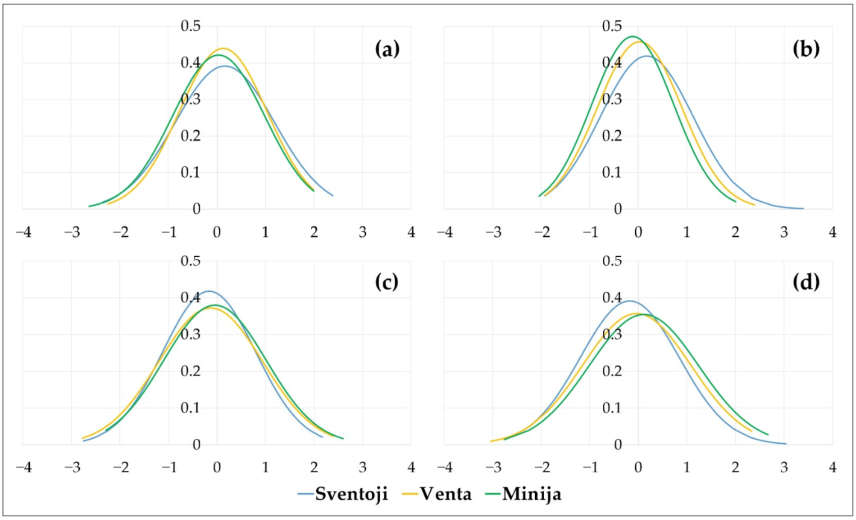

Figure 16. SDI index with 12-month accumulation period: (**a**) RCP 4.5 near future; (**b**) RCP 8.5 near future; (**c**) RCP 4.5 far future; (**d**) RCP 8.5 far future.

The RCP 4.5 scenario shows an increase in drought intensity for the rivers of the Central and Southeastern hydrological regions. The RCP 8.5 scenario projects a slight decrease in drought intensity for the rivers of the Southeastern hydrological region and an increase for the Western and Central hydrological regions.

4. Discussion

The study aimed to explore the hydrological drought phenomenon in Lithuanian lowland rivers. The problem of droughts has accompanied humanity since time immemorial. Because of the changing climate, droughts tend to get more severe and make life for humans and ecosystems even more complicated [6,63]. Research is changing the view that drought can only be described as a lack of rainfall and shows that there are still many gaps and uncertainties in our knowledge of hydrological droughts [64–67]. Every new finding and knowledge gained might help better understand the occurrence, spread, and changes of this complex phenomenon over time.

The present study revealed that the Lithuanian lowland river catchments distinguish by considerable differences in precipitation and river runoff as well as drought formation. The diversity of catchment physico-geographical features and climate variability, which mainly depends on the distance of the river catchments from the Baltic Sea, define the origin of runoff formation and make the basis for the regionalization of Lithuanian rivers. In general, the following three distinct hydrological regions: the Western, Central and Southeastern, are used in hydrological studies [68]. The present study shows that the Western region is the wettest, while the Central and Southeastern regions have almost the same amount of precipitation, with a slight predominance in the second one. Considering the river discharge, the driest years in the Western hydrological region are observed in the first half of the study period. In contrast, in the Central and Southeastern hydrological regions, in most catchments, the driest year were observed in the 21st century.

It was found that the SE-LT region is more prone to extreme summer hydrological droughts, and they have a shorter formation period compared to the C-LT and W-LT regions. However, with a longer accumulation period, the discharge deficit is reduced in the SE-LT region due to its leveling by wet months and the maintenance of a more stable water level through groundwater supply. Whereas, in the catchments of the W-LT and C-LT hydrological regions, long periods with discharge deficit lead to more prolonged droughts, as these regions are more dependent on precipitation.

These findings broadly support the results of other studies, suggesting that the identified specifics of river catchments from different hydrological regions and climatic conditions help analyze and project extreme hydrological phenomena in the conditions of changing aridity [28,29,34,69,70]. SPI and RDI parameters showed that in most cases, the number of dry months and the minimum value of the index increased with an extension of the accumulation period. These results reflect those of Kubiak-Wójcicka et al. [71], which, based on the meteorological (SPI) and hydrological (SRI) indices, revealed a weaker response to the precipitation over short time scales (1 and 3 months) and a stronger response over more extended accumulation periods (6, 9 and 12 months). The study of Minea et al. [72] also noticed that the established connection between meteorological and hydrological drought tends to be closer when longer periods (for 6 and 12-month time-scale) are considered.

The analysis on drought in a Slovakian river catchment [71] established high correlations between the SPI and SRI in more extended accumulation periods (6 to 12 months). In the present study, the highest number of strong correlations was estimated between RDI-12 and SDI-12, RDI-12 and SDI-9, SPI-12 and SDI-12. Comparing our results with [71], it was discovered that, with some exceptions, hydrological drought followed the meteorological drought with a 3-month delay. In contrast, studies of the Nemunas River basin [27] found a relatively weak correlation between the droughts (based on the SPI and SDI). Barker et al. [10] determined that catchments underlain by aquifers tended to show more delay in the propagation of drought from meteorological to hydrological drought.

For May and June, a stronger relationship was estimated between long accumulation periods (9 and 12 months). For September and October, there was a stronger relationship when the hydrological index was calculated for shorter accumulation periods (1 and 3 months) and meteorological indices with longer accumulation periods of (6, 9 and 12 months). In Kubiak-Wójcicka et al. [71] study, some high correlations were also recorded in shorter accumulation periods (1 and 3 months) in the summer (VI–VIII) and autumn (X–XI) months.

The present investigation found that the SPI index based on precipitation alone provides much more significant differences in data distribution, while the RDI index eliminates significant precipitation deviations due to evaporation data (calculated from temperature) and gives a more even distribution of values. These results are in line with those of previous studies [73–75]. This is especially true for the projection data, as precipitation is almost impossible to model correctly.

The modelling of future drought conditions showed that spatial variation between hydrological regions will be maintained in the future. The amplitude between the extremely wet and dry values of river runoff based on the RCP 8.5 will increase compared to the historical period. The projections revealed that hydrological drought intensity in the Central hydrological region is expected to increase even more under both analyzed RCP scenarios. This tendency is identified in the past and future due to specific conditions of river feeding sources (the smallest amount of precipitation and groundwater feeding in the C-LT region). This could be the reason why almost all Lithuanian intermittent rivers are located in this region [69]. In the future, the hydrological droughts are expected to be more extreme in the C-LT region, and the number of intermittent rivers may even increase. The findings from other studies suggest that, under an ongoing process of warming, the spatial aridity patterns of continentality and oceanicity are not expected to change significantly [76].

The estimated dependence of river runoff on precipitation does not necessarily indicate that there are no other important factors for runoff formation. Critical runoff values are likely to be due to other factors such as land use, water abstraction, changes in river channel morphology, reservoir regulation. Lack of information on human impact is considered an important challenge in modeling and projecting droughts [67,77].

5. Conclusions

In of this study, drought indices were calculated for 17 rivers from three hydrological regions for the period of 1961–2020. The analysis results revealed differences between hydrological regions in terms of the maximum duration of dry months for each accumulation period, extreme values of indices and the distribution of summer severe and extreme droughts by the duration of accumulation periods. A delay of 1 to 3 months was estimated between meteorological and hydrological droughts. The most extreme hydrological droughts were concentrated in the dry periods of 1961–1977, 2000–2007 and 2018–2020.

Correlation analysis showed more cases of a stronger correlation between SDI and RDI than between SDI and SPI. The largest number of significant correlations between rivers was estimated between the indices RDI-12 and SDI-9 in May, but the strongest correlation was found between the indices RDI-12 and SDI-12 ($r = 0.907$) in the same month.

Three rivers were selected to project droughts in the near (2021–2060) and far future (2061–2100) periods. The findings revealed that most droughts (meteorological and hydrological) would be observed at the end of the century. Under both climate scenarios, the amplitude between the extreme maximum and minimum values will increase. In the Venta River, there an increase in droughts is projected under both climate scenarios. In the Šventoji and Minija, the trends differ depending on the climate scenario.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. SPI parameters which present the lowest value for each catchment.

No	River-WGS	Parameters	SPI-1	SPI-3	SPI-6	SPI-9	SPI-12
		South-eastern hydrological region					
1.	Merkys-Puvočiai	Number of dry months	111/720	116//718	116/715	122/712	131/709
		Index minimum value (month)	−3.99	−3.83	−3.05	−2.95	−2.84
2.	Ūla-Zervynos	Number of dry months	110/720	116/718	118/715	121/712	131/709
		Index minimum value (month)	−4.04	−3.83	−3.06	−2.94	−2.84
3.	Verknė-Verbyliškės	Number of dry months	109/720	112/718	124/715	122/712	130/709
		Index minimum value (month)	−4.00	−3.73	−2.99	−3.10	−2.61
4.	Strėva-Semeliškės	Number of dry months	110/720	116/718	118/715	121/712	131/709
		Index minimum value (month)	−4.04	−3.83	−3.06	−2.94	−2.84
5.	Žeimena-Pabradė	Number of dry months	112/720	113/718	121/715	121/712	125/709
		Index minimum value (month)	−4.16	−3.24	−3.07	−2.74	−2.58
6.	Šventoji-Anykščiai	Number of dry months	115/720	114/718	120/715	119/712	126/709
		Index minimum value (month)	−4.14	−3.28	−3.06	−2.78	−2.63
7.	Šventoji-Ukmergė	Number of dry months	113/720	121/718	113/715	125/712	128/709
		Index minimum value (month)	−3.75	−3.56	−3.33	−3.31	−3.03
		Central hydrological region					
8.	Nevėžis-Panevėžys	Number of dry months	113/720	123/718	109/715	124/712	118/709
		Index minimum value (month)	−3.80	−2.89	−3.31	−3.50	−3.24
9.	Šušvė-Šiaulėnai	Number of dry months	106/720	112/718	115/715	123/712	127/709
		Index minimum value (month)	−4.24	−3.06	−3.09	−2.62	−2.73
10.	Nemunėlis-Tabokinė	Number of dry months	113/720	120/718	122/715	116/712	130/709
		Index minimum value (month)	−4.37	−2.96	−3.00	−2.78	−2.54
11.	Mūša-Ustukiai	Number of dry months	105/720	114/718	119/715	124/712	129/709
		Index minimum value (month)	−3.61	−3.14	−3.07	−2.54	−2.69
12.	Venta-Papilė	Number of dry months	107/720	106/718	103/715	123/712	124/709
		Index minimum value (month)	−4.40	−3.24	−3.27	−2.73	−2.66
13.	Venta-Leckava	Number of dry months	108/720	99/718	112/715	118/712	127/709
		Index minimum value (month)	−4.73	−3.51	−3.39	−2.77	−2.66
		Western hydrological region					
14.	Jūra-Tauragė	Number of dry months	114/720	115/718	121/715	123/712	115/709
		Index minimum value (month)	−4.54	−3.15	−3.27	−2.84	−3.30
15.	Akmena-Paakmenis	Number of dry months	114/720	115/718	121/715	123/712	115/709
		Index minimum value (month)	−4.54	−3.15	−3.27	−2.84	−3.30
16.	Minija-Kartena	Number of dry months	102/720	104/718	117/715	118/712	126/709
		Index minimum value (month)	−5.29	−3.46	−3.38	−2.71	−2.63
17.	Bartuva-Skuodas	Number of dry months	109/720	106/718	113/715	121/712	126/709
		Index minimum value (month)	−3.31	−3.45	−3.38	−2.81	−2.53

Table A2. RDI parameters which present the lowest value for each catchment.

No	River-WGS	Parameters	RDI-1	RDI-3	RDI-6	RDI-9	RDI-12
		South-eastern hydrological region					
1.	Merkys-Puvočiai	Number of dry months	77/561	94/667	123/715	118/712	118/709
		Index minimum value (month)	−3.67	−2.63	−2.87	−2.73	**−3.07**
2.	Ūla-Zervynos	Number of dry months	71/545	91/656	121/715	122/712	122/709
		Index minimum value (month)	−3.92	−3.84	−2.92	−2.78	−3.01
3.	Verknė-Verbyliškės	Number of dry months	77/545	95/656	118/715	116/712	118/709
		Index minimum value (month)	−3.88	−3.61	−2.83	−2.90	−2.79
4.	Strėva-Semeliškės	Number of dry months	71/545	91/656	121/715	122/712	122/709
		Index minimum value (month)	−3.92	−3.84	−2.92	−2.78	−3.01
5.	Žeimena-Pabradė	Number of dry months	78/523	98/637	124/715	117/712	126/709
		Index minimum value (month)	−3.85	−3.37	−3.14	−2.84	−2.51
6.	Šventoji-Anykščiai	Number of dry months	72/527	94/640	122/715	117/712	124/709
		Index minimum value (month)	−3.74	−3.41	−3.10	−2.85	−2.51
7.	Šventoji-Ukmergė	Number of dry months	80/537	100/648	109/715	113/712	119/709
		Index minimum value (month)	−3.13	−3.69	−2.88	−3.29	−2.85
		Central hydrological region					
8.	Nevėžis-Panevėžys	Number of dry months	72/543	94/653	104/715	121/712	116/709
		Index minimum value (month)	−3.29	−2.56	−2.96	**−3.43**	−3.01
9.	Šušvė-Šiaulėnai	Number of dry months	65/545	98/653	121/715	120/712	120/709
		Index minimum value (month)	−4.18	−3.03	−2.91	−2.58	−2.80
10.	Nemunėlis-Tabokinė	Number of dry months	79/529	100/642	115/715	115/712	118/709
		Index minimum value (month)	−3.60	−3.02	−3.04	−2.82	−2.68
11.	Mūša-Ustukiai	Number of dry months	67/546	103/655	118/715	134/712	129/709
		Index minimum value (month)	−3.61	−3.07	−2.72	−2.66	−2.75
12.	Venta-Papilė	Number of dry months	67/545	94/653	108/715	119/712	116/709
		Index minimum value (month)	−4.34	−3.16	−3.02	−2.77	−2.86
13.	Venta-Leckava	Number of dry months	76/546	92/654	111/715	114/712	115/709
		Index minimum value (month)	−4.63	−3.21	−3.36	−3.00	−2.82
		Western hydrological region					
14.	Jūra-Tauragė	Number of dry months	82/532	98/646	121/715	116/712	115/709
		Index minimum value (month)	−4.37	−3.04	−3.20	−2.77	−3.07
15.	Akmena-Paakmenis	Number of dry months	82/532	98/646	121/715	116/712	115/709
		Index minimum value (month)	−4.37	−3.04	−3.20	−2.77	−3.07
16.	Minija-Kartena	Number of dry months	74/561	81/666	111/715	114/712	120/709
		Index minimum value (month)	**−5.16**	−3.13	−3.30	−2.86	−2.91
17.	Bartuva-Skuodas	Number of dry months	77/565	81/669	104/715	112/712	116/709
		Index minimum value (month)	−3.30	−3.11	−3.29	−2.89	−2.83

Table A3. SDI parameters which present the lowest value for each catchment.

