LITHUANIAN ENERGY INSTITUTE

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PROJECTION OF HYDROPOWER RESOURCES OF LITHUANIAN RIVERS IN THE CONTEXT OF CLIMATE CHANGE

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Technological Sciences, Environmental Engineering (T 004)

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SUMMARY
INTRODUCTION

Increasing energy demand meeting from fossil fuels is leading to an increase in greenhouse gas emissions. This is leading to a rise in average temperature - one of the consequences of global climate change. Governments and scientists around the world have agreed that climate change impact can be mitigated by using more renewable energy sources, and have defined the scale at which this should be done. Lithuania's renewable energy commitments are set out in the National Energy and Climate Plan, which sets out targets for all EU Member States by 2030 to halt climate change. The aim is to reduce greenhouse gas emissions by 40% compared to 1990, improve energy efficiency by at least 32.5% and increase the share of renewables in total energy mix to 32% (Lietuvos Respublikos Seimas, 2018a). Hydropower is one of the renewable forms of energy. It is divided into hydropotential and hydrokinetic power. Worldwide, hydroelectricity generated by conventional hydropower plants accounts for the largest share of electricity from renewable sources. It is therefore necessary to assess Lithuania's hydropotential and hydrokinetic energy resources. As the development of hydropotential power plants is currently restricted by law in Lithuania, the emergence of hydrokinetic power plants and the use of hydrokinetic energy resources could add to the share of renewables in the country's overall electricity generation. The hydrological regime of Lithuania's rivers is affected by climate change, resulting in changes in riverine runoff. Changing riverine runoff affects transformation in the hydropower resources (hydropotential and hydrokinetic) of rivers. The question is, how will the ongoing climate change affect the hydropotential and hydrokinetic energy resources of Lithuanian rivers? Will small hydropower plants be able to operate under conditions where the seasonal shift in river flows, especially during the dry summer season, results in reduced river discharge? How will small hydropower plants change the hydrological regime of rivers? The potential hydropower resources of Lithuanian rivers have been quite well explored so far, while there only have been few studies on hydrokinetic resources. What is the theoretical potential for hydrokinetic power generation in Lithuania and how will it change due to climate change? Moreover, there is no forecast of Lithuanian river hydropower resources under RCP climate scenarios for the 21st century.

This work examines how climate change will change the runoff of Lithuanian rivers, leading to changes in the kinetic and potential hydropower of rivers. It is important to identify a targeted research methodology that answers the questions raised. With the increasing impact of global climate change, which is also being felt in Lithuania, hydrological forecast is playing an increasingly important role in scientific research. In order to assess the forecast of river runoff in Lithuania, it is necessary to investigate how it has varied in the past. Using different climate models and climate scenarios, it is necessary to forecast river runoff, on which river hydropower resources depend directly.

Hydroenergy is undoubtedly one of the most widely used forms of renewable energy, due to its advantages such as dams for water supply, irrigation, flood control, recreation, navigation, etc., but the production of electricity from hydropower is also associated with negative environmental impacts, such as changes in the hydrological regime of rivers due to hydropower plant operations. It is therefore necessary to determine how the operation of small hydropower plants has affected the hydrological regime of rivers. By assessing the impact of hydropower plants on the hydrological regime of rivers, it is possible to make recommendations for the efficient use of hydropower in the future, taking into account environmental protection requirements.

Taking into consideration that the development of hydropotential power plants in Lithuania has been stopped by legislation, as well as the impact of these plants on the hydrological regime of rivers, it will be possible to make recommendations to the legislators to create the necessary legislation for the development of hydrokinetic power plants in Lithuania. This would pave the way for the emergence of a new type of renewable energy in Lithuania or could increase the contribution of hydropower to Lithuania's overall electricity generation.

Relevance of the research

In recent decades river runoff is being changed by climate change phenomena (increased air temperature and evaporation, changed frequency of extreme climate phenomena). In future there are even greater alterations of river runoff, especially in the dry and wet seasons. River water content determines hydropower resources, which consist of river water flow (kinetic) and river water head (potential) energy. Potential future changes of river runoff are going to influence conditions and amounts of energy production. Absence of the projections of Lithuanian hydropower resources for the periods (2021-2040) and (2081-2100) make it difficult to plan efficiently the resource management in changing environmental conditions.

Object of the research

The hydropotential and hydrokinetic energy resources of the rivers Nemunas, Venta and Lielupe river basin districts (Nemunas, Merkys, Neris, Šventoji, Žeimena, Nevėžis, Šušvė, Dubysa, Šešupė, Jūra, Šešuvis, Minija, Bartuva, Venta, Mūša, and Lėvuo) were studied.

The aim of the doctoral thesis

To assess the change of hydropower resources of Lithuanian rivers in the past (1961-2020) and in the near (2021-2040) and distant (2081-2100) future, to study the impact of small hydropower plants on the hydrological regime of rivers, and to develop recommendations for the efficient use of hydropower resources in respect to environmental requirements.

The tasks of the doctoral thesis

1. Creation of hydrological models of Lithuanian rivers and, using them and the hydromodule mapping method, to project runoff for gauged and ungauged rivers under climate scenarios.

2. Projecting of hydrokinetic and hydropotential resources for the 21st century based on river discharge forecasts and to assess the uncertainties in these forecasts.

3. Assessing the impact of small hydropower plants on the hydrological regime of rivers.

4. Preparation of recommendations on efficient use of hydropower in future with respect to environmental requirements.

The hypothesis of the doctoral thesis

In the future, change in Lithuanian riverine runoff due to climate change will lead to a reduction in hydropower resources.

Doctoral thesis defence statements

- A changing climate will not only reduce both kinetic and potential hydropower resources of rivers in the future, but will also lead to their seasonal shift: an increase in winter and a decrease in spring
- Climate models have a greater impact on the uncertainty of hydropower resources projections than climate scenarios
- Hydropower plants cause significant changes in the hydrological regime of rivers.

