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Risk Analysis Related to Impact of Climate Change on Water Resources and Hydropower Production in the Lusatian Neisse River Basin

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Abstract: Water resources are one of the most important issues affected by climate change. Climate scenarios show that in the upcoming decades, further climate change can occur. It concerns especially air temperature and sunshine duration, whose prognosis indicates a significant rising trend till the end of the century. The goal of the paper was the evaluation of water resources and hydropower production in the future, depending on climate scenarios with a consideration of risk analysis. The analysis was carried out on the basis of observation data for the Lusatian Neisse river basin (Poland) for 1971–2015 and climate projections till 2100 for the RCP2.6 and RCP8.5 (representative concentration pathways) scenarios. The results of the research showed that, especially in terms of RCP8.5, very high risk of decrease in water resources and hydropower production is expected in the future. Therefore, recommendations for mitigation of the possible effects are presented.

Keywords: water resources; climate change; environmental flow; hydropower production

1. Introduction

One of the most important problems related to future development of environment conditions are water resources. Such problems are noticeable especially in the regions of the mining industry, because of the high influence of mines on both ground and surface waters. The influence is noticeable especially in river valleys, which are one of the most vulnerable regions because of water ecosystems and water users, including hydropower stations. The basin of the Lusatian Neisse River, located in south-west Poland at the Polish–German–Czech border, is a good example of the regions where issues related to hydrological conditions are a crucial problem. Lusatian Neisse is a left tributary to Odra River (Figure 1). The region is characterized by significant variability in terms of altitude, relief and land use. The southern part of the basin is located in a mountainous area (Western Sudetes and their foreland), while the lowlands form the northern part. Total hypsometric differentiation of the region varies from 100 m a.s.l. (above sea level) in the north to over 1000 m a.s.l. in the south. Most of the region is comprised of agriculture and forest areas; however, an important role is played by industry, represented by opencast mines and hydropower stations. The Lusatian Neisse River forms a border between Poland and Germany, and the problem of water management is discussed within trans-border international commissions. Numerous opencast mines located in the Polish, German and Czech parts of the region significantly affect hydrological conditions. Furthermore, flooding of some of the former open mine pits, planned in the following decades with the use of water transfer from the Lusatian Neisse River, makes future water management extremely important.