No	River-WGS	Parameters	SDI-1	SDI-3	SDI-6	SDI-9	SDI-12
		South-eastern hydrological region					
1.	Merkys-Puvočiai	Number of dry months	112/720	112/718	121/715	124/712	124/709
		Index minimum value (month)	−2.34	−2.76	−2.87	−3.01	−2.69
2.	Ūla-Zervynos	Number of dry months	108/720	112/718	114/715	118/712	120/709
		Index minimum value (month)	−2.29	−2.57	−2.71	−2.79	−2.84
3.	Verknė-Verbyliškės	Number of dry months	84/720	89/718	89/715	104/712	99/709
		Index minimum value (month)	−2.05	−2.24	−2.14	−1.99	−2.03
4.	Strėva-Semeliškės	Number of dry months	111/719	109/717	125/714	136/711	126/708
		Index minimum value (month)	−2.60	−2.43	−2.03	−2.06	−2.11
5.	Žeimena-Pabradė	Number of dry months	103/720	108/718	117/715	117/712	128/709
		Index minimum value (month)	−2.28	−2.24	−2.41	−2.28	−2.24
6.	Šventoji-Anykščiai	Number of dry months	94/715	98/709	113/700	122/691	114/682
		Index minimum value (month)	−2.08	−2.26	−2.27	−2.10	−2.39
7.	Šventoji-Ukmergė	Number of dry months	106/716	105/710	111/701	125/692	125/683
		Index minimum value (month)	−2.06	−2.56	−2.56	−2.53	−2.46

Table A3. *Cont.*

No	River-WGS	Parameters	SDI-1	SDI-3	SDI-6	SDI-9	SDI-12
		Central hydrological region					
8.	Nevėžis-Panevėžys	Number of dry months	125/720	118/718	109/715	111/712	110/709
		Index minimum value (month)	−2.59	−2.78	−3.11	−3.16	−3.05
9.	Šušvė-Šiaulėnai	Number of dry months	110/720	110/718	121/715	134/712	143/709
		Index minimum value (month)	−2.54	−2.69	−2.72	−2.80	−2.74
10.	Nemunėlis-Tabokinė	Number of dry months	112/720	115/718	116/715	121/712	124/709
		Index minimum value (month)	−2.43	−2.25	−2.18	−2.34	−2.45
11.	Mūša-Ustukiai	Number of dry months	107/720	112/718	124/715	130/712	130/709
		Index minimum value (month)	−2.17	−2.44	−2.44	−2.33	−2.72
12.	Venta-Papilė	Number of dry months	99/720	110/718	119/715	125/712	127/709
		Index minimum value (month)	−2.21	−2.64	−2.48	−2.47	−2.51
13.	Venta-Leckava	Number of dry months	109/720	119/718	118/718	114/712	107/709
		Index minimum value (month)	−2.32	−2.86	−2.74	−2.60	−2.43
		Western hydrological region					
14.	Jūra-Tauragė	Number of dry months	101/720	119/718	129/715	122/712	121/709
		Index minimum value (month)	−2.21	−2.76	−3.05	−3.05	−2.91
15.	Akmena-Paakmenis	Number of dry months	114/720	126/718	134/715	128/712	119/709
		Index minimum value (month)	−2.30	−2.68	−2.61	−2.65	−2.81
16.	Minija-Kartena	Number of dry months	114/720	125/718	127/715	119/712	123/709
		Index minimum value (month)	−2.33	−2.70	−2.66	−2.70	−2.68
17.	Bartuva-Skuodas	Number of dry months	109/708	117/704	119/698	117/692	113/686
		Index minimum value (month)	−2.27	−3.11	−2.83	−2.63	−2.54

Appendix B

Table A4. Correlation matrix between SPI and SDI indices for the Venta river.

Venta (Leckava)	V	VI	VII	VII	IX	X
SPI_1m-SDI_1m	0.438566	0.52179	0.522196	0.432577	0.511287	0.517274
SPI_3m-SDI_1m	0.439635	0.677741	**0.729274**	**0.733918**	**0.74253**	**0.739166**
SPI_6m-SDI_1m	0.113354	0.494797	0.601909	**0.748575**	**0.757464**	**0.847492**
SPI_9m-SDI_1m	0.081331	0.405502	0.6076	0.578648	0.634412	**0.770859**
SPI_12m-SDI_1m	0.081105	0.268421	0.460981	0.507884	0.516487	**0.722681**
SPI_1m-SDI_3m	0.035133	−0.0408	0.171667	0.155903	0.393833	0.286132
SPI_3m-SDI_3m	0.46934	0.283162	0.48995	0.610626	**0.724616**	0.686152
SPI_6m-SDI_3m	0.300222	0.00152	0.490719	**0.718403**	**0.776125**	**0.826458**
SPI_9m-SDI_3m	0.304656	−0.10348	0.410175	0.636726	0.671734	**0.739972**
SPI_12m-SDI_3m	0.360282	0.01429	0.262677	0.551994	0.594173	0.69634
SPI_1m-SDI_6m	0.032039	0.221978	0.026692	0.035433	0.372737	0.263181
SPI_3m-SDI_6m	0.431848	0.315926	0.27886	0.170803	0.356854	0.579309
SPI_6m-SDI_6m	0.699706	0.69863	0.57025	0.433641	0.501551	**0.75319**
SPI_9m-SDI_6m	**0.793667**	0.694251	0.60626	0.390036	0.33608	**0.711345**
SPI_12m-SDI_6m	**0.828129**	**0.724013**	0.560023	0.373205	0.22315	0.66654
SPI_1m-SDI_9m	−0.04632	0.145703	0.100638	−0.05173	0.253752	0.216767
SPI_3m-SDI_9m	0.232695	0.136184	0.251505	0.211968	0.270961	0.420208
SPI_6m-SDI_9m	0.457959	0.429043	0.423859	0.457612	0.418885	0.565521
SPI_9m-SDI_9m	**0.758522**	0.682662	0.661398	0.694014	0.674152	0.673338
SPI_12m-SDI_9m	**0.882964**	**0.856286**	**0.804855**	**0.748443**	0.699335	**0.718789**
SPI_1m-SDI_12m	−0.04585	0.132035	0.103784	−0.03116	0.147464	0.170617
SPI_3m-SDI_12m	0.228471	0.109841	0.203879	0.186348	0.219857	0.304002
SPI_6m-SDI_12m	0.438818	0.381528	0.339196	0.321838	0.279446	0.435852
SPI_9m-SDI_12m	**0.736912**	0.624787	0.562608	0.500811	0.469398	0.509169
SPI_12m-SDI_12m	**0.883212**	**0.852088**	**0.783614**	**0.718392**	0.682026	0.692041

Table A5. Correlation matrix between RDI and SDI indices for the Venta river.

Venta (Leckava)	V	VI	VII	VII	IX	X
SPI_1m-SDI_1m	0.422751	0.538263	0.527077	0.453273	0.533017	0.455596
SPI_3m-SDI_1m	0.582746	0.681573	**0.75476**	**0.756971**	**0.776756**	**0.743278**
SPI_6m-SDI_1m	0.370211	0.606282	0.672286	**0.8092**	**0.805992**	**0.881525**
SPI_9m-SDI_1m	0.285118	0.498874	0.69302	0.680835	**0.73178**	**0.829062**
SPI_12m-SDI_1m	0.225049	0.349344	0.535786	0.618231	0.626306	**0.795132**
SPI_1m-SDI_3m	0.011056	−0.0291	0.180125	0.172375	0.402495	0.232847
SPI_3m-SDI_3m	0.506038	0.429392	0.425472	0.126592	−0.05476	−0.09243
SPI_6m-SDI_3m	0.44694	0.151508	0.598191	**0.780142**	**0.820816**	**0.870169**
SPI_9m-SDI_3m	0.403485	0.036881	0.530402	**0.737399**	**0.758702**	**0.81402**
SPI_12m-SDI_3m	0.477185	0.17955	0.363737	0.655712	0.69666	**0.785597**
SPI_1m-SDI_6m	0.001228	0.224248	0.056605	0.05283	0.38707	0.229194
SPI_3m-SDI_6m	0.297243	0.39832	0.462469	0.465396	0.313494	0.130515
SPI_6m-SDI_6m	0.621902	0.677149	0.628834	0.497074	0.242101	0.270968
SPI_9m-SDI_6m	**0.703749**	0.652796	0.667311	0.50781	0.471564	**0.798675**
SPI_12m-SDI_6m	**0.812572**	**0.713131**	0.616483	0.490953	0.370681	**0.768149**
SPI_1m-SDI_9m	−0.08721	0.151522	0.10543	−0.03842	0.246979	0.178806
SPI_3m-SDI_9m	0.128766	0.15413	0.164223	0.288418	0.333946	0.30909
SPI_6m-SDI_9m	0.398717	0.440392	0.497524	0.639634	0.652861	0.532271
SPI_9m-SDI_9m	**0.708252**	**0.737927**	**0.733605**	**0.706605**	0.624919	0.488545
SPI_12m-SDI_9m	**0.900809**	**0.870797**	**0.828021**	**0.758949**	**0.723791**	**0.7894**
SPI_1m-SDI_12m	−0.09215	0.137399	0.105944	−0.01863	0.13692	0.141561
SPI_3m-SDI_12m	0.128035	0.143992	0.132195	0.133378	0.126168	0.105677
SPI_6m-SDI_12m	0.384629	0.403476	0.41951	0.429169	0.44735	0.463396
SPI_9m-SDI_12m	0.69338	**0.706672**	**0.707485**	**0.719752**	**0.713447**	0.671286
SPI_12m-SDI_12m	**0.906566**	**0.907277**	**0.896123**	**0.888607**	**0.860717**	**0.781048**

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Article

The Development of a Hydrological Drought Index for Lithuania

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Abstract: Recently, the number and intensity of hydrological droughts have been increasing; thus, it is necessary to identify and respond to them quickly. Since the primary hydrological data in Lithuania are water levels, and converting these data into discharge takes additional time, there is a need to develop a methodology or adapt these data to analyze and detect hydrological droughts. This paper examines the concept of the standardized water level index (SWLI) calculation, which is based on the standardized precipitation index (SPI) and streamflow drought index (SDI) methods. SDI and SWLI data were compared; SWLI was used to analyze the situation in the past and future. A total of 15 main sub-basins were considered, and the future discharge of three rivers was estimated; SWLI showed good compatibility with SDI. To better analyze droughts, the use of severe drought threshold values (SDTV) was suggested as some river data (especially those for small rivers) needed to be corrected due to dense riverine flora. The dry years and trends identified by SWLI are consistent with previous studies.

Keywords: hydrological droughts; Lithuanian rivers; HBV model; SWLI; SDI; trends; projections

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1. Introduction

Most European countries are considered to have sufficient water resources; however, water scarcity and droughts are increasing and spreading. From 1980–2020, the total economic loss from weather- and climate-related events was EUR 450–520 billion (in 32 countries of the European Economic Area [1]). Climate change, global warming and human activity may unprecedentedly exacerbate the problem of drought [2–4].

Even among drought experts, there is no single definition of drought that everyone would agree on [5–7]. Water Directors within the CIS (a Common Strategy for the implementation of the Water Framework Directive) process have decided on the following definition of drought: it is a temporary, negative and severe deviation along a significant period and over a large region from average precipitation values (a rainfall deficit), which may lead to meteorological, agricultural, hydrological and socio-economic drought, depending on its severity and duration [8]. Water deficit typically propagates through the hydrological cycle, impacting different ecosystems and human activities accordingly [9].

Accomplished studies challenge the view that hydrological drought can only be described as a lack of precipitation and show many gaps and uncertainties in our knowledge of this extreme event. A number of interrelated phenomena may cause hydrological drought [10,11]; many efforts are being made to study the various aspects of droughts and aim to provide early warning and information to decision-makers, policy-makers, water managers, water users and the general public about droughts. To prevent or at least mitigate the effects of a drought, it is necessary to understand this phenomenon, identify its signs as quickly as possible and prepare for a drought's impact [12–14].

Scientists have developed numerous methods to identify hydrological drought. Criteria for identifying an impending hydrological drought and its beginning or end can include the simplest indicators (e.g., river or groundwater level, flow rate) or complex drought indices (e.g., aggregate dryness index, palmer hydrological drought severity index, surface water supply index) that require several or more indicators. When managing drought, it is convenient to use indices to reduce the complex problem to one single number. However, water managers should be cautious in choosing indices [6,15]. It would be beneficial to develop a composite drought index that integrates all relevant data and drought descriptions, considering the predominant types of droughts in time and space and climate change scenarios [16]. However, a recent report published by the Intergovernmental Panel on Climate Change [4] warns that droughts are a complex and difficult-to-predict natural phenomenon, and that differences between drought types are not unambiguous and cannot be described by a single universal definition or directly measured by a single variable. The National Meteorological and Hydrological Services around the world are encouraged to use the standardized precipitation index (SPI) to characterize meteorological drought; however, a comprehensive indicator to describe agricultural and hydrological droughts still needs to be proposed [17].

Although Lithuania belongs to a humid continental climate, the drought phenomenon is quite well known. The recent dry and warm summers are causing major changes in river runoff. For three consecutive summers of 2018–2020, a hydrological drought for the entire country was declared. Although scientific studies based on available observational data do not reveal clear trends in rising dryness and extreme droughts [18,19], end-of-century climate change may enhance the likelihood of more intense and frequent meteorological droughts, which may increase the threat of hydrological droughts [20,21]. Rising warm-season temperatures and consequent increasing evaporation are likely to have a particular impact on runoff during the warm season, which is a critical time for water users and aquatic ecosystems, even under normal climatic conditions. With the growing evidence of climate change, Lithuanian scientists have been paying closer attention to droughts in recent years. The meteorological effective drought index (EDI) proposed by Byun and Wilhite [22] was used to identify hydrological drought during the warm period [23]. A study of drought dynamics during the warm period of the year using the meteorological standardized precipitation index (SPI) proposed by McKee et al. [24] and the hydrological standardized water level index offered by Nalbantis and Tsakiris [25] was carried out [19]. The suitability of the hydrological standardized runoff index (SRI) proposed by Shukla and Wood [26] to determine hydrological drought was also investigated [27]. The ability of the analyzed indices to identify hydrological droughts in Lithuanian rivers mainly depended on the nature of river feeding, e.g., some indices performed better on groundwater-fed rivers and others on snowmelt-fed rivers. To our knowledge, thus far, only one scientific study has been devoted to assessing hydrological drought in Lithuania using river water levels [28]. This study aimed to identify the warm-period hydrological drought cases in Lithuania using the streamflow drought index (SDI; calculated based on discharge data) and standardized water level index (SWLI; calculated based on water level data) to compare and evaluate the possibilities of their practical application. The findings based on data from seven rivers (eight water gauging stations) revealed that a modified SDI methodology based on water level data (i.e., SWLI) could become a good alternative for detecting hydrological droughts in Lithuania.