Scientific novelty and application of doctoral thesis

The work develops a methodology for the first time to project the hydrokinetic and hydropotential energy resources of the gauged and ungauged rivers in Lithuania in the near (2021-2040) and distant (2081-2100) future using hydromodule (q, $l/s \cdot km^2$) mapping method, regional climate models and RCP climate scenarios. To assess the accuracy of the forecasts, an assessment of the uncertainty in hydropower forecasts was carried out and the impact of small hydropower plants on the hydrological regime of rivers was determined. The new knowledge on the changes in Lithuania's riverine energy resources in the 21st century has led to the development of good practice recommendations for legislators, environmental authorities and hydropower plant owners on how to make rational use of the changed water resources.

Publications

The material of the doctoral thesis has been published in 2 papers in Clarivate Analytics journals with citation index and 3 papers in international scientific conferences.

The structure of doctoral thesis

The doctoral thesis consists of 118 pages. It contains an introduction, six chapters with 35 figures, 7 tables and 5 conclusions. The literature list contains 222 references.

1. METHODOLOGY and DATA

The thesis research was carried out in 8 phases (Figure 1). In the first stage, hydrometeorological and geographical databases were compiled and used in the study. In the second stage, the kinetic and potential energy resources of Lithuanian rivers in the period 1961-2020 were assessed. In the third stage, hydrological models of 15 Lithuanian river basins (Nemunas, Merkys, Neris, Šventoji, Žeimena, Nevėžis, Šušvė, Dubysa, Šešupė, Jūra, Minija, Bartuva, Venta, Mūša, and Lėvuo) have been developed with the use of HBV software. In the fourth stage, the data from three climate models for the RCP2.6 and RCP8.5 scenarios were adapted to the Lithuanian territory using the QM method. In the fifth stage, the runoff of the gauged and ungauged rivers was projected for the near (2021-2040) and distant (2081-2100) future. In the sixth stage, the hydrokinetic and hydropotential energy resources of the rivers in the near and distant future were estimated using the runoff forecasts and the uncertainties in the forecasts were assessed. In the seventh stage, an assessment of the impact of small hydropower plants on the hydrological regime of rivers was carried out using the IHA methodology. In the final stage, the results of this study were used to develop recommendations for the efficient use of hydropower in the future, considering environmental aspects.

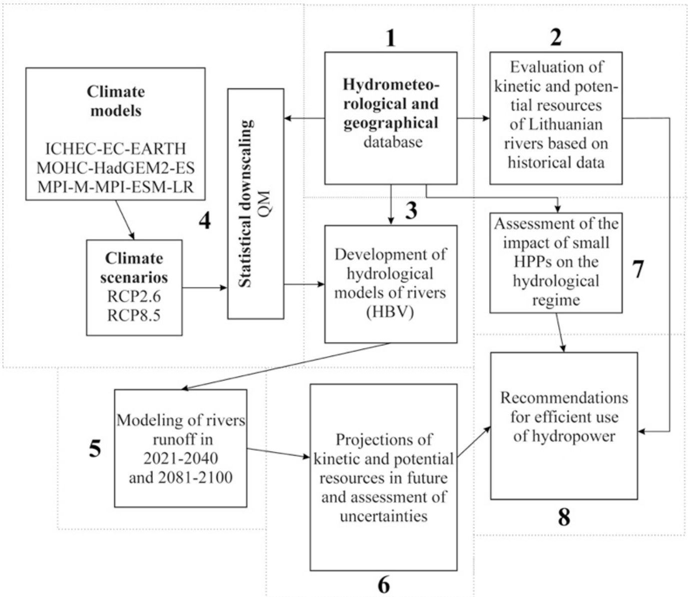

Fig. 1 Operating principle diagram

1.1. Hydropower assessment of Lithuanian rivers using historical data

1.1.1. Kinetic energy assessment

Kinetic resources were assessed in the major Lithuanian rivers (the Nemunas and Neris) and separately in the smaller ones. The assessment of technically available resources (flow technical capacity obtained from a hydrokinetic device) was made using the equation:

$$P_{TK} = \eta \frac{\rho}{2} v^3 A_D \frac{BL}{20h^2} \quad (1)$$

$$h=0.29\, \bar{Q}^{0.45} k^{0.39} I^{-0.2} \quad (2)$$

$$B=8\bar{Q}^{0.30} k^{0.08} I^{-0.2} \quad (3)$$

$$v=0.43\bar{Q}^{0.25} k^{0.53} I^{0.4} \quad (4)$$

$$E_{TK} = P_{TK}\, t_{TK} \quad (5)$$

where P_{TK} is technical hydrokinetic capacity, W; η is device power coefficient (average value is 0.30 according to), ρ is fluid density, kg m^{-3}, v is flow velocity, m s^{-1}, A_D is device swept area, m^2, *B* is a part of the river channel width, where depth is greater than turbine diameter, m, *L* is segment length, m, *h* is bed depth equal to device turbine diameter, m, Q is the average annual discharge, m^3 s^{-1}, k is the modular discharge coefficient, I is the bed slope, E_{TK} is hydrokinetic generation, Wh, t_{TK} is hydrokinetic device's working time in hours.

1.1.2. Potential energy assessment

Potential hydropower resources were assessed at existing hydropower plants, without planning for their future development. Currently, there are 97 operating hydroelectric power plants, which are built on 57 Lithuanian rivers. The projection of potential hydropower resources was performed using discharge rates derived from the specific runoff isoline maps generated for different future periods.

The potential hydropower resources of the selected HPP were evaluated using the formula:

$$P_P = 7\, \Delta H\, Q \quad (6)$$

$$E_P = P_P\, t_P \quad (7)$$

where P_P is hydropotential capacity, kW, E_P is potential generation, kWh, ΔH is the height of the HPP dam head, m, Q is monthly discharge (m^3s^{-1}), t_P is HPP working time in hours (in Lithuania, on average, 4000 h a^{-1}).