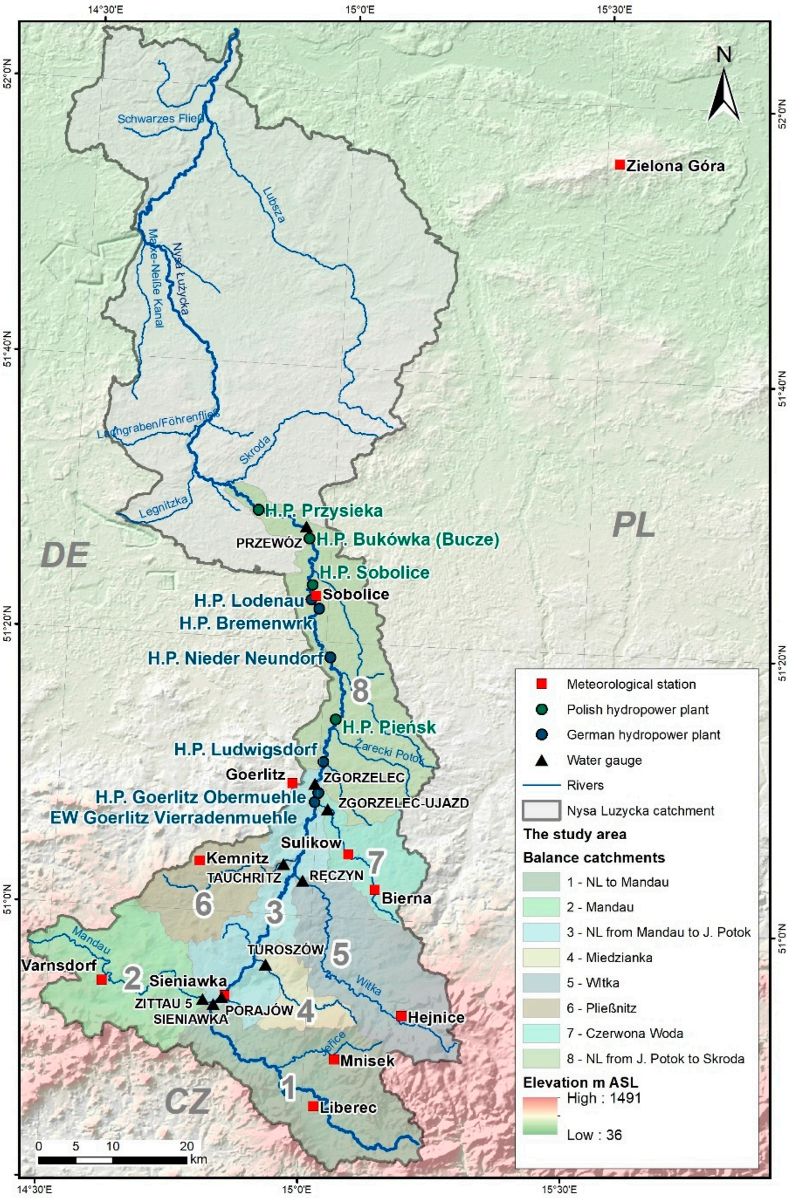


Figure 1. The Lusatian Neisse river basin with its eight sub-basins, the location of the meteorological stations of Zielona Góra and hydropower plants.

Besides mining, water resources in the discussed region are also affected by climate change. Increasing trends of air temperature and sunshine duration affect evaporation and consequently contribute to limitation of water resources. As a result, a deterioration of the ecological state and a decrease in water availability for various water users (including hydropower plants) can occur. Climate prognosis indicates further changes in the future, which can additionally affect water conditions. In the upcoming years, these changes can lead to frequent drought occurrence that have negative influences on forestry, agriculture and water availability [1,2]. In the case of the discussed region, analysis carried out within various EU projects (i.e., KLAPS—Climate change, air pollution and critical load of ecosystems in the Polish-Saxon border region; NEYMO—Lausitzer Neiβe/Nysa Łużycka, Climatic and hydrological modeling, analysis and forecast; NEYMO-NW—Lausitzer Neiße/Nysa Łużycka—modeling of climate and hydrology, analysis and forecast of water resources in low-water conditions) showed that the availability of water resources had significantly decreased during last decades [3–6]. Additionally, climate prognoses indicate further negative trends that can result in serious difficulties at the end of the century [7,8]. Taking into consideration potential changes in water conditions, appropriate measures have to be undertaken in order to minimize the effects of climate change in the future. Numerous analyses showed that undertaking such measures related to reasonable management of water resources is a crucial issue in the case of many countries and in various climate zones [9–25].

Potential climate change and its impact on various sectors can be evaluated with the use of risk analysis. Such an analysis is usually based on a risk matrix that considers both the probability of changes of defined conditions and their consequences. The aspects of risk evaluation and risk matrixes were widely discussed in papers devoted to this problem in the fields of numerous sectors [26–40]. They may concern hydrological issues, like floods or droughts. Problems concerning water resources in Poland are one of the most crucial factors affecting society [2,41–44]. Consideration of environmental flow is also very important. It is a crucial factor in the context of ecological state. Climate changes and decreased water resources can cause serious problems in terms of this type of flow [45–48]. The changes can also negatively affect hydropower production. Analyses concerning hydropower stations show that energy production in the future is strongly dependent on climate scenarios [49–61].

Climate scenarios related to potential carbon dioxide concentration show that the climate may change in different ways, depending on socioeconomic development [62]. Such diversity can have a significant impact on water resources and hydropower production in the future. In the context of future climate change, one of the most important tasks consists of measures concerning downscaling and the use of regional climate models for climate projections and the evaluation of water resources and hydropower production. The measures are related to bias correction, which refers to the definition of a perturbation of the control time series in order to force some of their statistics closer to the historical ones [63]. It assumes that the bias between statistics of the model and data will not change in the future [63–65]. Delta change techniques assume that regional climate models are a good tool for the assessment of relative changes in the statistic between present and future, but that they do not assess absolute values [63]. In the case of precipitations projections, several bias correction techniques should be taken into consideration [66]. Various correction methods were used for the evaluation of changes in water conditions, i.e., in the river basin regions of Spain, Canada, Germany, Bulgaria and Greece [66–68]. It should also be emphasized that reduction of uncertainty related to climate projections could not have importance when the hydrological models have their own sources of uncertainty [67].