As the operational information of the hydrology network in Lithuania consists of (hourly) water level data, it should be used to characterize the hydrological drought and declare the state of severe hydrological drought. Such an assessment has a significant advantage. Water levels can be easily measured directly, while discharge is estimated indirectly from the water level using a water level-discharge ratio. This study aimed to analyze the past conditions of hydrological drought and project future drought scenarios for the entire territory of Lithuania based on its major sub-basins using the improved methodology for calculating the standardized water level index (SWLI).

2. Materials and Methods

2.1. Study Area and Data

Lithuania is located on the eastern coast of the Baltic Sea. It covers an area of 65,200 square kilometers and is the largest and southernmost of the three Baltic States. It is a country of plains (the highest point being 294 m above sea level) with more than 22,000 rivers and rivulets having a total length of over 77,000 km [29]. According to the Köppen-Geiger climate classification, Lithuania belongs to a humid continental climate. It falls into the water surplus zone as the annual ratio of precipitation to evaporation is 1.47. The annual river runoff varies from 4.2 to 14.0 L/(s·km^2) and depends on the distance from the sea, topographic features, catchment morphology, lithology, underground feeding patterns, etc. The Nemunas River is a major Lithuanian river. It is 937 km long and drains approximately 98,000 square kilometers (46,600 km^2 belongs to Lithuania and comprises 72% of its territory). Its average multiannual discharge at Smalininkai is 540 m^3/s. The longest and largest Nemunas tributaries in Lithuania (in terms of catchment area) are Šventoji, Neris, Nevėžis, Šešupė, Merkys, Jūra and Minija. Typically, the annual hydrograph of the Lithuanian river consists of the peak discharge in early spring, indicating the maximum amount of water in the river bed due to spring snowmelt flooding; additional, less significant peak discharges (due to flash floods) may be observed in late summer or autumn, but the discharge remains mostly low throughout the warm period. In the warm period, in the small rivers and streams, the phenomenon of flow intermittency can be observed under certain physical-geographical conditions. It was estimated that the maximum duration of flow intermittency could range from 6 to even 152 days [30].

The study of the hydrological drought was based on streamflow records from 15 river catchments (Figure 1). These rivers were chosen to represent the main sub-basins of Lithuania because (i) they are semi-natural (i.e., the least anthropogenically affected), (ii) they have 30 years (1991–2020) of observational data series, and (iii) their discharge data (based on the stage-discharge curve, Q-H) are the most accurate and reliable in the sub-basin. The list of selected rivers and their gauging stations is given in Table 1. The above data were received from the Lithuanian Hydrometeorological Service (LHMT). Monthly precipitation and air temperature data from the observational period of 1991–2020 needed for modeling were also obtained from LHMT.

Table 1. List of the studied water gauging station (WGS) catchments and their main characteristics (1991–2020).

№	River	WGS	Abbreviation	Sub-Basin	WGS Catchment Area, km^2	Qav *, m^3/s	Q30 **, m^3/s	Qav/Q30
1	Nemunas	Smalininkai	Nem-Sma	Nemunas and its small tributaries	81,200	479.9	259.3	1.85
2	Merkys	Puvočiai	Mer-Puv	Merkys	4300	32.1	21.8	1.47
3	Neris	Jonava	Ner-Jon	Neris and its small tributaries	24,600	162.6	89.6	1.81
4	Žeimena	Pabradė	Zei-Pab	Žeimena	2580	20.2	11.9	1.70
5	Šventoji	Ukmergė	Sve-Ukm	Šventoji	5440	41.1	16.3	2.52
6	Nevėžis	Panevėžys	Nev-Pan	Nevėžis	1090	6.1	1.1	5.55
7	Dubysa	Lyduvėnai	Dub-Lyd	Dubysa	1070	8.2	1.9	4.32
8	Mituva	Žindaičiai	Mit-Zin	Mituva	403	2.6	0.1	26.00
9	Šešuvis	Skirgailai	Ses-Ski	Jūra	1880	14.7	2.3	6.39
10	Minija	Kartena	Min-Kar	Minija	1230	16.7	2.7	6.19
11	Svyla	Guntauninkai	Svy-Gun	Dauguva	148	0.9	0.023	39.13
12	Nemunėlis	Tabokinė	Nem-Tab	Nemunėlis	2690	20.2	2.9	6.97
13	Mūša	Ustukiai	Mus-Ust	Mūša	2280	10.1	1.3	7.77
14	Venta	Leckava	Ven-Lec	Venta	4060	28.2	4.4	6.41
15	Bartuva	Skuodas	Bar-Sku	Lithuanian coastal rivers	612	7.1	0.6	11.83

Notes: * Qav—average discharge for 30 years (1991–2020). ** Q30—average of annual 30-day minimum discharge in the warm period (1991–2020).

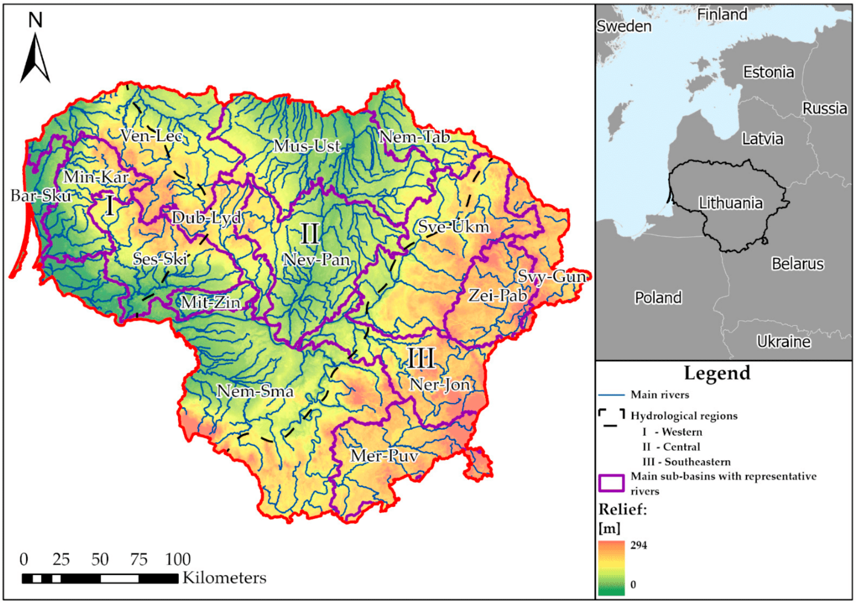


Figure 1. Fifteen main river catchments of Lithuania used in the analysis.

2.2. Methods

2.2.1. Calculation of Hydrological Drought Indices

The standardized water level index (SWLI) proposed by [28] and streamflow drought index (SDI) developed by Nalbantis and Tsakiris [25] were used to identify hydrological droughts in Lithuanian rivers. These indices are based on the measured water level (SWLI) and discharge (SDI) values. Since these indices are based on the SPI calculation methodology, the minimum time period for calculation should be identical. For SPI, it is 30 years [24]. According to this, we used the same minimum period. A drought of a relevant magnitude is recorded when the index value is lower than −1.0 [15]. The essence of indices is that they calculate anomalies of a certain magnitude (of water level or discharge) over a selected period based on a comparison of that magnitude using data from a long-term period. As an input, daily water level and discharge data were used; a 10-day accumulation period was also selected.

SWLI and SDI were calculated as follows:

$$SWLI = \frac{H_{i,j} - H_j}{\sigma_{j(H)}}, \quad (1)$$

$$SDI = \frac{Q_{i,j} - Q_j}{\sigma_{j(Q)}}, \quad (2)$$

where $H_{i,j}$ and $Q_{i,j}$ indicate the water level and discharge for a given 10-day period, respectively, H_j and Q_j indicate the multiannual decadal values of the mean water level and discharge, respectively, $\sigma_{j(H\ or\ Q)}$ indicate the standard deviation of the multiannual mean

H_j or Q_j and i equals a period of 10 days. All received data were checked for normality and, for that, we devised data distribution histograms and calculated the Shapiro-Wilk test for smaller samples from the main data set; all results confirmed the data normality.

An index value below zero indicated hydrological drought. The state of hydrological drought is defined as follows: the average drought is when $-1.49 < \text{SDI} < -1.0$, severe drought is when $-1.99 < \text{SDI} < -1.5$ and extreme drought is when $\text{SDI} < -2.0$ [25]. Because SWLI and SDI values are indicated as standard deviations from the long-term mean, they can be used to compare anomalies over any period.

In operational work, to identify hydrological droughts, it would be more rational to use a standardized water level index (SWLI), which is calculated from directly measured water level values. Although discharge better describes the water content in rivers and their ecological conditions, it is determined indirectly from water level data. However, the drought estimated according to water levels must also match the actual water conditions as the drought indicated by discharge. Theoretically, the SWLI and SDI values must have a linear (1:1) relationship. Deviations from this relationship may be due to various processes taking place in the river bed (e.g., development of aquatic vegetation, bottom deformation, etc.); therefore, the relationship needs to be adjusted for objectivity. Thus, we could not use the usual scale to assess severe drought through the SWLI index.

To determine the extent to which the correlation curves of SWLI and SDI varied from linear dependence (y = x) in each river, calculations were performed by inputting an x-value (SDI coefficient) of −1.5 (this value represents the threshold for severe drought in the SDI index and theoretically should be the same for the SWLI index) into the equation of determination. According to this, the new severe drought threshold values (SDTV) were used for SWLI using equations of determination.

2.2.2. Preparation of Climate Change Models

To predict future drought trends, three regional climate models (RCM) were chosen for data preparation and analysis (Table 2). A more detailed description of the selection process of regional climate models suitable for the conditions of Lithuania is provided in a previous article [31]. The two most commonly used RCP scenarios (RCP4.5 and RCP8.5) [4] were applied to analyze drought evolution in the future.

Table 2. Main information about chosen RCMs.

№	Driving Model	RCM	Institute	Resolution	Ensemble
1	CNRM-CERFACS-CNRM-CM5	RCA4	SMHI	0.11°	r1i1p1
2	ICHEC-EC-EARTH	RACMO22E	KNMI		
3	MPI-M-MPI-ESM-LR	REMO2009	MPI-CSC		

The models mentioned above were extracted from the EURO-CORDEX database (www.euro-cordex.net (accessed on 21 October 2022)). Daily temperature and precipitation data were used to calculate river discharge. It was decided to use the quantile mapping method to adapt climate data to Lithuanian conditions [32,33]:

$$St^{Obs} = h\left(St^{CM\ RP}\right) = ECDF^{OBS-1}\left(ECDF^{CM\ RP}\left(St^{CM\ Fut}\right)\right) \quad (3)$$

where St^{Obs} indicates the observed meteorological parameter, $St^{CM\ RP}$ indicates the climate model output for the reference period, $ECDF^{OBS}$ indicates the empirical cumulative distribution function for an observed period, $ECDF^{CM\ RP}$ indicates the empirical cumulative distribution function for the climate model reference period and $St^{CM\ Fut}$ indicates the meteorological parameter, which is modeled by the climate model for the future period [32,33].

2.2.3. Discharge Projections Using the HBV Model

The drought projections were made for three rivers using the HBV hydrological model. This software was created by the Swedish Meteorological Hydrological Institute (SMHI) [34]. HBV is a rainfall-runoff modeling technique applied to calculate the total water balance in a catchment. For the modeling process, it is necessary to specify the following characteristics of the watershed: total area of the watershed, area of territories covered by forests and under lakes, height above sea level, daily flow of rivers and daily values of precipitation and air temperature for the area in the simulated watershed [21]. The HBV model is based on the water balance equation [35]:

$$P - E - Q = \frac{d}{dt}[SP + SM + UZ + LZ + V], \quad (4)$$

where P indicates precipitation, E indicates evaporation, Q indicates discharge, SM indicates soil moisture, SP indicates snow-pack, UZ indicates groundwater zone, LZ indicates lower groundwater zone and V indicates lake or dam volume. The computations were carried out in three steps: (i) estimation of the amount of precipitation reaching the ground; (ii) estimation of slope runoff; and (iii) estimation of runoff in the watercourse and runoff transformation. For such a complex model, a data set of physical-geographical data from the CORINE database was also used for each river (Table 3). Their processing was performed using the ArcGIS software.

Table 3. Main characteristics of the selected river catchments.

River—WGS	Land Use Characteristic		
	Lakes, %	Wetland, %	Forests, %
Nemunas-Smalininkai	1.17	0.82	48.50
Žeimena-Pabradė	9.28	1.29	60.07
Šešuvis-Skirgailiai	1.07	0.69	23.21

Since the main task of this work was to study the drought of the warm period (May–October), the main emphasis during calibration was on the parameters responsible for the runoff formation in the summer period and the baseflow. In addition, 19 main parameters were used to calibrate the developed catchment-based hydrological models. Calibration was performed in the recommended order by the software developers [35]: volume parameters, snow parameters, soil parameters, response parameters and damping parameters. The primary focus was on parameters that directly impact warm-season runoff, such as maximum soil moisture storage (fc), percolation capacity (perc) and recession of summer and autumn discharge (khq, k4), among others. The suitability and quality of the developed hydrological models were confirmed by the strong correlation between the measured and calculated water discharges (r were higher than 0.7) (Table 4).

Table 4. Results of calibration and validation of hydrological models.

River—WGS	Calibration (1986–1995)			Validation (1996–2005)		
	r	NSE *	RE, %	r	NSE	RE, %
Nemunas-Smalininkai	0.84	0.706	−0.6	0.81	0.700	0.7
Žeimena-Pabradė	0.87	0.765	−5.7	0.81	0.717	3.2
Šešuvis-Skirgailiai	0.88	0.779	3.1	0.87	0.786	−0.8

Notes: * Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance [36].

3. Results

Based on SDI and SWLI indices, 15 rivers with a 30-year data set (from 1991 to 2020) were selected for drought analysis. Additionally, three rivers were chosen for analysis in the near (2021–2060) and distant (2061–2100) future.