1.2. Prediction of kinetic and potential energy of rivers using regional climate model outputs

1.2.1 Application of the HBV model for river runoff prediction

The HBV model was used to simulate the runoff of gauged Lithuanian rivers. HBV model calculations were performed in three steps, estimating (1) precipitation amount entering the ground, (2) slope runoff, as well as (3) runoff in the watercourse and runoff transformation. HBV is based on water balance equation:

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

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

The daily values of Q in the Lithuanian river and of air temperature and precipitation were used to create hydrological models. Information about the modelled catchment area, presence of lakes and forests, mean elevation (above sea level) of the area, hydrometeorological data from WGS and MS were required as well. Main output data of HBV model was time series of daily water discharge in the modelled river catchments. The period from 1986 to 1995 was selected for model calibration, whereas the period of 1996-2005 was used for validation. The calibration procedure consisted of changing model calibration parameters and comparing calculated discharge values with the measured ones.

1.2.2. Adaptation of regional climate model outputs for river runoff modelling

Air temperature and precipitation data extracted from three regional climate models were used to simulate river runoff and to evaluate its projections in the future. The projections were prepared using RCP2.6 and RCP8.5 scenarios. Adaptation of climate models data (air temperature and precipitation) for the Lithuanian territory was performed using the quantile mapping method:

$$\mathrm{St}^{\mathrm{Obs}} = h(\mathrm{St}^{\mathrm{CM\,RP}}) = ECDF^{OBS}(ECDF^{\mathrm{CM\,RP}}(\mathrm{St}^{\mathrm{CM\,Fut}})) \quad (9)$$

where $\mathrm{St}^{\mathrm{Obs}}$ is the observed meteorological parameter, $\mathrm{St}^{\mathrm{CM\,RP}}$ is climate model output for the reference period, $\mathrm{ECDF}^{\mathrm{Obs}}$ is the empirical cumulative distribution function for the observed period, $\mathrm{ECDF}^{\mathrm{CM\,RP}}$ is the empirical cumulative distribution function for climate model reference period, $\mathrm{St}^{\mathrm{CM\,Fut}}$ is a 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).

1.2.3. The runoff projection of ungauged rivers in the 21st century

When assessing the potential energy resources of ungauged Lithuanian rivers, there is a problem of lack of hydrological data. Therefore, it was not possible to develop hydrological models for the rivers in which observations were carried out only briefly or not at all. For this reason, the method of specific runoff (q, $\mathrm{l{\times}s\ km^{-2}}$) mapping was chosen to project the runoff of ungauged rivers. Using this method, isoline maps of specific runoff of Lithuanian rivers were created in the following order:

1) based on the results of hydrological modelling, monthly, seasonal and average annual runoff (Q, m^3s^{-1}) were calculated at the studied WGSs for the periods of 1986-2005, 2021-2040 and 2081-2100 under RCP2.6 and RCP8.5 scenarios;

2) discharge of the gauged rivers Q (m^3s^{-1}) was converted to specific runoff q ($\mathrm{l{\times}s\ km^{-2}}$) according to:

$$q = \frac{1000 \times Q}{A} \quad (10)$$

where q is specific discharge, $\mathrm{l\ s\ km^{-2}}$, Q is discharge, m^3s^{-1}, A is river catchment area in the conversion place, km^2;

3) using the Spline method of interpolation (in ArcGIS), isoline maps of monthly, seasonal and annual q were created for the whole territory of Lithuania for the past (1985-2005) and future (2021-2040 and 2081-2100) periods;

4) in the ungauged river catchments, specific runoff q was calculated from coordinates of hydropower plant places in the created isoline maps;

5) for ungauged rivers where water resources were assessed, q was converted to Q:

$$Q = \frac{q \times A}{1000} \quad (11)$$

In order to assess the reliability of the created map of specific runoff isolines, four rivers (the Akmena, Lėvuo, Šalčia and Ūla) having discharge observation data of 1986-2005 and not used for the mapping were selected.

1.3. Assessing uncertainties in hydropower resources projections

The uncertainties of hydropower projections arise from the selection of climate models and RCP scenarios. All possible combinations of uncertainty sources were made to identify two main sources of uncertainty. Uncertainty was assessed in three steps: 1) the kinetic and potential energies for each model and RCP scenario were calculated; 2) the difference between the lowest and highest result was estimated; 3) using the ratio method, the contribution of each model and scenario to the final result was evaluated.

1.4. Assessing the impact of small hydropower plants on the hydrological regime of rivers

There are currently 97 small hydropower plants operating in Lithuania, with a total installed capacity of 27 MW. The operation of these plants has the potential to impact the hydrological regime of rivers. 10 HPPs (Aukštadvaris, Kavarskas, Širvintai, Angiriai, Balskai, Skuodas, Rudikiai, Kuodžiai, Akmeniai, Dvariukai) have been selected for the assessment of the impacts. The potential impact of HPP on the hydrological regime of the rivers was done by comparing the pre- and post-impact flow regimes using the IHA software. An easy-to-use open-access tool, called the Indicators of Hydrologic Alteration (IHA) was used to calculate the characteristics of natural and altered hydrologic regimes. The IHA method estimates 33 ecologically relevant, yet sensitive to human influences, statistics divided into five major groups (1. Magnitude of monthly water conditions; 2. Magnitude and duration of annual extreme water conditions; 3. Timing of annual extreme water conditions; 4. Frequency and duration of high and low pulses; 5. Rate and frequency of water condition changes). In the first step of the research, using daily discharge data, the IHA software was applied to calculate the annual means of all analysed flow characteristics and then evaluate the deviation between the modified and natural regime values. In the second step, the Range of Variability Approach (RVA) was applied to compare the variation in the IHA parameters before and after the installation of HPP on the river. The RVA uses the pre-development natural variation of IHA parameter values as a reference to define the extent to which natural flow regimes have been altered. Water managers should strive to keep the distribution of annual values of the IHA parameters as close to the pre-impact distributions as possible. RVA target range of ±1 standard deviation from the mean was selected.