The main goal of the article was to evaluate the influence of potential climate change in the upcoming decades of the century on water resources and hydropower production with the use of risk assessment. The results of the analysis can be used in long-term planning activities focused on water use. They can also be useful for the evaluation of water resources in the context of currently operating hydropower stations located on the transborder Lusatian Neisse River.

2. Case Study and Data

In the case of climate conditions, meteorological data from the IMWM-NRI (Institute of Meteorology and Water Management—National Research Institute) stations of Zielona Góra (192 m a.s.l.), Sobolice (140 m a.s.l.), Sulików (215 m a.s.l.) and Bierna (270 m a.s.l.) were used. Zielona Góra is located about 60 km to the east of Lusatian Neisse River, while the other mentioned stations represent the lowlands (Sobolice) or the mountain foreland of the Isera Mountains (Sulików, Bierna). Meteorological data concerned the 1971–2015 period and considered precipitation (all of the stations) as well as air temperature and sunshine duration (Zielona Góra). The data were the basis for carrying out an analysis concerning trends for these variables. Besides the observation records, data from climate projections were also used in the context of the evaluation of possible climate change till 2100. Characteristics were carried out for two future periods: the near (2012–2050) and far future (2071–2100). Subsequently, the results were compared to the reference period (1971–2000). The climate projections were developed within the KLAPS and NEYMO projects by Climate and Environment Consulting Potsdam GmbH [7] on the basis of global models simulations: ECHAM5 MPI-OM (European Centre Hamburg Model) and MPI-ESM-LR (Max Planck Institute for Meteorology Earth System Model). In the case of downscaling, the regional climate model of WETTREG (weather-related regionalization method) was considered. It is a statistical model used for evaluations of climate projections for the region of Central Europe. The process of downscaling was connected with the evaluation of circulation conditions, a stochastic weather generator and the use of a statistical regression method. In terms of circulation conditions, WETTREG defines weather in different classes, depending on considered meteorological factors. The stochastic weather generator enables the development of various projections that are independent from each other and characterized by equal probability. Statistical regression is connected with calculations of parameters on the basis of the modeled simulations. 1971–2000 was considered as a base period for the projections' development. The period was used for model validation, comparing measurement and simulated data. Two types of climate scenarios were used: RCP2.6 and RCP8.5 (representative concentration pathways). They are new generation scenarios that are related to CO_2 concentration in the atmosphere. They represent different radiative forces in 2100, which are equal to 2.6 W/m^2 and 8.5 W/m^2, respectively. These scenarios are dependent on various social-economic aspects: world population, changes in GDP, use of fossil fuels and energy intensity. RCP2.6 is based on a principle that maximal emission will be noticed in 2010–2020 and the increase in air temperature will not be higher than 2 °C in comparison to the preindustrial era. On the other hand, for RCP8.5 a constant increase in emission is projected until 2100. In the case of RCP8.5, energy intensity and use of fossil fuels at the end of the century can be twice as higher as for RCP2.6 [69]. The scenarios of RCP2.6 and RCP8.5 were presented in one of the latest IPCC (Intergovernmental Panel on Climate Change) reports [62].

Climate analysis concerned changes in mean annual values of air temperature, sunshine duration and annual precipitations totals. The calculations and analysis for these sectors mainly concerned the periods of the near (2021–2050) and far (2071–2100) future. The results for these periods were compared with simulated values for the reference period (1971–2000).