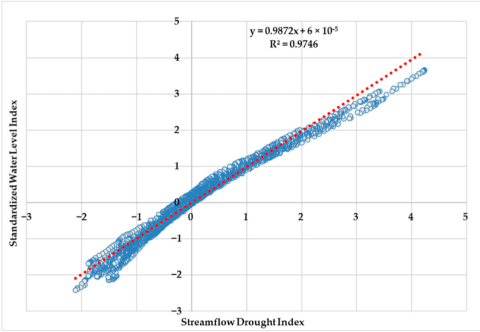
3.1. Assessment of the Suitability of SDI and SWLI in Lithuania

Based on the hydrological data of 15 water gauging stations (WGS) of Lithuanian rivers, the suitability of two selected hydrological drought indices—the standardized water level index (SWLI) and streamflow drought index (SDI)—was investigated. The values of these indices were expected to have a linear relationship (y = x), in which case, SWLI could be directly applied to identify hydrological droughts. All established linear equations had different coefficients and free terms, i.e., they indicated the absence of a clear linear relationship. The linear relationships (Figure 2) showed that the SWLI and SDI indices evaluated drought differently due to the differences in the range of negative values. Therefore, corrections were made to use the SWLI index to identify drought. The SWLI corresponding to the limit value of severe hydrological drought (according to SDI, i.e., when SDI = −1.5; Table 5) was calculated from the equations of the correlation curves between the mentioned indices in the studied rivers.

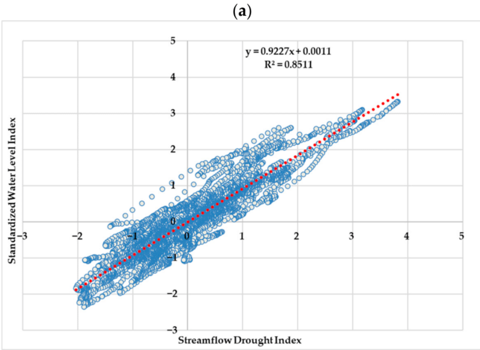
Table 5. Coefficients of determination between SWLI and SDI values; SDTV according to SWLI.

№	WGS	R^2	SDTV
1	Nem-Sma	0.97	−1.48
2	Mer-Puv	0.85	−1.38
3	Ner-Jon	0.95	−1.46
4	Zei-Pab	0.85	−1.38
5	Sve-Ukm	0.77	−1.32
6	Nev-Pan	0.89	−1.41
7	Dub-Lyd	0.82	−1.27
8	Mit-Zin	0.91	−1.40
9	Ses-Ski	0.92	−1.43
10	Min-Kar	0.91	−1.42
11	Svy-Gun	0.95	−1.41
12	Nem-Tab	0.90	−1.41
13	Mus-Ust	0.78	−1.32
14	Ven-Lec	0.91	−1.43
15	Bar-Sku	0.81	−1.34

The number of dry events for each month was calculated. It was found that May had the highest number of severely dry days in Lithuania during the warm period. This trend was observed for seven out of 15 rivers investigated in Figure 3a. The greatest number of severely dry days over a 30-year period was also estimated in May, as shown in Figure 3b. October had the lowest number of severely dry days according to the SWLI (SDTV) index, and there were no significant changes during the June–September period. This distribution was caused by the physical-geographical and climatic characteristics of each individual sub-basin and the influences of other sub-basins, as in the cases of the Nemunas and Neris rivers. Figure 3c,d depict the distribution of severely dry days for the Nemunas and Žeimena rivers and provide the ratio of dry days between the two indices, SDI and SWLI. Although the SWLI index and SWLI with SDTV threshold indicated a higher number of severe drought events, the general trends persisted with SDI.



(**a**)



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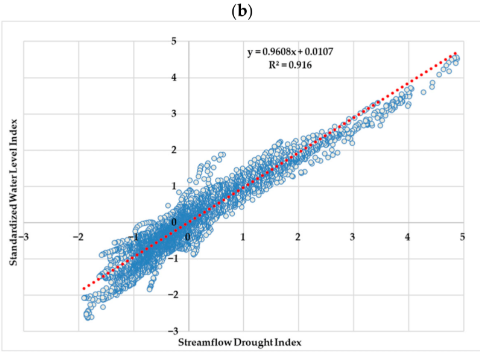


(**c**)

Figure 2. Relationships between SWLI and SDI with equations and coefficients of determination: (**a**) Nemunas-Smalininkai; (**b**) Žeimena-Pabradė; (**c**) Šešuvis-Skirgailiai. The red dotted lines represent the trend lines for data set.

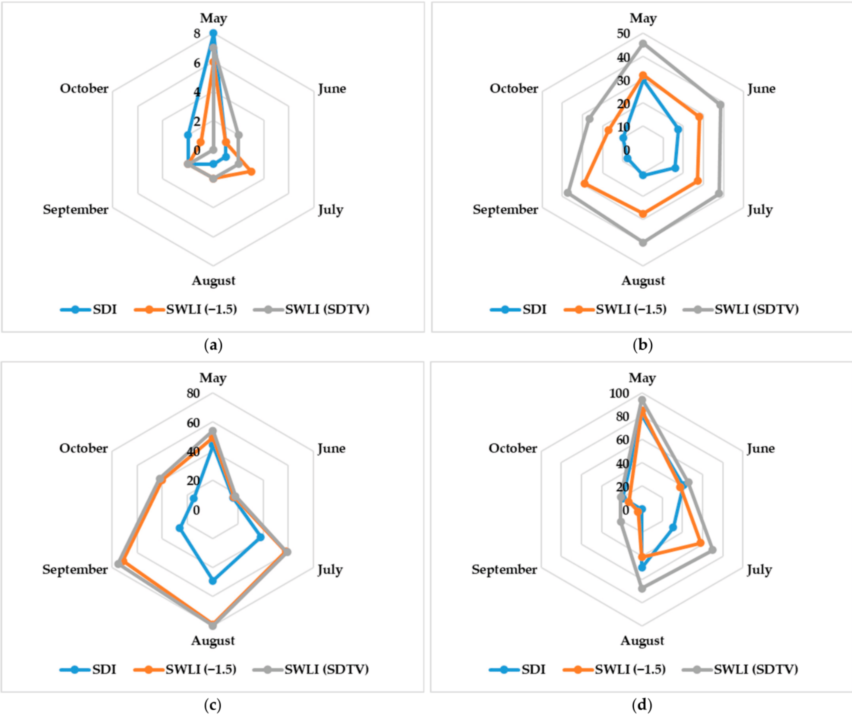
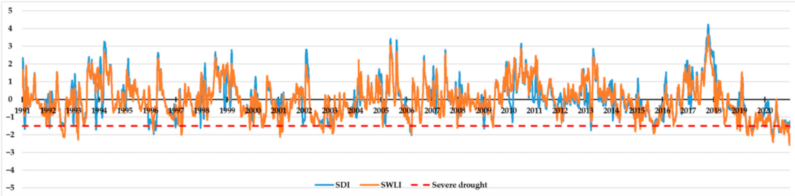


Figure 3. Comparison between SWLI and SDI: (**a**) the number of rivers with the driest months (the largest number of severely dry days); (**b**) average number of severely dry days by month (during 1991–2020) for rivers within Lithuania; (**c**) Nemunas-Smalininkai; (**d**) Žeimena-Pabradė.

3.2. Analysis of Hydrological Drought in Lithuania Using SWLI

As mentioned above, 15 representative rivers were analyzed using the SWLI index. Fluctuations of the SWLI and SDI indices are presented in Figure 4. Several severe droughts were observed in most rivers: the first quarter of 1996 (corresponds to the cold period), the first quarter of 2003 (corresponds to the cold period), the end of 2005 and most of 2006, and short-term periods of severe drought during 2013–2016. Additionally, from mid-2018, the SWLI index had practically no positive values. The prolonged wet period with maximum values from the middle of 2017 (lasting from 6 to 12 months), which preceded the drought in 2018–2020, should also be noted.

The number of days with a drought index lower than −1.5 (in the warm period) was estimated for each river (Figure 5). During the observed 30 years, drought was most widespread in 2006, 2019 and 2020, but the driest period occurred in 2019. Local, prolonged phenomena of severe drought were also found in 1992 and 2002. It should be emphasized that a general trend of an increase in severely dry days was observed.



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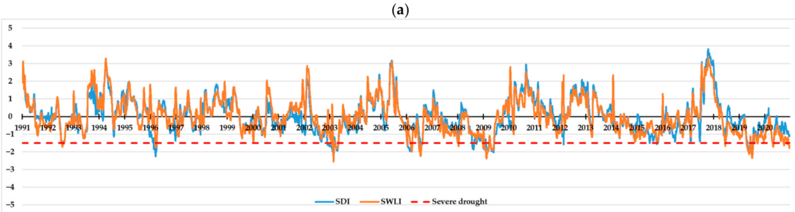

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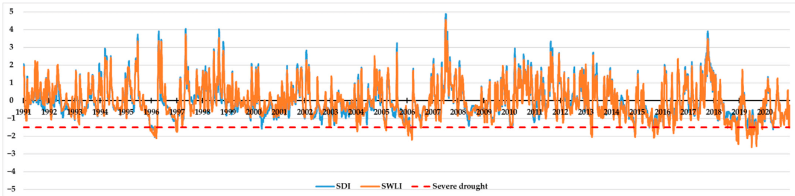


(**c**)

Figure 4. Comparison between SWLI and SDI over 30 years: (**a**) Nemunas-Smalininkai; (**b**) Žeimena-Pabradė; (**c**) Šešuvis-Skirgailai.

Year:	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	SUM
Nem-Sma	0	65	0	0	0	0	0	0	0	6	0	41	0	0	0	0	0	0	4	0	0	0	0	0	35	2	0	0	92	83	328
Mer-Puv	0	4	0	0	0	0	0	0	19	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	24	8	0	0	83	161	304
Ner-Jon	0	61	33	0	0	7	10	0	6	15	0	40	4	0	0	0	0	0	37	0	0	0	0	0	13	0	0	0	82	17	325
Zei-Pab	0	48	0	0	0	0	0	0	0	0	0	0	16	0	0	57	0	0	42	0	0	0	0	0	3	0	0	14	100	40	320
Sve-Ukm	54	134	59	13	0	0	0	0	3	8	0	0	3	0	0	49	9	4	35	0	0	0	0	2	0	0	0	0	6	14	393
Nev-Pan	0	0	0	0	0	0	0	0	0	6	0	25	30	10	10	112	0	0	0	0	0	0	0	0	1	11	0	36	131	59	431
Dub-Lyd	0	2	30	0	0	0	0	0	0	3	0	0	0	0	0	24	0	4	0	0	0	0	0	0	0	0	0	0	16	9	88
Mit-Zin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	15	0	5	0	0	0	0	0	6	0	0	0	14	7	17	72
Ses-Ski	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	5	48	9	0	14	114	8	210
Min-Kar	0	0	3	10	0	0	0	0	0	5	0	13	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	9	0	51
Svy-Gun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
Nem-Tab	0	8	35	0	0	11	0	0	1	21	0	48	0	2	0	28	0	0	0	0	0	0	0	0	0	0	0	0	13	4	171
Mus-Ust	0	30	5	0	0	0	0	0	68	0	0	126	12	0	0	30	0	15	0	0	0	0	0	0	17	0	0	0	16	5	324
Ven-Lec	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39	0	0	0	0	0	0	0	0	24	4	0	34	57	60	218
Bar-Sku	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	3	10	0	0	0	17	15	0	0	5	24	52	142

Figure 5. Temporal distribution of hydrological droughts according to SDTV. For each river the number of dry days were represented by color scale, where green—year without dry days and red—the highest number of dry days per year.

Certain patterns can be distinguished if we consider the spatial distribution of droughts (Figure 6). From 1991 to 1995, the highest number of severe and extreme hydrological droughts was concentrated in the southeastern hydrological region. Between 2001 and 2010, most droughts occurred in the central hydrological region. In recent years, drought has covered the entire territory of Lithuania.

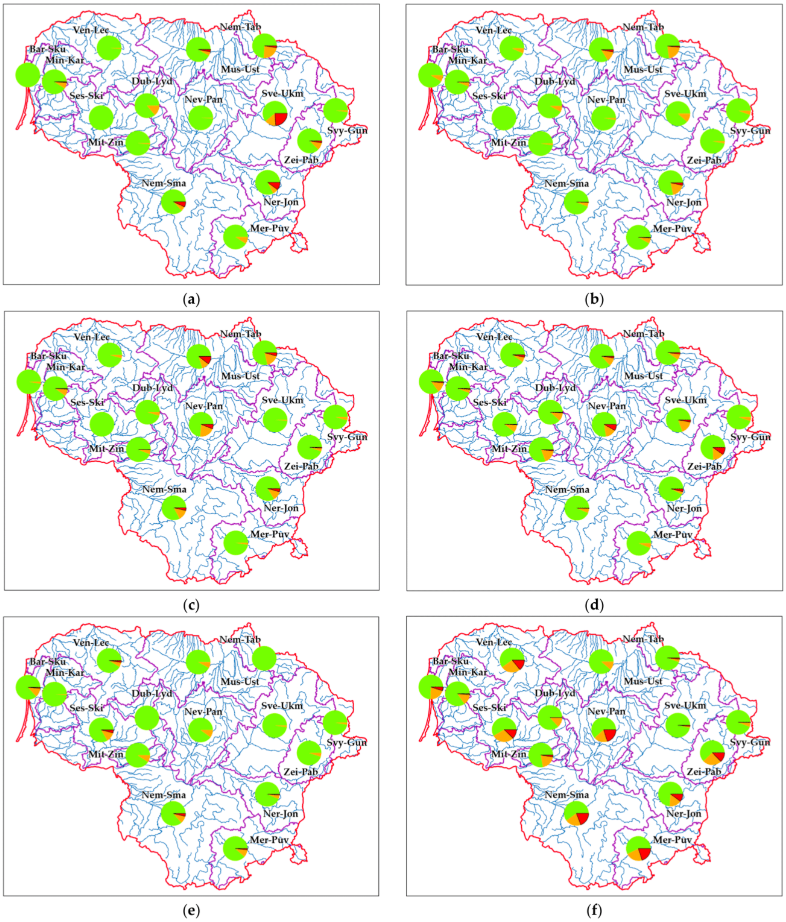


Figure 6. Spatial and temporal distribution of hydrological droughts (in %) for six historical periods: (**a**) 1991–1995; (**b**) 1996–2000; (**c**) 2001–2005; (**d**) 2006–2010; (**e**) 2011–2015; (**f**) 2016–2020. On the circular diagrams, conditions close to normal are shown in green, the average drought in orange, severe and extreme droughts in red.

Table 6 shows the maximum duration of drought with SWLI values below −1.5. Overall, the prolonged droughts were consistent with the driest years identified above. According to this table, rivers in the southeastern and central hydrological regions tended to experience the most prolonged droughts at the end of the study period. On the contrary, they were present in the rivers of the central hydrological region in the middle of the study period.

Table 6. Maximum drought duration in days according to threshold −1.5 and SDTV.