1.5. Subject of research and data used

The object of this thesis was the following Lithuanian rivers: Nemunas, Merkys, Šalčia, Ūla, Neris, Šventoji, Žeimena, Nevėžis, Šušvė, Dubysa, Šešupė, Jūra, Akmena, Šešuvis, Minija, Bartuva, Venta, Mūša, and Lėvuo. Daily river discharge data from 25 water gauging stations (WGS) and daily air temperature and precipitation data from 15 meteorological stations (MS) were used from 1986 to 2005. Hydrokinetic resources were estimated in all main Lithuanian rivers. Potential hydropower resources were assessed for 97 currently operating hydropower plants installed on 57 rivers. The near (2021-2040) and distant future (2081-2100) projections of the hydrokinetic and hydropotential resources were made using daily step output data (average air temperature, C°; precipitation amount, mm) from ICHEC-EC-EARTH, MOHC-HadGEM2-ES, and MPI-M-MPI-ESM-LR regional climate models (a grid cell of 11x11 km). The data of regional climate models were derived from the EURO-CORDEX database (www.euro-cordex.net).

2. RESEARCH RESULTS

The research presented in these chapters is further described in published articles (see list of publications).

2.1. Assessment of the kinetic and potential resources of Lithuanian rivers using historical data

This research assessed the hydrokinetic energy resources of Lithuanian rivers for the period 1961-2020. The hydrokinetic energy resources of the smaller Lithuanian rivers varied from 202.6 to 276.1 GWh (Fig. 2, a.), and those of the Nemunas and the Neris from 962.0 to 1114.7 GWh (Fig. 2, b). During the study period, 97 hydroelectric power plants were in operation in Lithuania, producing electricity. Their number varied from 5 in 1981-1990 to 98 in 2011-2020. Electricity production in small hydroelectric power plants is also strongly linked to the change in their numbers. Between 1981 and 1990, they produced 4,387 GWh/year, and between 2011 and 2020 they produced 65,175 GW (Fig. 2, c). Meanwhile, the electricity production of Kaunas HPP varied from 338 GWh (2011-2020) to 395 GWh (1971-1980) (Fig. 2, d). The highest resources were in the spring season and the lowest in the summer season.

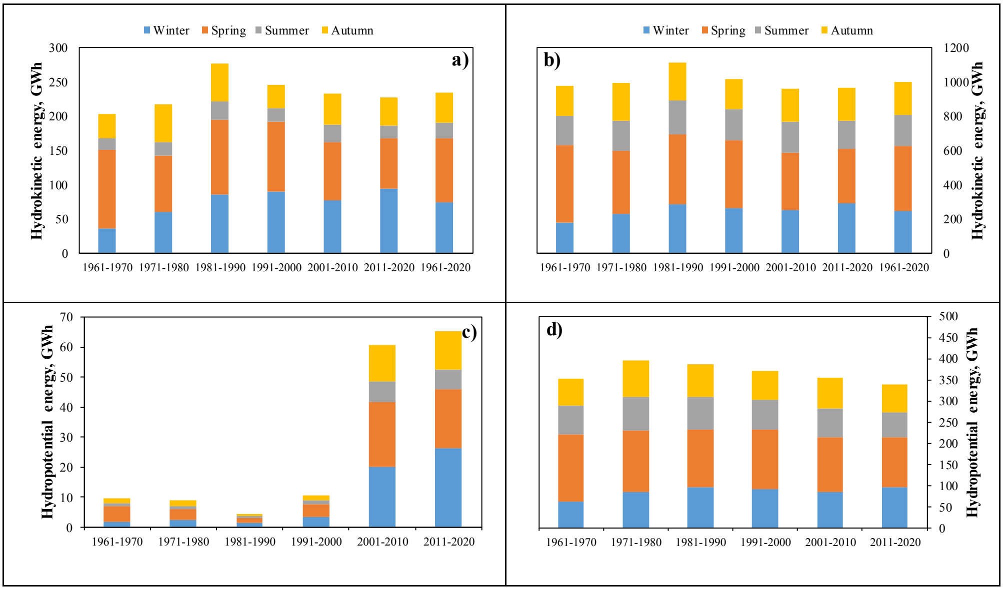

Fig. 2. Changes in hydro resources in Lithuania 1961-2020: kinetic resources of smaller Lithuanian rivers (a) and the Nemunas and Neris (b), potential resources of small hydropower plants (c) and the Kaunas hydropower station (d).

2.2. Projection of hydropower resources of Lithuanian rivers in the 21st century under climate scenarios

2.2.1. Calibration and validation of hydrological models

Calibration and validation of the created hydrological models of Lithuanian rivers was performed. The R of the selected river catchments ranged from 0.75 to 0.89 during the calibration period and from 0.60 to 0.83 during the validation period. NSE and RE (%) are also very important indicators describing the accuracy of calibration and validation. During the calibration period, NSE varied from 0.60 to 0.80, and during the validation period from 0.50 to 0.75. Meanwhile, the difference between the measured and modelled discharge (RE, %) was mostly positive during the calibration period and negative by a similar amount during the validation period.

2.2.2. Verification of the isoline mapping method

The isoline mapping verification method was done in two ways: (1) exported from a runoff isoline map using ArcGIS; or (2) calculated using real observation data at a particular WGS. Using the isoline method, the average annual q differed only by -7.7% - 3.8% from the calculated q based on observational data. The difference in Q varied from -11.5 to + 11.5% in individual seasons. Considering that in practice, the discharge is determined with an error of 40%, the result obtained was reliable and suitable for use in further studies .