In terms of hydrological conditions, discharges for RCP2.6 and RCP8.5 scenarios for the same periods were calculated. They were the basis for calculations of environmental flow according to Kostrzewa's formula [70], and were also used for the evaluation of unitary runoff. The hydrological modeling was carried out with the use of rainfall-runoff MIKE NAM software [71,72]. In the NEYMO project, the model was calibrated with the use of precipitation, evapotranspiration and discharges data. The model uses algorithms concerning the hydrological cycle within the basin. Such an approach enables simulations related to precipitations to outflow transformations. The analysis on hydrological conditions was based on sixteen rainfall-runoff models for balance sub-basins that were developed within MIKE NAM during the realization of the NEYMO project. The models concerned the whole region of the Lusatian Neisse basin and were developed and calibrated for observation data for the 1971–2000 period and subsequently validated for 2000–2010 data [4] (Table 1). They were examined for particular sub-basins. Finally, models developed for eight balance sub-basins were taken into consideration. Based on the results of the models, tendencies for discharges changes were analyzed for eight balance areas (Table 2). The results were summarized for Przewóz gauge, which is a closing gauge of the discussed balance region. The input for the models consisted of precipitation data and the meteorological variables necessary for the calculation of potential evapotranspiration mean, maximum and minimum air temperature, wind speed, sunshine duration and air humidity. Potential evapotranspiration was calculated with the use of ETO software, developed by the Land and Water Division of the FAO (Food and Agriculture Organization of the United Nations).

Table 1. List of measuring stations used to build and calibrate run-off models [4].

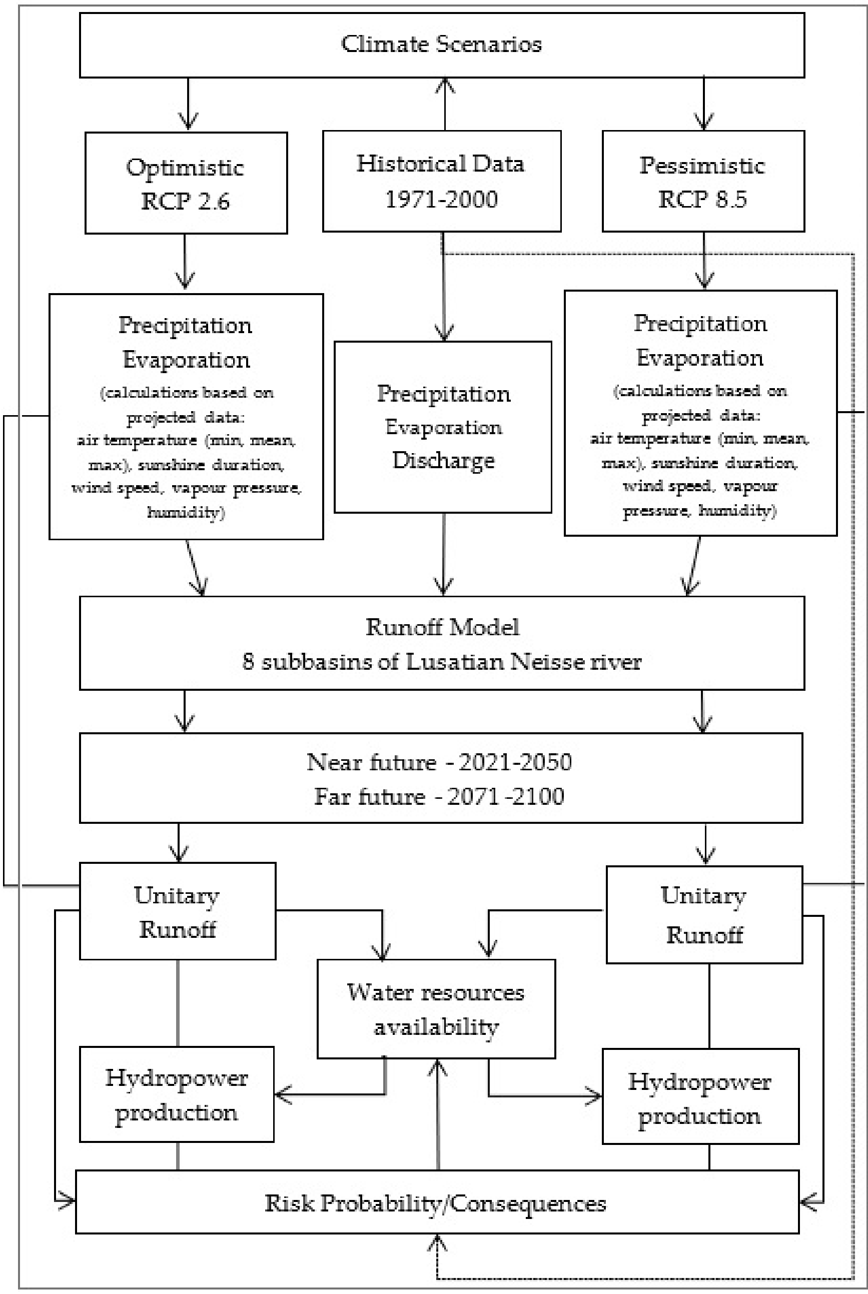
Sub-Basin Number	Name of Sub-Basin	Water Gauge	Precipitation	Evaporation
1	Nysa Łużycka from. Mandau river	Porajów	Liberec	Görlitz
2	Mandau	Zittau 5	Varnsdorf	Cottbus
3	Nysa Łużycka from Mandau river to Jędrzychowicki Potok river	Porajów, Sieniawka, Zgorzelec	Sieniawka	Görlitz
4	Miedzianka	Turoszów	Minsek	Görlitz
5	Witka	Ostróżno	Hejnice	Görlitz
6	Pließnitz	Tauchritz	Kemnitz	Görlitz
7	Czerwona Woda	Zgorzelec Ujazd	Sulików	Görlitz
8	Nysa Łużycka from Jędrzychowicki Potok to Skroda river	Zgorzelec, Przewóz	Sobolice	Görlitz