№	WGS	The Longest Drought at Warm Period (SDTV)	Year	The Longest Drought at Warm Period (−1.5)	Year
1	Nem-Sma	65	1992	64	1992
2	Mer-Puv	48	2020	46	2020
3	Ner-Jon	82	2019	81	2019
4	Zei-Pab	57	2006	43	2006/2019
5	Sve-Ukm	134	1992	119	1992
6	Nev-Pan	58	2019	37	2006
7	Dub-Lyd	30	1993	7	2006
8	Mit-Zin	12	2020	11	2020
9	Ses-Ski	34	2019	29	2019
10	Min-Kar	11	2006	10	2006
11	Svy-Gun	3	2020	2	2020
12	Nem-Tab	32	2002	28	2002
13	Mus-Ust	76	2002	44	2002
14	Ven-Lec	44	2019	43	2019
15	Bar-Sku	23	2020	17	2019

3.3. *Projections of Hydrological Droughts Using SWLI*

Analysis of the hydrological drought in the future (Appendix A and Table 7) reveals that most droughts are expected in the distant future. The only exception is the behavior of the Šešuvis River in the RCP4.5 scenario. This may be caused by a stronger dependence on precipitation, while the Nemunas and Žeimena have a dominant underground feeding source.

Table 7. Days with severe drought (based on SWLI) in the near and distant future.

	Nem-Sma		Zei-Pab		Ses-Ski	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Near Future	219	25	269	293	375	214
Far Future	433	701	785	761	371	482

A comparison of the projected and historical data (Table 8) revealed an increase in the percentage of severe and extreme drought in the future in rivers such as the Žeimena and Šešuvis. However, for the Nemunas River, the opposite tendency was observed. Such a difference may be due to the larger catchment area and a decrease in the range of water level fluctuations.

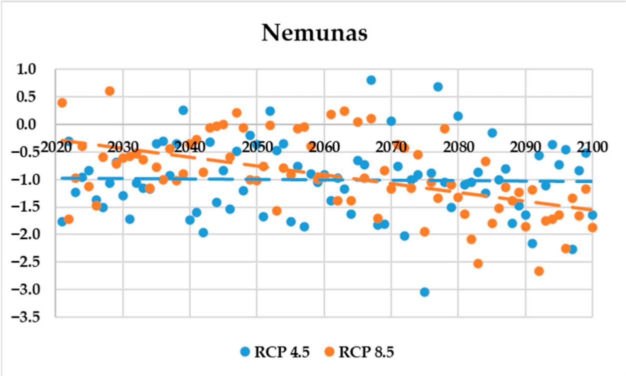
Table 8. Droughts percentages in past and future scenarios.

		Nem-Sma	Zei-Pab	Ses-Ski
Historical	1991–2020	5.94	5.80	3.80
RCP 4.5	2021–2060	2.98	3.65	5.10
	2061–2100	5.88	10.67	5.04
RCP 8.5	2021–2060	0.34	3.98	2.91
	2061–2100	9.52	10.34	6.55

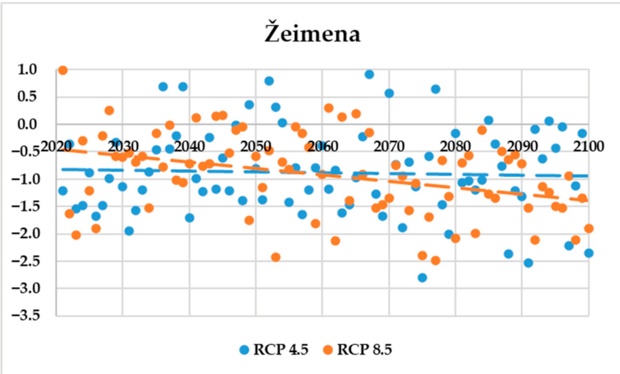
According to Table 9 and Figure 7, it can be concluded that the appearance of more extreme hydrological droughts is expected in the future, especially in the period 2061–2100. Under scenario RCP4.5, all three rivers showed a slight negative decreasing trend in the long term. For scenario 8.5, we can observe more significant negative changes for the Nemunas and Žeimena rivers, but, at the same time, significant positive changes for the Šešuvis.

Table 9. Minimum values of SWLI index in the past and future.

	Observation (1986–2005)	RCP4.5 NF	RCP4.5 FF	RCP8.5 NF	RCP8.5 FF
Nem-Sma	−2.42	−1.96	−3.04	−1.71	−2.67
Zei-Pab	−2.35	−1.95	−2.79	−2.43	−2.48
Ses-Ski	−2.63	−3.01	−3.33	−2.59	−3.25

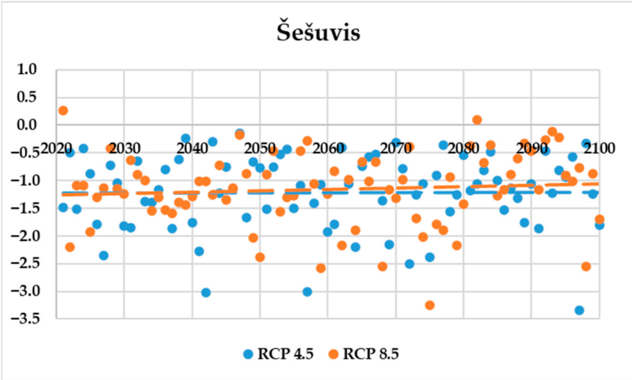


(**a**)



(**b**)

Figure 7. *Cont.*

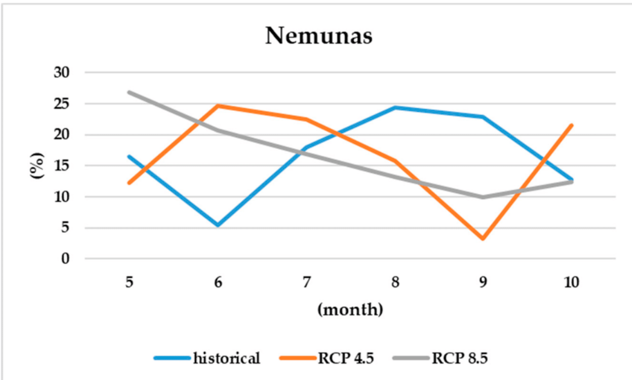


(**c**)

Figure 7. Minimum values of the warm period according to modeled data during the period of 2021–2100 (SWLI index): (**a**) Nemunas-Smalininkai; (**b**) Žeimena-Pabradė; (**c**) Šešuvis-Skirgailai. The dotted lines represent the trend lines for each RCP scenario according to color.

The models predict the formation of a wet period for the Nemunas and Žeimena rivers in the period 2040–2070 (Figure 7).

The distribution of severe and extreme droughts during the warm period was also investigated (Figure 8). When comparing the projection data with the historical period, changes were observed in all three basins, but no clear trends were identified. This type of change can be related to feeding sources and climate change.



(**a**)

Figure 8. *Cont.*

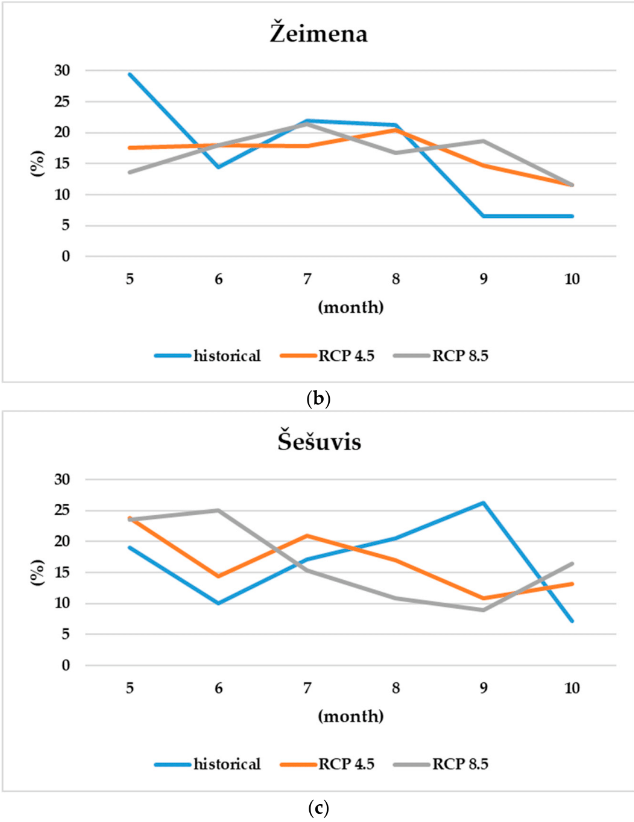


Figure 8. Percentage of droughts (according to SDTV) by month: (**a**) Nemunas-Smalininkai; (**b**) Žeimena-Pabradė; (**c**) Šešuvis-Skirgailai.

4. Discussion and Conclusions

The present study was designed to determine the suitability of the standardized water level index (SWLI) to monitor, follow and forecast hydrological drought conditions in Lithuania.

The hydrological drought index SDI, in turn, was developed [25] based on the concept of the widely known and recognized standardized precipitation index (SPI) [17,24]. A number of other hydrological indices are calculated similarly to SPI (e.g., standardized reservoir supply index (SRSI), standardized streamflow index (SSFI), standardized water-level index (SWI)) [15].

The developed methodology was adapted to analyze hydrological droughts in Lithuanian river catchments over the past three decades. The hydrological identification and quantification of droughts using the modified SWLI have led to the discovery of past and future trends.

The results indicated the most severe droughts over the 30 years in 1992, 2002, 2006, 2019 and 2020. Droughts in Lithuania in 1992, 2002 and 2006 were identified using other methodologies [19,37]. The vegetation seasons of 1992 and 2002 were also described as extremely dry in the eastern Baltic Sea region [38]. The highest rates of flow intermittence in 1992, 2002, 2006 and 2018 were established by Šarauskienė et al. [30]. According to agricultural drought criteria, from 1992 to 2006, as well as in 2018 and 2019, large areas of Lithuania suffered from extreme dryness [39]. According to [40], over the studied period of 1950–2012, the longest and most severe and widespread drought event in the Baltic States was recorded during 2005–2009; in Eastern Europe, the most prolonged was in 1992–1995 and the most severe in 1989–1991. The year 2019 was the warmest year on record in Poland [41]. Blauhut et al. [42] listed the Lithuanian neighbors—Belarus, Latvia and Poland—as particularly affected by the multi-year drought of 2018–2019. Furthermore, the 2018–2020 drought event of extraordinary intensity covered a significant part of Europe [43]. Moreover, it was followed by a drought in 2022 that was considered the worst in at least 500 years [44].

In general, using the developed methodology, a positive trend in the number of severely dry days was detected over the last three decades. A similar pattern of results was obtained in the neighboring northern part of Poland: based on different indices, river flow decrease was identified for the period of 1981–2016 [45]. These basic findings are consistent with research [46] showing the ongoing negative water balance of the Greater Poland region in the years following 1988. In Latvia, since the early 1990s, remarkably drier conditions have been observed more often as well [47]. Our findings are consistent with what was found in the study [48], which analyzed long-term changes in drought indices of central and eastern European countries during 1949–2018. These authors estimated drying trends in the north, the Baltic countries and northern Belarus.

In individual rivers, the maximum duration of severe droughts lasted from 3 to 161 days. According to SWLI, in 1992, hydrological drought covered eight sub-basins (out of 15) and had the maximum duration from 2 to 134 days in 2006–2012 and 5–112 days in 2019–2020—14 rivers in each year—with a maximum duration of 131 days in 2019 (Nevėžis River) and 161 days in 2020 (Merkys River). According to SWLI, in 1992, hydrological drought covered 8 sub-basins (out of 15) and had the maximum duration from 2 to 134 days; 2006–2012, with 5–112 days; and in 2019–2020 period—14 rivers in each year, with maximum duration 131 days in 2019 (Nevėžis River) and 161 days in 2020 (Merkys River). At the beginning of the study period, hydrological drought events were identified in the southeastern catchments, while, in the first decade of this century, they were indicated in the rivers of the central part of Lithuania. However, more recently (2016–2020), drought events were detected in each analyzed river catchment. The most prone to the hydrological drought was the Nevėžis river, where the percentage of severe droughts in the warm period was 7.81% (when, on average in Lithuania, it is 4.08%). These findings agree with a previous study [31], which, based on three different drought indices, revealed different patterns of drought in the hydrological regions of Lithuania.

As was already mentioned, the lowest amount of drought events were detected in the Svyla river. Since it is considered intermittent [30], we expected that this small river would distinguish itself by the most prolonged drought. A possible explanation for this case might be that our study applied the drought index based on river water levels. We suppose that during the period of low flow (which almost coincides with the warm period), the vegetation of the channel might have changed the hydrodynamics, i.e., the river stopped flowing. However, some water (the level of which can be measured) was still available in the river channel (the complex influence of aquatic macrophytes in regulating flow rates and water levels is discussed by [49]). Therefore, the case of this intermittent river shows some limitations of the SWLI methodology.

The developed methodology was applied to forecasting hydrological drought. In general, the obtained results demonstrated that the selected river catchments would likely suffer from more extreme hydrological droughts, especially under RCP8.5 at the end of the century. At the same time, it is evident that, in climate change conditions, the behavior of river catchments with different physical-geographical features is complex and challenging to predict. These findings support the arguments that the results of drought projections highly depend on the regions and drought indices considered [50,51].

It should be emphasized that the results obtained using the widely recognized stream drought index (SDI) developed by Nalbantis and Tsakiris [25] with the standardized water level index (SWLI) proposed by Kugytė and Valiuškevičius [28] are rather similar. SWLI can, therefore, be used as an operational index for hydrological drought monitoring and severe drought detection. It covers the essential criteria of a (hydrological) drought index [15,52,53] as it is simple (can be understood by non-experts), easily calculated, based on available real-time data, has a physical meaning, is sensitive to various drought conditions and can be used for forecasting.

Author Contributions: Conceptualization, S.N. and J.K.; methodology, S.N., D.Š. and A.P.; software, S.N.; modeling, S.N.; formal analysis, D.Š. and A.P.; investigation, J.K.; data curation, S.N.; writing—original draft preparation, S.N. and D.Š.; writing—review and editing, J.K. and A.P.; visualization, S.N. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

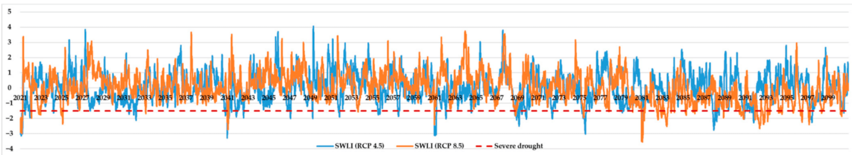

Figure A1. Comparison SWLI at RCP 4.5 and SWLI at RCP 8.5, the Nemunas river.