2.2.3. Riverine runoff projections in gauged and ungauged river basins

Runoff projections of the gauged rivers were evaluated using hydrological modelling method. The reference period's runoff and its projections in the near and distant future were modelled according to an ensemble of three climate models and two RCP scenarios. In Lithuania, rivers are divided into three hydrological regions according to their runoff regime: western Lithuania, central Lithuania, and southeastern Lithuania. One river from each region was selected for runoff analysis: the Jūra from western Lithuania, the Mūša from central Lithuania, and the Merkys from the hydrological region of southeastern Lithuania (Fig. 3). According to this study, the river runoff will change the least in western Lithuania. The projections showed that, in the near future, the Jūra runoff will decrease from 4.0 to 7.5% compared to the reference period. Even greater changes are projected in the distant future when, according to the RCP2.6 scenario, the Jūra discharge is going to decline by 7.9% and under the RCP8.5 scenario by 10.4% (Fig. 3, a). The most unfavourable situation is possible in the hydrological region of central Lithuania. In the near future, according to the applied emission scenarios, the Mūša runoff will decrease by 6.6–10.7%, and in the distant future, from 11.9% under the RCP2.6 scenario and to 22.7% under the RCP8.5 scenario (Fig. 3, b). Meanwhile, in the hydrological region of southeastern Lithuania, the average changes in runoff have been identified. In the near future, the runoff in the Merkys will be lower from 2.2 to 5.8% compared to the reference period. However, at the end of the century, it will change more significantly and will be lower from 1.2 (RCP2.6) to 16.9% (RCP8.5) (Fig. 3, c).

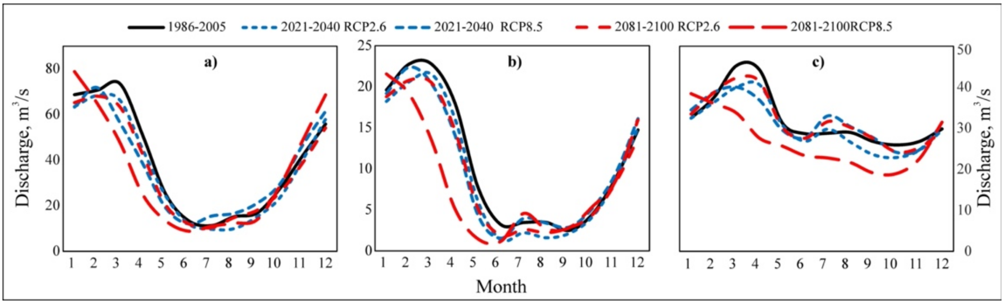

Fig. 3. Projected discharge variation in the investigated rivers in the 21st century: a) the Jūra river, b) the Mūša river, c) the Merkys river.

The method of specific runoff (q) mapping was used to project the runoff of ungauged rivers. Four maps in Fig. 4 show the change (%) in the projections of average annual specific runoff relative to the reference (1986-2005) period in the three hydrological regions. The smallest changes in q are predicted in the hydrological region of western Lithuania. In the near future, depending on the applied RCP scenario, the average q of the whole region will be from 2.2% to 4.5% lower than in the reference period. Small changes in q are likely in the distant future as well. Depending on the RCP scenario, the average values of q of the hydrological region will decrease by 5.5 - 5.9% according to RCP2.6 and RCP8.5 scenarios respectively compared to the reference period. More considerable changes are possible in the hydrological region of south-east Lithuania; in this region, in the near future, the average region q will decrease from 0.7% to 5.5% depending on the RCP scenario, and in the distant future from 1.8% (under RCP2.6) to 13.3% (under RCP8.5). The biggest changes are projected in the hydrological region of central Lithuania. In the near future, the average q is expected to decline by at least 5.8% to 9.1%, and by the end of the century, from 8.7 (RCP2.6) to 16.6% (RCP8.5) compared to the reference period. Values of specific runoff (q) differ among rivers in the same hydrological region. This is due not only to local physical and geographical conditions, which are heterogeneous in individual hydrological region but also to microclimatic features.

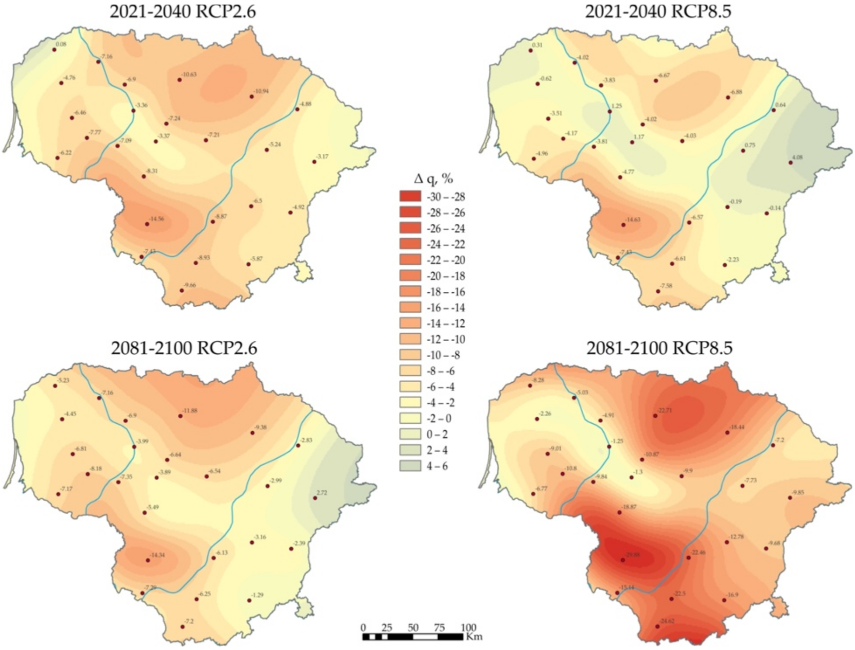

Fig. 4. Changes (in %) of specific runoff in Lithuanian rivers in the 21st century compared to 1986-2005.