Table 2. Results of the assessment of MIKE NAM (Nedbor-Afstromnings-Model) models using Nash–Sutcliffe Efficiency (NSE) statistics and comparison of simulated and observed discharge in eight sub-basin areas.

Sub-Basin Number	Statistics NSE	Average Discharge [m^3/s]	
		Observed	Simulated
1	0.5	6.05	6.02
2	0.6	3.41	3.46
3	0.5	1.28	1.29
4	0.5	0.94	0.92
5	0.5	3.60	3.52
6	0.5	1.09	1.07
7	0.5	0.77	0.77
8	0.5	3.04	3.17

Results of calculations of discharges were also the basis for the evaluation of hydropower production in the future (Scheme 1). In the discussed region, it concerns Polish and German hydropower plants that are the main water users in the Lusatian Neisse river basin. The analysis presented in the paper is focused on changes in nominal energy production between the near (2021–2050) and far (2071–2100) future and the current period (2015–2020).

Both Polish and German hydropower plants were taken into consideration. Energy generated by hydropower plants depends on differences in water levels before and behind the turbines, the turbine's gullet, and the efficiency of the turbines, transmission and generator. There are eight German and three Polish hydropower stations located on the Lusatian Neisse River that provide energy for the region (Table 3). In the paper, analyses were carried out for nine of them, as in case of two German plants (Altes Sagewerk and Apelt Mühle) no data on the turbines' gullet were available.



Scheme 1. Methodological approach related to the impact of climate change on water resources.

Table 3. Main features of the Polish and German hydropower station on the Lusatian Neisse River.

Hydropower Station	Turbine's Gullet [m^3/s]	Differences in Water Level [m]	Efficiency Index	Nominal Hydropower Production [kWh/year]
Obermühle	7.3	1.80	0.84	948,522.78
Vierradmühle	10	2.70	0.86	1,995,424.63
Ludwigsdorf	22	2.46	0.86	3,999,717.82
Pieńsk	10	4.20	0.86	3,103,993.87
Nieder-Neundorf	24	3.64	0.86	6,456,307.25
Bremenwerk	22.4	3.00	0.86	4,966,390.20
Lodenau	24	4.70	0.86	8,336,440.68
Sobolice	22	3.60	0.80	5,444,879.62
Bukówka	20.6	5.50	0.83	8,081,297.89

Depending on possible changes in discharges in the future, calculations for potential power generation for RCP2.6 and RCP8.5 were carried out. They concerned the following formula:

$$N = 9.81 \cdot Q \cdot H \cdot \eta,$$

In the equation, N refers to generated power [kW], Q to the turbine's gullet [m^3/s], and H means differences in water levels before and behind the turbines [m]. Furthermore, η is an efficiency index and 9.81 refers to standard gravity [m/s^2]. The calculations were carried out on the basis of technical-exploitation data concerning the hydropower plants, which were presented in the paper devoted to the water balance of the Lusatian Neisse River [73]. The results of the analysis were shown for various multiannual future periods.