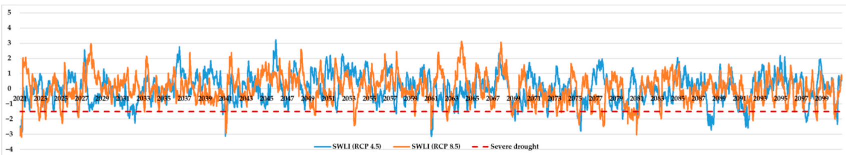

Figure A2. Comparison SWLI at RCP 4.5 and SWLI at RCP 8.5, the Žeimena river.

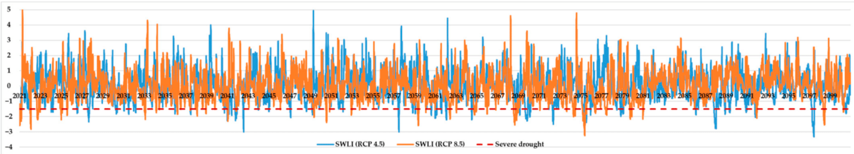

Figure A3. Comparison SWLI at RCP 4.5 and SWLI at RCP 8.5, the Šešuvis river.

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Article

Evaluating Hydrological Drought Risk in Lithuania

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Abstract: Hydrological drought poses a major global challenge, exacerbated by climate change and increasing water demand, leading to water scarcity, environmental degradation, and socioeconomic impacts. Thereby, there is a need for comprehensive methods to assess and predict hydrological droughts. The methodology part was based on the calculation of hydrological drought risk components—hazard and vulnerability—according to the equal weight scale of each variable. The spatial distribution of point values was performed by the inverse distance weighting interpolation method. To calculate indices, the spatial layer overlapping of variables was performed using the Raster Calculator tool. Statistical tools were used to estimate drought risk in river catchments. As a result, three main maps were prepared: The hydrological drought hazard index, the hydrological drought vulnerability index, and the hydrological drought risk. These maps highlight regional variations in drought hazards, vulnerability, and risk. Hazard and risk index values are higher in the northern part of Lithuania and lower in the south. The central region exhibits the highest percentage of areas at high and very high risk; the western region shows less risk due to a maritime climate; and the Southeastern region demonstrates the lowest susceptibility to hydrological drought due to physical-geographical factors.

Keywords: hydrological drought; low land rivers; risk assessment; hazards; vulnerability; geospatial analysis

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1. Introduction

Drought is a pressing issue in the modern world. This phenomenon is widely known because it can occur in any climate region worldwide [1–4]. Climate change, which is largely induced by humans, contributes to an increase in the frequency and severity of extreme weather events, including droughts [4–7]. Due to population growth, the water demand and deficit have been considerably increasing [7,8], and even though the drought has been with humanity for a long time, there is still a lack of necessary methods for assessing and predicting droughts [3].

Generally, four types of droughts are distinguished: Meteorological, agricultural, hydrological, and socioeconomic. The first three types of droughts generally have a cascading effect, as the lack of precipitation leads to decreased soil moisture, followed by decreased runoff [9]. In recent years, there has been a growing interest in developing and applying various methods and techniques for drought assessment, ranging from statistical analyses to sophisticated modeling approaches. Some of these techniques are created for specific types of drought (such as the soil moisture deficit index [10] used for agricultural drought or the standardized streamflow index [11] used for hydrologic drought). Some of them are universal (such as the standardized precipitation index (SPI) [12] or the Palmer drought severity index [13]).

However, it is very important not only to be able to identify drought events but also to understand their causes and the vulnerability of areas to drought in order to minimize the impact of droughts in the future. Ignoring the problem of drought in strategic development plans can have devastating consequences, leading to water scarcity, food insecurity, and economic losses. The economic losses due to a single drought can reach several billion euros [14].

Unlike other natural hazards, droughts do not occur suddenly (often called a “creeping phenomenon”) and can cover large areas for an extended period of time. Therefore, this slow onset and growth give a huge opportunity to prepare to withstand the pressure of drought events [3,15]. Mitigating the direct and indirect social, environmental, and economic impacts of drought through targeted risk reduction and adaptation becomes a global priority [16]. According to the United Nations Secretariat of the International Strategy for Disaster Reduction [17], drought risk is the combination of the natural hazard and the human, social, economic, and environmental vulnerability of a community or country, and managing risk requires understanding these two components and related factors in space and time. The drought hazard component usually consists of evaluating past droughts that have occurred in the studied area and may include indices such as SPI, streamflow drought index (SDI), vegetation condition indices, or an analysis of drought based on certain criteria [18–20]. The drought vulnerability component is relatively subjective and shows the degree of impact of a specific event on the system [21]. Drought vulnerability may include an analysis of total gross domestic product (GDP), irrigated lands, agricultural lands, livestock density, population density, proximity to infrastructure, municipal water, and other factors (depending on the goals of the study and the research area) [18–20,22]. Changes in both the climate system and socioeconomic processes are essential drivers of the core components (vulnerability, exposure, and hazards) that constitute risk [23].

Overall, the development and application of various methods and techniques are critical for improving the understanding of droughts and their impacts on water resources, as well as for developing effective drought management and adaptation strategies. However, adaptation or increasing resilience to drought should be based on a prior analysis of the territory’s vulnerability [18].

A systematic literature review of existing drought risk assessments made by [16] discovered that most studies applied quantitative or mixed-methods approaches, while qualitative approaches were relatively rare. The same review revealed that, in terms of assessment methodology, more than half of the studies applied index-based approaches. The choice of approach depends on the scale and scope of the assessment.

The creation of a global drought risk map by Carrão et al. [24], covering multiple regions, population groups and economic sectors, was one of the first such attempts to identify where local risk assessments should be conducted to improve drought preparedness and strengthen appropriate drought management policies. This global assessment revealed lower drought risk in remote regions (such as tundras and tropical forests) and higher risk in populated areas extensively exploited for crop production and livestock farming, such as South-Central Asia, the Southeast of South America, Central Europe and the Southeast of the United States. The study at the pan-European scale found that, in general, southeastern Europe and northern Europe (Iceland, Norway, and Finland) are under low drought risk in comparison to the other European regions, whereas parts of maritime Europe and the western Mediterranean show increasing drought risk [25]. Meanwhile, smaller-scale studies identify drought risk zones in regions of individual countries. For example, an analysis conducted in Turkey revealed seven administrative provinces at moderate to high risk of drought out of 81 [20]. The most exposed province was characterized by extensive agricultural and irrigated land. The assessment in Iran also highlighted the unique role of land use in mitigating drought risk and the close relationship between the two [26]. The created risk map indicated that Iran’s central part, northeast, southeast and western areas fall into the high-risk drought class and that the drought risk decreases from the center of Iran to the southwest and northwest. The temporal and spatial patterns of drought risk indicators for the regions of Peninsular Malaysia revealed two districts at moderate drought risk and 35 districts at low hydrological drought risk out of 42, as well as the trend towards dry conditions [19]. Often, the assessments of drought risk are directed to the selected study regions in a single country [27–29] or in multiple countries [18] or selected river basins (especially in the case of hydrological drought; [30,31]).

Although there has been an increase in the number of studies devoted to droughts in Lithuania recently [32–36], not a single study has been conducted to assess the risk of droughts and susceptibility to hydrological drought. This work aims to make a risk assessment of hydrological drought using an index-based approach by creating a map based on an integrated assessment of hydrological drought hazards and vulnerabilities. The work focuses entirely on Lithuanian river catchments and will help shape more drought-resistant systems in the future.

2. Materials and Methods

2.1. Study Area and Data

The total study area is 65,200 km^2, which corresponds to the entire territory of Lithuania. The area belongs to the plain and includes only four main forms of relief: two highlands (Žemaičiai highland and Baltic highland) and two lowlands (Pajūris lowland and Middle Lithuania lowland). The maximum height above sea level reaches 294 m. The territory of Lithuania belongs to a temperate continental climate with the influence of the Baltic Sea on the coastal areas, which forms a strip of maritime climate. Precipitation ranges from 572 mm/y to 856 mm/y. These physiographic conditions form three main hydrological regions in Lithuania (Figure 1): western (W-LT), central (C-LT), and southeastern (SE-LT).

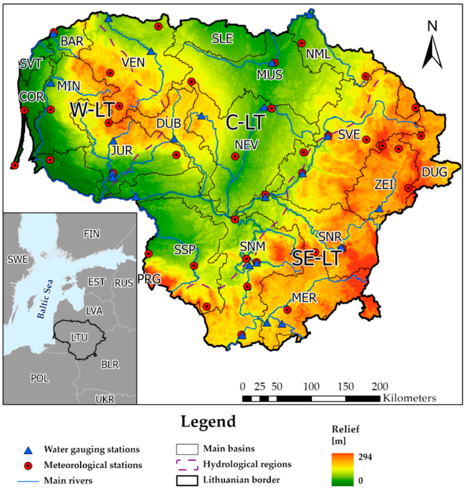


Figure 1. Map of Lithuania (hydrological regions, main basins, WGS and MS).

Despite the small size of Lithuania, it has more than 22,000 rivers with a total length of over 37,000 km identified within its borders. River flow in the summer period ranges from 0.1×10^{-3} m^3/s·km^2 in the C-LT region to 4.7×10^{-3} m^3/s·km^2 in the SE-LT region. River-feeding sources vary from predominant rainfall in the W-LT region to groundwater in the SE-LT region.

For the study, hydrological data from 24 water gauging stations (WGS) were used for the period from 1961 to 2020. Data from 38 meteorological stations that operated during the study period were used to investigate the distribution of precipitation in Lithuania. Daily hydrological and meteorological datasets were obtained from the Lithuanian Hydrometeorological Service. For the overall analysis of Lithuania, 1059 catchments from 19 main Lithuanian basins (Table 1) were taken; two of them were joined due to the small area of one of them (Prieglius river basin connected to Šešupė river basin). SRTM raster with a resolution of 1 arc-second was downloaded from the website: https://earthexplorer.usgs.gov/ (accessed on 21 April 2023). Information about land cover, soils, and lakes was taken from https://www.geoportal.lt/geoportal/ (accessed on 22 April 2023).

Table 1. Characteristics and abbreviation of river basins.

No.	Basin	Abbreviation	A, km^2
	Nemunas river district		
1.	The small tributaries of the Nemunas river (with the Nemunas river)	SNM	9294.3
2.	Merkys river basin	MER	3781.0
3.	The small tributaries of the Neris river (with the Neris river)	SNR	4378.6
4.	Žeimena river basin	ZEI	2792.7
5.	Šventoji river basin	SVE	6800.7
6.	Nevėžis river basin	NEV	6143.8
7.	Dubysa river basin	DUB	1972.6
8.	Jūra river basin	JUR	3996.6
9.	Minija river basin	MIN	2970.9
10.	Coastal rivers basin	COR	1100.0
11.	Šešupė river basin	SSP	4899.0
12.	Prieglius river basin	PRG	88.4
	Lielupe river district		
13.	Mūša river basin	MUS	5296.7
14.	Nemunėlis river basin	NML	1892.0
15.	The small tributaries of the Lielupe river	SLE	1749.6
	Venta river district		
16.	Venta river basin	VEN	5140.4
17.	Bartuva river basin	BAR	747.7
18.	Šventoji river basin	SVT	398.0
	Dauguva river district		
19.	Dauguva river basin	DUG	1857.0

Note: Small Prieglius river basin was joined to Šešupė river basin for calculation. Basins that merge are highlighted in color.

2.2. Methods

2.2.1. Data Preparation

As mentioned above, daily water discharge data from 24 WGSs were used for analysis, but two data sets had missing values for measurements. These gaps did not exceed 2% of the total data series length, so it was decided to restore the missing data using two approaches.

If there was another hydrological station on the river, the following equation was used to restore daily discharge data:

$$\alpha = \frac{\beta \times A_\alpha}{A_\beta} \tag{1}$$

where α is the unknown discharge at the gauging station, β is the known discharge at the adjacent station on the respective river, and A is the catchment area for each water gauging station.

If there was no second station on the river, it was decided to select a catchment area similar in size and physiographic characteristics. The next step was to compare the two data sets and use the equation of determination to fill in the missing data.

2.2.2. Drought Risk Calculation

The analysis of hydrological drought risk (HDR) includes two components: Drought hazard and drought vulnerability. This work focused only on water bodies; therefore, socio-economic indicators were not included in the consideration. The general calculation process is depicted in Figure 2.

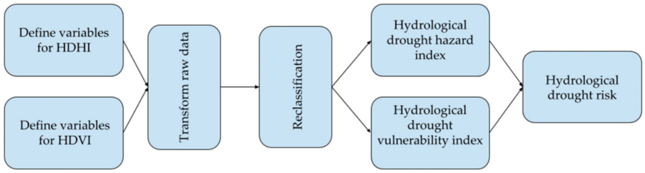


Figure 2. Scheme of the general process of hydrological drought risk calculation.

Thus, the hydrological drought hazard index (HDHI) included four variables for assessing hydrological drought and its dependence on climate:

- Number of hydrological droughts lasting 5–16 days—WSD;
- Number of hydrological droughts lasting more than 16 days—WLD;
- Average precipitation—R;
- Dependence of river runoff on rainfall—RD.

The hydrological drought vulnerability index (HDVI) consisted of the following physico-geographical variables affecting river runoff:

- Slope—S;
- Land use/land cover type—LULC;
- Morphological composition of soils—SL;
- Lake density—L.

The general equation for calculating hydrological drought risk was as follows:

$$\mathrm{DR} = ((\mathrm{WSD} + WLD + R + RD)/4 + (\mathrm{S} + LULC + SL + \mathrm{L})/4)/2, \quad (2)$$

where the first part ($WSD + WLD + R + RD$)/4 represents the drought hazard index and the second part ($S + LULC + SL + L$)/4 represents the drought vulnerability index.

2.2.3. Spatial Analysis

Spatial analysis of variables was performed using ArcGIS 10.5 software (ESRI, Redlands, CA, USA, distributed in Lithuania by HNIT-BALTIC). The values of the hydrological drought hazard component indexes were interpolated from the study points across the entire territory of Lithuania using the IDW (inverse distance weighted interpolation) tool. The spatial layers of the drought vulnerability component were also analyzed and reclassified using the Raster Calculator tool in the ArcGIS software. The average value for each catchment was calculated with the Zonal Statistics as Table tool.

Maps of the hydrological drought risk, hazard, and vulnerability were created using the Calculate Field tool based on Equation (2). Further analysis of the catchment areas and calculations of potentially hazardous areas were also carried out using GIS tools.