2.2.4. Future changes in riverine kinetic energy resources

The assessment of kinetic energy resources of Lithuanian rivers was performed by applying technical restrictions, according to which the depth of the river bed must be greater than 0.5 m, and the flow velocity must exceed 0.4 m s^{-1}. During this study, the kinetic energy resources of the main Lithuanian rivers (excluding the major rivers Nemunas and Neris) were estimated, which amounted to 242 GWh a^{-1} in the reference period. The results show that hydrokinetic resources are expected to decline in both near and distant future. In the near future, the kinetic resources of the smaller Lithuanian rivers will decrease by 3.8% to 7.9%, and in the distant future by 6.9% to 12.8% compared to the baseline period (Fig. 5, a.). The kinetic resources of the Nemunas and the Neris will change in a very similar way. In the near future, they will shrink between 4.5% and 7.2% and in the distant future between 6.0% and 14.9% (Fig. 5, b.). In the near future, the higher changes will be in the RCP2.6 scenario and in the distant future in the RCP8.5 scenario. It also shows the redistribution of kinetic energy between seasons. At the end of the 21st century, in the RCP8.5 scenario, the percentage of the annual amount (compared to the base period) will change as follows: in the winter season it will increase from 8.3% to 12.7%, in the spring season it will decrease from 8.8% to 14.2%, and in the summer and autumn seasons it will change slightly.

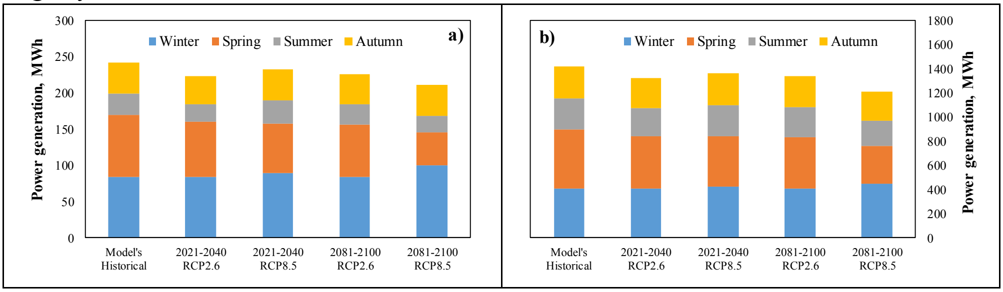

Fig. 5. Projections of kinetic resources of the main Lithuanian rivers (a) and Nemunas and Neris (b) in the near and distant future.

2.2.5. Future changes in the potential energy resources of rivers

During the reference period, 97 small HPPs generated 75 GWh a^{-1} of electricity. In 2021-2040, depending on the RCP scenario, the hydropower production of small hydropower plants is projected to decrease from 4.5% to 8.6% compared to the reference period. In 2081-2100, even larger decrease in hydropower is expected: from 7.1% (RCP2.6) to 13.7% (RCP8.5) (Fig. 6, a). In 1986-2005, Kaunas HPP produced 386 GWh a^{-1} of electricity. The projections indicated that the hydropower production of Kaunas HPP would decrease from 6.9% (RCP2.6) to 11.4% (RCP8.5) in the near future (Fig. 6, b) and decline from 7.4% to 30.6% under the selected scenario in the distant future. As shown in Figure 6, electricity production of Small HPPs and Kaunas HPP will gradually decrease during spring and increase slightly during the winter season. These changes are expected to occur due to altered runoff in the rivers of the Nemunas basin.

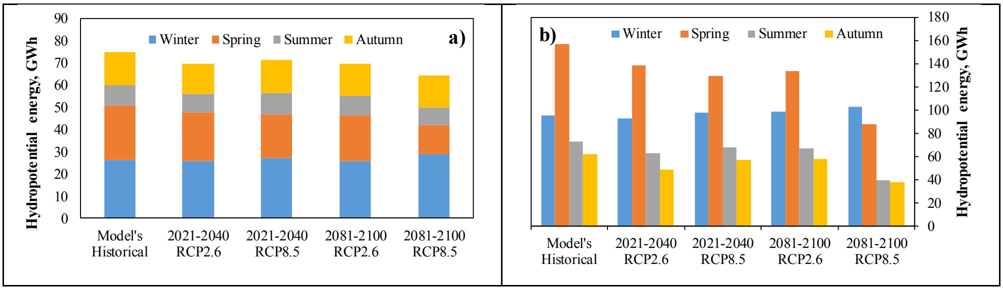

Fig. 6. Projection of energy production in small Lithuanian hydropower plants (a) and Kaunas HE (b) in the near and distant future.

2.2.6. Summary of riverine runoff and hydro-resources projections

Other research has shown that climate change will change river runoff in the future. However, different regions of the Earth may have different runoff projections due to differences in natural conditions. The thesis results demonstrate that even among diferent hydrological regions of Lithuania, river runoff projections may differ. The most significant and intimidating changes are likely to occur under the RCP8.5 scenario at the end of the 21st century. In the rivers of the hydrological region of western Lithuania, the runoff will decrease from 4.5 (RCP2.6) to 10.4% (RCP8.5), in central Lithuania from 4.0 (RCP2.6) to 31.2% (RCP8.5), and in southeastern Lithuania from 1.3 (RCP2.6) to 24.6% (RCP8.5) relative to the reference period. According to studies by other researchers, by the end of the 21st century, depending on the climate model used, the projected change in global hydropower generation under RCP8.5 will range between -8% and +5%. However, regional variations will be even greater. For example, in Norway, total hydropower production at the end of the 21st century will increase by 8% under the RCP8.5 scenario. In Germany, however, hydropower production in the mid-21st century will decrease between 10 and 30% depending on the region under the RCP8.5 scenario. The results of this thesis and others conclude that differences in predictions between and within regions are influenced by differences in natural conditions and the nature of river response to climate change.

2.2.7. Uncertainties in riverine energy resource projections

Finally the impact of climate models and RCP scenarios on hydro resource projections in the different hydrological regions was determined. The analysis demonstrated that the uncertainty in river kinetic resource projections for the western Lithuanian hydrological region was mainly caused by the choice of the climate model (70% of the uncertainty in the near future and 82% in the distant future) (Fig. 7, a). Meanwhile, the lowest spread of results was for the RCP scenarios (30% in the near future and 18% in the distant future). In central Lithuania, the influence of climate models drops to 64% in the near future and 68% in the distant future. By contrast, the impact of RCP scenarios was 36% in the near future and 32% in the distant future. In the southeastern hydrological region, the influence of climate models was 62% in the near future, and 54% in the distant future, and the influence of the RCP scenario was 38% and 46%, respectively.

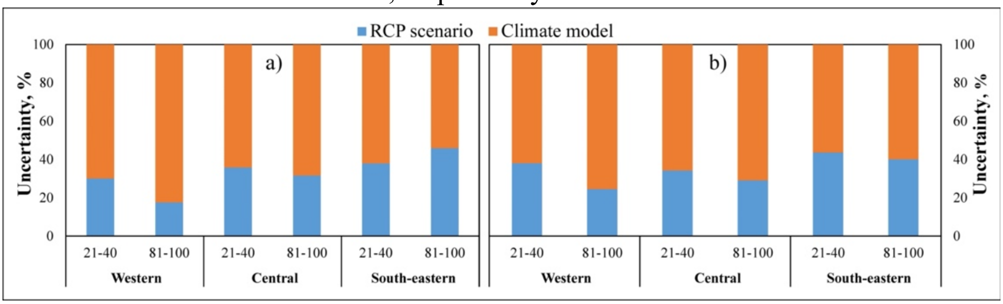

Fig. 7. Uncertainties in hydrokinetic (a) and hydro potential (b) resources projections in the near and distant future.

The uncertainty in the prediction of hydro potential resources in the western Lithuanian hydrological region significantly depended on climate models, ranging from 62% in the near future to 75% in the distant future (Fig. 7, b). The impact of RCP scenarios on the uncertainty was almost twice as small as that of climate models, at 38% in the near future and further reduced to 25% in the distant future (Fig. 7, b). In the central Lithuanian hydrological region, the influence of climate models on the projection of hydro potential resources was 66% in the near future and 71% in the distant future. The other part of the uncertainty was due to the scenarios. The smallest influence of climate models was in the southeastern hydrological region, 56% in the near future and 60% in the distant future. The impact of the scenarios became the highest of all the hydrological regions, with 44% and 40%, respectively.

Estimated that the influence of climate models on the uncertainty of kinetic and potential resource projections is highest in the hydrological region of western Lithuania, slightly lower in the hydrological region of central Lithuania, and the lowest in the hydrological region of southeastern Lithuania. The reason for these tendencies is the different conditions of runoff formation in three hydrological regions.

2.3. Impact of small hydropower plants on the hydrological regime of rivers

Initially, before the detailed investigation of hydrological regime variables using the IHA method, a statistical significance (at $p < 0.05$) of the average, maximum and minimum discharges of the pre- and post-impact periods was tested using a t-test. No statistically significant changes in the average discharges were identified. This confirms that the small HPP reservoirs, which were studied, are mostly daily regulated and do not considerably affect average annual flows. Conversely, the t-test results of extreme (minimum and maximum) flows in some rivers downstream of the dams showed significant changes, indicating substantial dam-induced modifications. The maximum flows changed significantly in the five studied river stretches, while the minimum flows changed significantly in the four stretches. Next, IHA analysis was performed. The results of deviations of the IHA parameter values are presented in Figure 8. They show that among the studied parameter groups, the most dramatic changes occurred in the frequency and duration of high and low pulses, i.e., in group 4. In contrast, IHA parameters indicating the timing of extreme flows were the least impacted hydrologic variable. The analysis revealed the most affected rivers downstream of the hydropower plants: the Šušvė, Mūša, and Bartuva, where the average of parameter groups exceeded 33%, indicating moderate changes. A possible explanation for the most significant changes in IHA parameters downstream of Angiriai HPP in the Šušvė River is the ratio of installed and multiannual discharges, which is the highest among the studied HPPs. The turbines installed in this HPP leak a large amount of water and are not regulated; therefore, their activation causes hydropeaking phenomena in the river reach below.

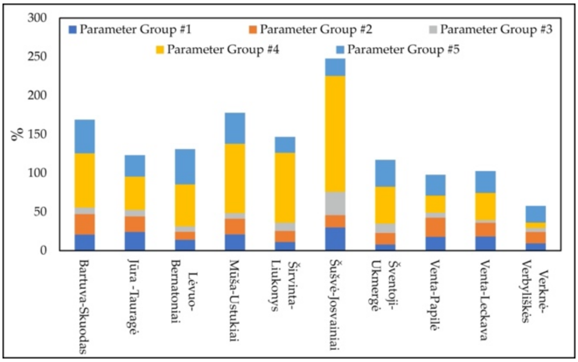

Fig. 8. Average changes of the IHA parameters groups at the studied WGSs.

In the second step of this research, the range of variability approach (RVA) was applied to calculate the alteration in a variation of the IHA parameters after installation of HPP on the river or, in other words, to estimate the degree to which the defined RVA target range (±1 SD from the mean) was not attained.

Figure 9 indicates the percentage of hydrologic indicators in each category of hydrologic alteration: low, moderate, and high. Records in the Bartuva and Jūra downstream of the HPPs show the largest percentage of flow indicators in the range of moderate and high alterations. Thirty-one hydrologic indicators fell in the low and only one of them was in the moderate alteration range at Venta-Papilė WGS downstream of the HPP.

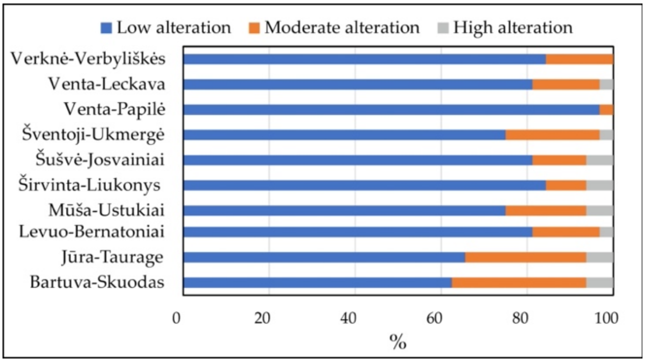

Fig. 9. The percentage of hydrologic indicators in each RVA category.