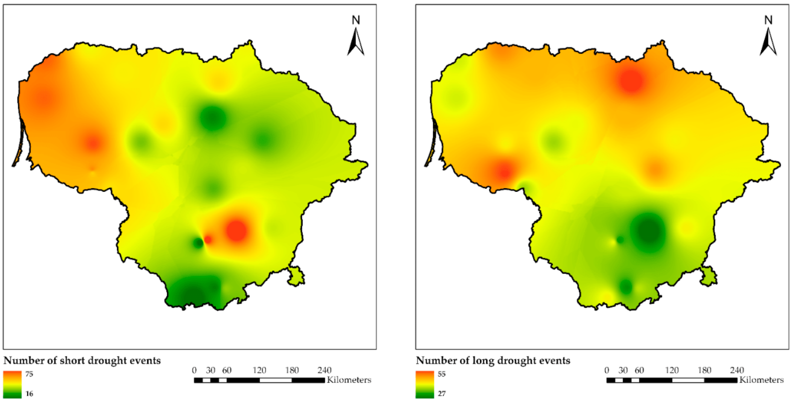
All classes of HDHI, HDVI and HDR were defined according to the natural breaks (Jenks) method of classification.

2.2.4. Index Calculation Method

Hydrological Drought Hazard Component Indices

- The number of droughts lasting 5–16 days and more than 16 days.

The threshold method was used to calculate these variables. The Q30 index was used as the threshold value and calculated as the average of the smallest 30-day continuous discharge value from May to October for the study period. The next step was to determine the hydrological drought by comparing the daily discharge values with the threshold value. Minimum and maximum thresholds were calculated from the probability curve of drought duration. Daily discharge values less than the threshold (with a duration of 1–4 days) were not considered as they were too short. The threshold between short-term and long-term hydrological droughts was equal to nearly 20% of the probability (16 days). The received results for 24 WGSs during the 60-year period were interpolated and displayed on maps (Figure 3a,b).



(**a**) (**b**)

Figure 3. Map of: (**a**) number of short drought events; (**b**) number of long drought events.

- Average precipitation.

The annual precipitation data of 38 meteorological stations were used to analyze average precipitation values. A separate raster of interpolated precipitation values for the territory of Lithuania was constructed for each year. The last step was to use the raster calculator to compute the average value over a 60-year period. The final map is shown in Figure 4a.

- The impact of rainfall regime.

The dependence on the rainfall regime was evaluated by distributing the annual runoff hydrographs into three types of river feeding. A detailed description of the calculation of the rainfall contribution to the total river runoff is presented in one of the previous articles [37]. The map of the river runoff dependence on rainfall feeding is shown in Figure 4b. Extreme values 0 and 1, as well as those close to them, were not used because there are no rivers in Lithuania entirely dependent or entirely independent on rainfall.

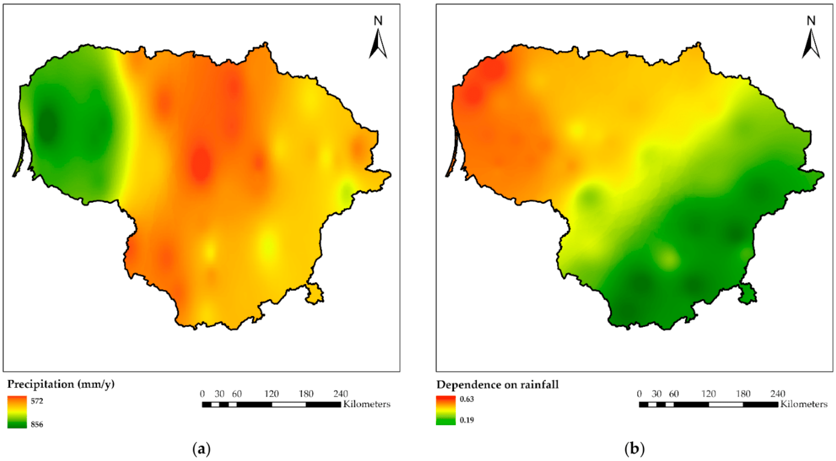


Figure 4. Map of: (**a**) average precipitation; (**b**) river runoff dependence on rainfall-type feeding.

Hydrological Drought Vulnerability Component Indices

Raster layers were used to estimate slope, land cover type, soil morphology, and lake density. For each variable, a raster with an already assigned score was created or loaded and then rescaled to a 0–1 scale based on the minimum and maximum values. In the case of the lake density in the catchment, the scale change occurred already after determining the percentage of the lake area for each catchment. The resulting spatial layers for the vulnerability index from the websites Earth Explorer and Geoportal were transformed and displayed on the maps in Figure 5.

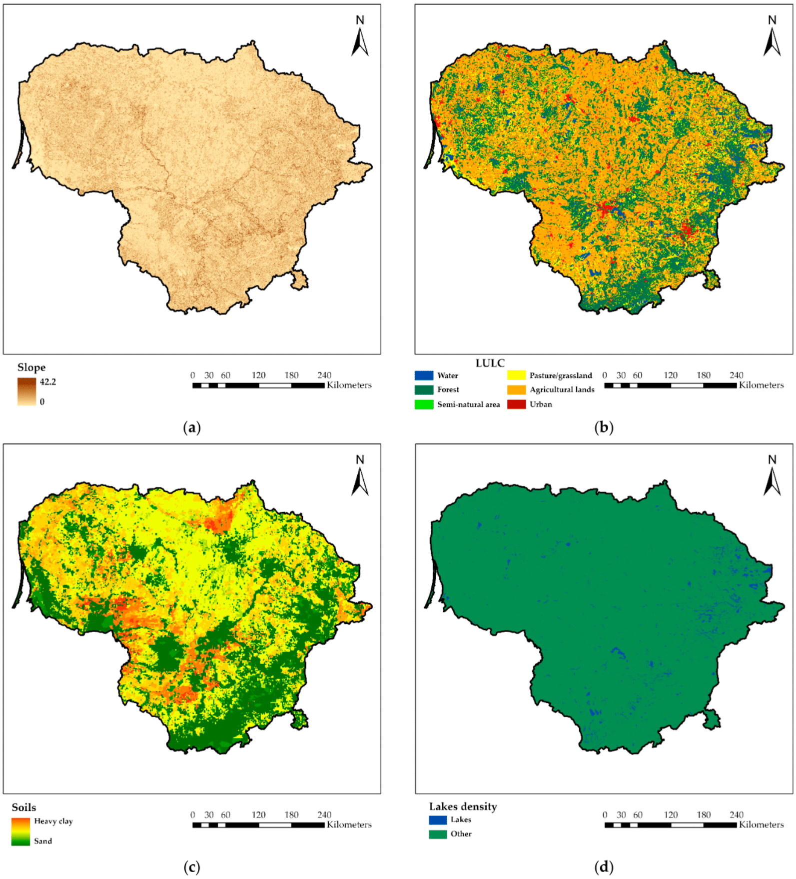


Figure 5. Map of: (**a**) slope; (**b**) land use and land cover; (**c**) dominant soils; (**d**) lakes.

2.2.5. Rescaling Sets of Variables

Since all variables at the first stage of analysis had different scales and values, we could not combine them without preliminary processing (Table 2). Thus, it was decided to change the evaluation scales to the same type. Each variable was rescaled according to one of the following two equations:

$$Y = \left(\frac{X - X_{min}}{X_{range}}\right)n \quad (3)$$

$$Y = \left(\frac{X_{max} - X}{X_{range}} \right) n, \quad (4)$$

where Y is the adjusted variable, X is the original variable, X_{min} is the minimum observed value of the original variable, X_{range} is the difference between the maximum and minimum potential scores of the original variable and n is the upper limit of the rescaled variable. Equation (4) was used when inverse scaling was necessary (e.g., rainfall, where lower rainfall rates corresponded to higher risk).

Table 2. Primary limits of variables.

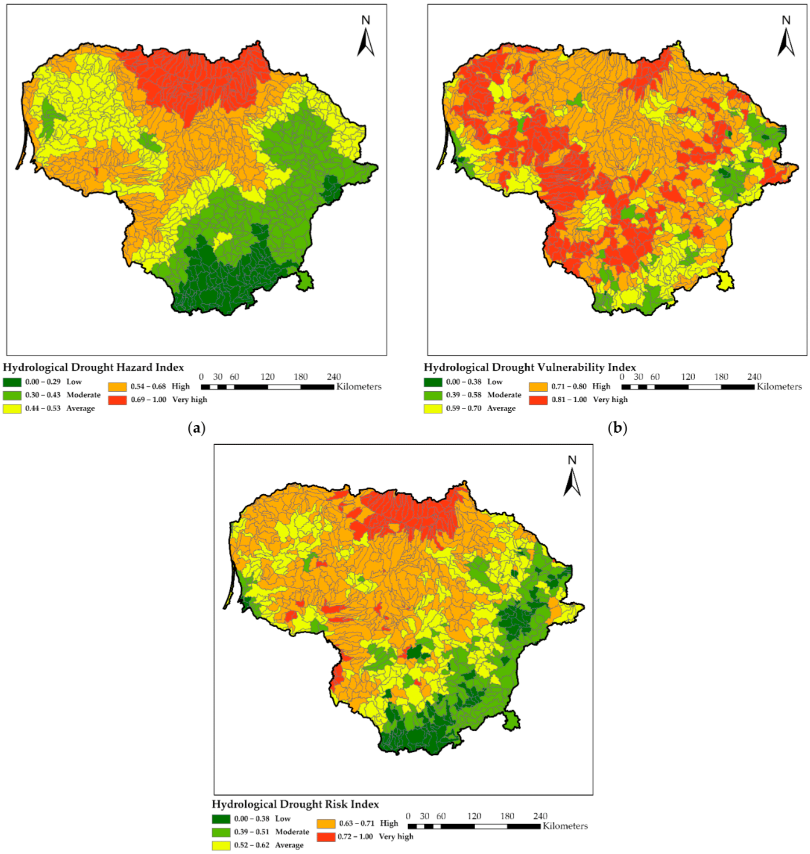
Variable	Limits of the Values Scale	Description
Number of droughts lasting 5–16 days	16–75 events	Rescaled before use in GIS
Number of droughts lasting more than 16 days	27–55 events	Rescaled before use in GIS
Average rainfall	572–856 mm/yr	The minimum and maximum annual values in Lithuania were taken as limits for rescaling
Dependence of river runoff on rainfall	0–1	In Lithuania, the maximum value of the river runoff dependence on the rainfall-type feeding is 0.63, and the minimum value is 0.19
Slope	0–42.2	Calculated from SRTM; calculated as an average for a catchment
Land use/land cover type	Water—0 Forest—1 Semi-natural area—2 Pasture/grassland—3 Agricultural lands—4 Urban—5	Calculated as an average for a catchment
Morphological composition of soils	Sand—1 ↓ Heavy clay—10	Given that clayey soils are associated with larger surface runoff and a certain dependence of these soils on the presence of intermittent rivers was revealed in previous work, it was decided to assign them the maximum vulnerability score; calculated as an average for a catchment
Lake density	0–30%	Lake density of 30% percent was taken as 0, as having the least impact on drought vulnerability in the region

After rescaling, all variables received the same weight (0–1). Only one exception was made for the variable "Dependence of river runoff on rainfall", since there is no river in Lithuania that is completely dependent or independent of rainfall, so the minimum and maximum values of this variable do not reach 0 and 1, respectively.

3. Results

3.1. Hydrological Drought Hazard, Vulnerability and Risk at the Lithuanian Scale

After the final merging of the layers, three main maps were obtained: The hydrological drought hazard index (Figure 6a), the hydrological drought vulnerability index (Figure 6b), and the hydrological drought risk (Figure 6c). From the distribution map of the HDHI, it can be seen that two poles are forming: The highest hazard score is observed in the north, while the lowest is in the south. The HDHI map shows similarities with the relief of Lithuania and the location of hydrological regions. The HDVI map reflects slightly different tendencies and does not clearly express significant clusters with the same vulnerability level. Only the northern part of the central hydrological region can be identified as the most homogeneous zone with high vulnerability indicators.



(**a**) (**b**) (**c**)

Figure 6. Hydrological drought hazard index (**a**); hydrological drought vulnerability index (**b**); hydrological drought risk map (**c**).

The HDR map shows a more pronounced cluster formation with very high values in the north and an elongated cluster with weak to moderate risk values in the southeast, which basically corresponds to the location of the southeastern hydrological region of Lithuania. These values in the south and east can be explained by the presence of more lakes and forests and the influence of the terrain in that area. On the contrary, the high drought risk values in the north can be attributed to the absence of lakes and forests, low precipitation and, to some extent, the influence of soils. Clayey soils, for example, contribute to lower subsurface flow, which could provide a more constant base flow in dry periods.

From the graph in Figure 7, it is evident that a significant part of Lithuania falls into the categories of high and very high risk (49.8%), while only about 24.4% fall into the categories of low and moderate risk. Another notable observation is the difference in the percentage composition of the HDHI and HDVI classes, which may be related to different variables. In the case of HDHI, the variables have a wider spatial distribution and are less directly influenced by human activity. In contrast, the HDVI variables are less spatially constant and more affected by human activities in both temporal and spatial dimensions, resulting in a less uniform or smooth distribution of variables.

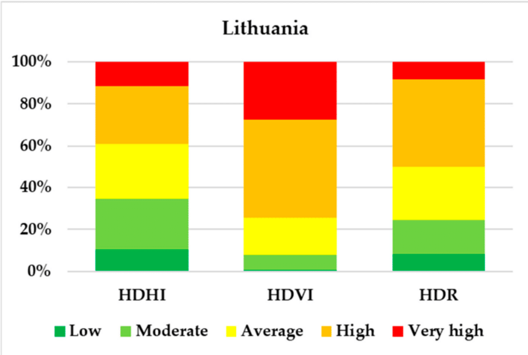


Figure 7. The composition of the territory in percentages according to hydrological drought hazard index (HDHI); hydrological drought vulnerability index (HDVI); hydrological drought risk index (HDR).

3.2. Hydrological Drought Hazard, Vulnerability and Risk at the Hydrological Regions Scale

Analysis of the HDHI, HDVI, and HDR within the hydrological regions reveals significant heterogeneity among the hydrological regions of Lithuania (Figure 8). The central hydrological region (Figure 8b) has the highest percentage of areas at high and very high risk, accounting for 65.1% for HDHI, 88.6% for HDVI, and 72.7% for HDR. In comparison, the percentage of the region in the low and moderate-risk classes is 12.2% for HDHI, 1.5% for HDVI (with a complete absence of the low-risk class), and 6.0% for HDR.

The western hydrological region (Figure 8a) has less area at high and very high risk: 36.2% for HDHI, 77.0% for HDVI, and 61.1% for HDR. The smaller risk is primarily associated with the influence of a maritime climate and precipitation, which create less favorable conditions for drought occurrence. However, the low and moderate-risk classes are also nearly absent, with only 4.2% for HDHI (with a complete absence of the low-risk class), 4.6% for HDVI, and 5.7% for HDR.