Figure 10 presents the overall degree (in %) of hydrologic alteration, taking into account both the mean and maximum values of the degree of alteration for each indicator group. At six WGSs, this degree was rated as moderate (higher than 40%), i.e., the rivers of Bartuva, Širvinta, Šušvė, and Mūša were identified as the most hydrologically modified by HPP operation. The applied concept of hydrologic variability revealed that Rudikiai HPP modified the Venta River the least.

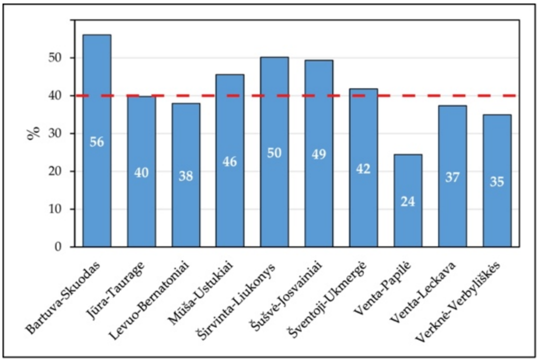

Fig. 10. The overall degree (%) of hydrological alterations.

3. RECOMMENDATIONS FOR THE SUSTAINABLE USE OF HYDROPOWER RESOURCES IN THE BACKGROUND OF CLIMATE CHANGE

The Lithuanian Government's National Energy and Climate Plan (NECP) for 2021-2030 commits to the European Union to increase the share of renewable energy sources in the country's energy mix to 45 % (Seimas of the Republic of Lithuania, 2018a.). In Lithuania, the potential energy resources of rivers represent 3.6 % of final consumption. The kinetic energy of rivers in Lithuania is currently untapped.

The following recommendations are proposed for the sustainable use of hydroenergy resources:

- As river runoff declines in the past and in the future, the electricity output of installed hydropower plants will also decline. The development of new hydropower plants in Lithuania is restricted by law (Seimas of the Republic of Lithuania, 2018 b.). Therefore, in the future, the kinetic resources of rivers should be harnessed, considering the real possibilities of their use, technologies and environmental impacts. However, there is currently no legislative framework in place. Therefore, it would be appropriate for lawmakers to develop legislation to regulate the potential use of Lithuanian rivers kinetic energy and the possible environmental impacts.

- An analysis of the impact of small hydropower plants on the hydrological regime of rivers has revealed changes in the hydrological regime associated with an increase in the number of low and high pulses and reversals. These changes reflect the fact that small hydropower plants operate in some cases in hydropeaking mode. The hydropower plants that have changed the hydrological regime of the river the most are those whose minimum operating flow (Q_{Hmin}) is higher than the regulatory minimum flow - environmental flow (Q_{gamt}). These hydropower plants cannot operate during the dry season, when the environmental flow is required to be passed through the hydropower plant, because their minimum operating flow is much higher than the environmental flow passed through the hydropower plant. It is recommended that the small hydropower plants should be reconstructed by replacing the turbines so that they can generate electricity while passing the environmental flow. The minimum flow to be passed by the hydropower plants must comply with the environmental flow established by the regulatory framework. This recommendation is most relevant for those hydropower plants with $Q_{gamt}/Q_{Tmin} \leq 0,6$.

CONCLUSIONS

1. Modelling of river runoff in Lithuania has shown that runoff will decrease by up to 15.2% between 2021 and 2040 compared to the period 1986-2005. However, in the period 2081-2100 these changes will be significantly higher and will depend on the hydrological region. Under the RCP8.5 scenario, the runoff in western Lithuania hydrological region will decrease by up to 10.4%, in central Lithuania hydrological region by up to 31.2%, and in southeastern Lithuania hydrological region by up to 24.6%, compared to the period 1986-2005.
2. Depending on the scenario and the hydrological region, the hydrokinetic resources in 2021-2040 are estimated to decrease by up to 4.3% or up to 18.8% compared to 1986-2005, while in 2081-2100 only the hydrological region of southeastern Lithuania is estimated to show a slight change (up to 2.7% according to RCP2.6), while in the rest of the regions they are estimated to decrease by between 8.8% and 36.2% compared to 1986-2005.
3. It has been estimated that in the period 2021-2040, a decrease in hydropower production of small hydropower plants is expected to reach 8.6%, and that of Kaunas HPP to 11.4%. The largest changes in hydropotential energy are likely to occur in 2081-2100, when small hydropower production will decrease by up to 14 % and Kaunas HPP by up to 30 % compared to 1986-2005. The largest negative changes in energy production will be experienced in spring season, when production will decrease by up to 40 %. Meanwhile, in the winter seasons, due to inter-seasonal redistribution of runoff, energy production may increase by up to 10%.
4. The assessment of the uncertainties in the future projections of kinetic and potential resources showed that the influence of climate models was up to 70% and 82% respectively, and up to 30% and 18% for RCP scenarios. The highest impact of climate models on uncertainties was in the hydrological region of western Lithuania and the lowest in southeastern Lithuania. This is due to the different runoff generation conditions: in western Lithuania

hydrological region, the majority of the runoff is from rain, while in southeastern Lithuania groundwater recharge dominates.

5. The IHA approach to assessing the impact of small hydropower plants on the hydrological regime of rivers has identified varying degrees of changes in the hydrological regime after the construction of hydropower plants. The most significant changes occurred in frequency and duration of large and small pulses. The number of low pulses increased on average by 151% after the installation of the hydropower plants, while the number of high pulses increased by 14%. Some of the most significant changes were found in the rate and frequency of change of runoff conditions. In ten of the eleven rivers studied, the number of reversals increased by an average of 45% after the construction of hydropower plants.

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