In contrast to the other two hydrological regions, the southeastern hydrological region has the lowest susceptibility to hydrological drought (Figure 8c). For example, the area of low and moderate-risk classes accounts for 83.3% for HDHI, 18.6% for HDVI, and 61.3% for HDR. At the same time, the percentage of high and very high-risk classes is 2.7% for HDHI (with a complete absence of the very high-risk class), 52.5% for HDVI, and 10.4% for HDR. Such index values can be explained by the greater dependence of this region on groundwater resources, as well as a higher percentage of forest cover and the presence of lakes, which enable a more resilient response to the risks of hydrological drought.

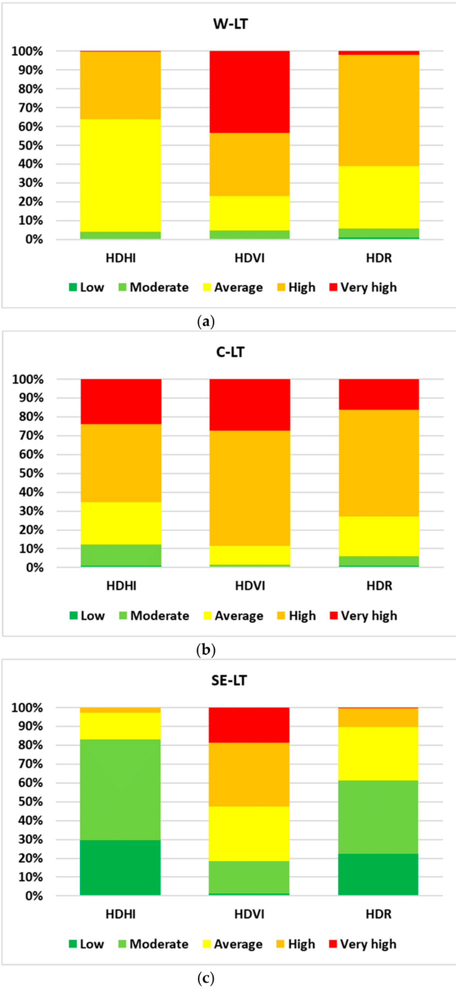


Figure 8. Distribution of HDHI, HDVI and HDR classes in hydrological regions of Lithuania: western (**a**); central (**b**); southeastern (**c**).

3.3. Hydrological Drought Hazard, Vulnerability and Risk at the Basins Scale

According to the drought hazard index within the main basins of Lithuania (Figure 9a), four basins can be identified in the north where a significant percentage of catchments belong to the category of a very high hazard: The Lielupe (100% of the territory), Musa

(72.9% of the territory), Nemunelis (45.1% of the territory), and Venta (17.6% of the territory) river basins. In the southeast, there are also four basins with catchments classified as having a low probability of hydrological drought hazard: The Merkys (83.8% of the territory, with 16.2% in the moderate class), the small tributaries of the Nemunas River basin (30.4%—catchments located in the eastern part of the basin), the Zeimena (13.9% of the territory, with the remaining 86.1% classified as moderate), and the Neris (8.3% of the territory) river basins. In the central and western hydrological regions, the dominant catchments fall into the moderate category (the Venta and Minija river basins have over 50% of their territory in this class) and the high hazard category (the Jura, Dubysa, Nevezis, Bartuva, Sventoji rivers, and coastal river basins have over 50% of their territory in this class).

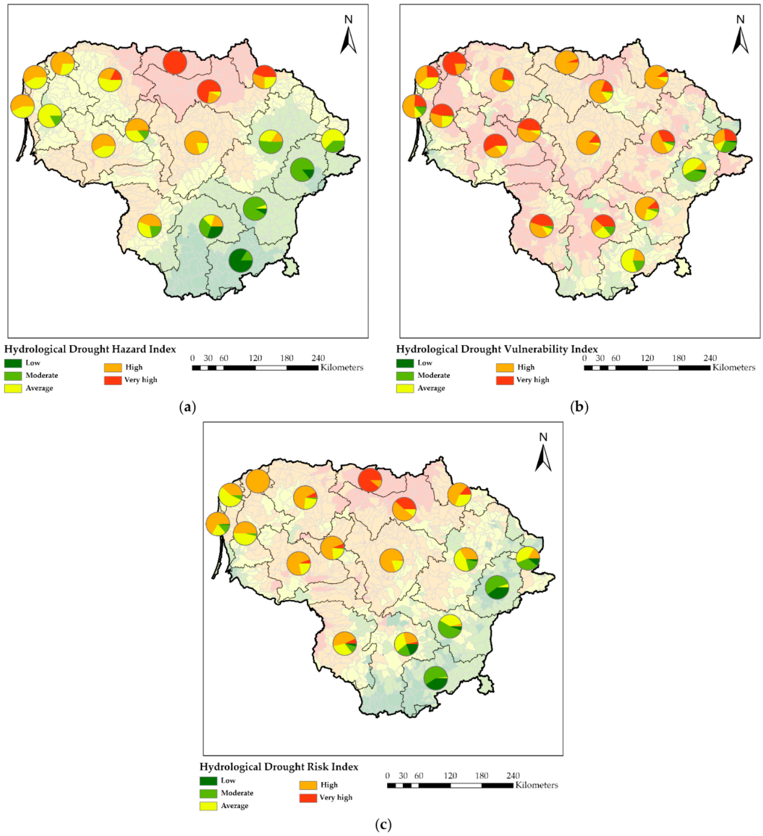


Figure 9. Distribution of the area of each class in percent for basins, according to: hydrological drought hazard index (**a**); hydrological drought vulnerability index (**b**); hydrological drought risk map (**c**).

Contrary to the drought hazard index, the drought vulnerability index is less optimistic (Figure 9b). Out of the 18 basins, only two have a percentage of catchments exceeding 30% in the low and moderate vulnerability classes, namely the Zeimena (42.2% of the territory) and Dauguva (32% of the territory) river basins. Three other basins have a relatively high proportion of catchments in the low and moderate vulnerability classes: The Merkys (19.6% of the territory), the Nemunas (13.9% of the territory), and the coastal (13.9% of the territory) river basins. All basins in the western and central hydrological regions of Lithuania consist of catchments, with over 60% belonging to the high and very high vulnerability classes for hydrological drought. The basins with the highest percentage in the high and very high classes include the Bartuva (100% of the territory), Dubysa (93.2% of the territory), and Jura (86% of the territory) river basins.

Analyzing the drought risk index (Figure 9c), it can be observed that the highest risk of hydrological drought occurrence is concentrated in the northern part of the central hydrological region, specifically in the basins of the Lielupe River (89.2% of the territory belongs to the class of very high risk and 10.8% to high risk) and the Musa River (38.7% of the territory belongs to the category of very high risk and 50.6% to high risk). Significant percentages with high-risk values are also found in the basins of the Bartuva, Venta, Nemunelis, Nevezis, Dubysa, Jura, Minija rivers, and coastal rivers. The basins with the lowest risk of hydrological drought are the Merkys (98.1% of the territory belongs to the low and moderate risk classes) and Zeimena (95% of the territory belongs to the low and moderate risk classes) river basins. Overall, there is a significant proportion of catchments with low and moderate risk classes in the southeastern region of Lithuania, with a slight increase in the basins located near the sea. For example, in the basin of the coastal rivers, catchments in the low- and moderate-risk classes account for 13.9% of the total territory.

4. Discussion

Many studies reveal the ineffectiveness of the traditional crisis management approach to the drought phenomenon and the need to move to a drought risk reduction approach instead. It is generally agreed that the costs of proactive drought risk management are lower than the costs of inaction [38]. This is why high-risk areas must be determined to implement risk mitigation measures [39]. The current study was intended to identify for the first time the territories with the highest risk of hydrological drought in Lithuania, down to the catchment scale.

The created methodology for hydrological drought risk assessment in lowland rivers of Lithuania included indices of natural hazards such as the number of short- and long-term hydrological droughts, average precipitation and river runoff dependence on rainfall feeding. This selection of indices was based on the methodologies used in other studies where, regardless of physical-geographical conditions, drought hazard is often assessed using drought indices (SPI, SDI, multivariate standardized drought index, etc.) that in one way or another describe the precipitation deficit or streamflow regime [18,20,26,29]. In the western and central hydrological regions, many river catchments fell into hazard-prone areas, likely due to their dependence on precipitation. Meanwhile, the rivers of the southeastern region get a considerable part (more than half) of their runoff from groundwater, so their annual runoff is more evenly distributed. A small number of long-term drought events and a higher number of catchments assigned to the average hazard index class in the W-LT region (compared with the C-LT) might result from more humid conditions and higher precipitation because of the proximity to the Baltic Sea. The previous studies [37,40] dedicated to the delineation of hydrological regions revealed that the amount of precipitation and the proportional contribution of river-feeding sources are the main factors that determine the particularities of Lithuanian river runoff formation.

According to the physical-geographical factors (watercourse slope, land use/land cover, soils, and lake density) that were expected to affect the susceptibility of Lithuanian river catchments, the SE-LT region emerged as having the lowest index values. A higher abundance of lakes and semi-natural and forested areas might have contributed to a more consistent and stable runoff in the catchments located in this region. In comparison, the C-LT region was distinguished by many areas used for agriculture due to the highest productivity of soils, thus having a higher water demand for irrigation needs. The C-LT and W-LT regions also have more urbanized areas and fewer semi-natural and forested lands than the SE-LT. Unlike [21,26], our study was unable to demonstrate that the region (SE-LT), having a terrain with high slopes (higher than the rest of the country), was more susceptible to drought. In contrast to most studies [21,41,42], in this work, the influence of sandy soils on hydrological drought vulnerability was estimated to be the smallest. The prevailing lighter soils contribute to faster infiltration and retention of subsurface flow in the groundwater layer. The more groundwater recharges, the more resilient rivers become [43,44]. One of the drawbacks of our study is that the selection of variables for vulnerability analysis was limited since it was based mainly on data availability. Such indicators as domestic water supply, population density or groundwater level could give a more accurate assessment of the susceptibility to the impacts of hydrological drought hazards.

According to previous work [36], drought vulnerability indexes on a regional scale are very closely related to drought severity calculated by the SDI index. For both works, the western region can be identified as the most vulnerable region with the most extreme drought values. On the other hand, the SE-LT region has lower severity values compared to other regions, which can be related to fewer catchments with very high vulnerability. In general, hydrological drought hazard and risk indexes also present SE-LT with a lower percentage of very high values.

Unfortunately, we could not find any studies of such scale and detail that reveal the results of similar spatial analyses concerning regional differences in adverse environmental or socio-economic consequences of drought. Only the related outcomes of a few studies concerning agricultural drought were discovered. According to agricultural drought indices (hydrothermal coefficient and temperature–precipitation index), droughts are recorded more often in the western and central parts of Lithuania and less frequently in the southeast and east [45,46].

The catchment-based analysis identified a cluster of high-risk values in the northern part of the C-LT region, specifically in the catchments of the Mūša and Lielupė rivers. This cluster represents the most hazardous area with the highest risk of hydrological drought occurrence in Lithuania. The findings also support previous research [47], which revealed the presence of five intermittent rivers in this most drought-prone area. The study by [48] discovered the highest recurrence of non-precipitation periods of different durations during the warm period in the Middle Lithuanian lowland as well. Considering the scale of the drought assessment, Hasan et al. [19] pointed out that drought characteristics should be evaluated at the catchment level to get better results.

It is worth mentioning the basin of the small tributaries of the Nemunas River separately. This elongated basin spans all three hydrological regions of Lithuania. Its shape provides valuable insights into the variation of drought risk indices from east to west. Consequently, the upper part of the basin exhibits one of the lowest drought risk indices. However, as it approaches the river mouth, the situation changes due to the inflow of tributaries from potentially drier areas of Lithuania. As a result, the middle part of the basin predominantly consists of catchments with high drought risk, while only near the river mouth, several catchments with low and moderate hydrological drought risk become noticeable. This trend is observed for all three indices.

This study covered all river catchments (over a thousand) in Lithuania, making it unique because previous hydrological drought investigations were based only on the selected sets of catchments [35,36,49]. Even though only physical-geographical aspects were analyzed, such a detailed assessment proved that Lithuanian rivers of different hydrological regimes assigned to separate regions have different drought risks. On the other hand, land use indirectly indicates water deficit and demands related to anthropogenic activities. Therefore, including urbanized and agricultural areas in the assessment indirectly represents socio-economic drivers. According to UNISDR [17], unlike meteorological drought, a natural phenomenon resulting from climatic causes that vary from region to region, hydrological drought highly depends on human and social aspects. Many studies demonstrate the decisive influence of an anthropogenic, not a climate, factor in drought risk studies since this phenomenon can occur in any type of climate [5,44,50].

5. Conclusions

The present study evaluated the hydrological drought risk in Lithuanian river catchments. The methodology integrating selected hazard and vulnerability indices was created and proposed as appropriate to be applied to lowland river catchments. The findings indicated that the distribution of catchments according to the drought hazard index generally corresponded well to the hydrological regions of Lithuania. The findings revealed that, in total, over 70% of Lithuania's territory falls into the categories of high and very high vulnerability, whereas almost half of the country is in high and very high-risk categories (49.8%).

The accomplished research highlights the need for future revisions in territorial planning in the identified most vulnerable catchments in the central and western parts of Lithuania to establish more drought-resistant ecosystems. Future studies should involve assessing socio-economic indicators, such as domestic water supply or population density, to determine water resource consumption. This would help in fully identifying regions with inadequate water resource provisions.

To obtain more reliable results, not only additional drought-sensitive indicators should be included in the assessment of hydrological drought risk, but also a transboundary approach should be applied. River catchments seldom coincide with political borders; therefore, the entire cross-border catchments should be included to obtain a more comprehensive view of the hydrological drought risk problem in Lithuania.

The obtained results are important for understanding how sensitive and vulnerable lowland river systems are becoming in a rapidly changing environment.

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Scientific papers related to the topic of dissertation:

1. ŠARAUSKIENĖ, Diana, AKSTINAS, Vytautas, NAZARENKO, Serhii, KRIAUČIŪNIENĖ, Jūratė and JURGELĖNAITĖ, Aldona. Impact of physico-geographical factors and climate variability on flow intermittency in the rivers of water surplus zone. *Hydrological Processes*. 2020. Vol. 34, no. 24, p. 4727–4739. DOI 10.1002/hyp.13912
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5. NAZARENKO, Serhii. Selection of regional climate models for use in hydrological modelling of Lithuania rivers. CYSENI 2021. 24-28 May 2021, Lithuanian Energy Institute, Kaunas, Lithuania.
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