3. Methods

The main purpose of the analysis was to evaluate risk related to the impact of climate change on water resources and hydropower production. In this case, a risk matrix was used. It considers both the probability and consequences of climate change. Probability was evaluated on the basis of selected meteorological elements, while consequences were assessed for water resources and hydropower production.

Probability refers to changes in three meteorological variables—air temperature, sunshine duration and precipitations. For each of the variables, five classes of probability were selected (where 5 is the highest probability of change). In the case of probability evaluation, aspects of projected changes in the future were taken into consideration.

According to the settings of the projections, each scenario is characterized by the same probability of occurrence. In the case of RCP2.6, the tendency of climate change after 2050 can be different than in the first half of the century. It indicates that climate conditions can change in different ways depending on the period. Therefore, in order to evaluate the probability of changes in particular meteorological variables, the level of local warming (for air temperature) and local changes in sunshine duration and precipitation, totals in the future were taken into consideration. These particular levels of climate change were evaluated on the basis of projected data for two periods—2021–2050 and 2071–2100. The analysis was carried out for two considered scenarios that represent the same scenario family—RCP2.6 and RCP8.5. Thus, in terms of probability evaluation, the following factors were considered:

1. Projected air temperature/sunshine duration/precipitations for 2021–2050, according to RCP2.6
2. Projected air temperature/sunshine duration/precipitations for 2021–2050, according to RCP8.5
3. Projected air temperature/sunshine duration/precipitations for 2071–2100, according to RCP2.6
4. Projected air temperature/sunshine duration/precipitations for 2071–2100, according to RCP8.5

On the basis of the mentioned criteria, four levels of local warming and local changes in sunshine duration and precipitation totals (W1, W2, W3, W4) were calculated (Table 4). They are defined as differences between mean values for the near (2021–2050) and far (2071–2100) future and the reference period (1971–2000), considering both RCP2.6 and RCP8.5 scenarios. Each positive value of local climate change level (W) for air temperature or sunshine duration, in the comparison to the reference period of 1971–2000, increases the probability rate by 1 (Table 5). The more criteria are met, the higher is the probability of future changes in a given meteorological variable. Probability was assessed separately for air temperature and sunshine duration.

Table 4. Evaluation of levels of local warming (T), local changes in sunshine duration (SD) and precipitation totals (RR) on the basis of climate projections for RCP2.6 and RCP8.5 for 1971–2000, 2021–2050 and 2071–2100.

Level of Local Climate Change	Difference between Projected Data for Future Periods (2021–2050 and 2071–2100) and the Reference Period of 1971–2000
W1	Projected T, SD, RR for 2021–2050 (RCP2.6)—Projected T, SD, RR for 1971–2000
W2	Projected T, SD, RR for 2021–2050 (RCP8.5)—Projected T, SD, RR for 1971–2000
W3	Projected T, SD, RR for 2071–2100 (RCP2.6)—Projected T, SD, RR for 1971–2000
W4	Projected T, SD, RR for 2071–2100 (RCP8.5)—Projected T, SD, RR for 1971–2000

Table 5. Criteria for probability (P) evaluation related to changes in air temperature (T) and sunshine duration (SD).

P	Criteria Fulfilled	Criteria
1	None	Projected T, SD according to W1 > Projected T, SD for 1971–2000
2	One criterion	Projected T, SD according to W2 > Projected T, SD for 1971–2000
3	Two criteria	Projected T, SD according to W3 > Projected T, SD for 1971–2000
4	Three criteria	Projected T, SD according to W4 > Projected T, SD for 1971–2000
5	Four criteria	

In the case of precipitation, the criteria are reversed (Table 6). Because of the fact that a decrease in precipitations affects water availability, the probability of changes in precipitation increases when projected totals for the future periods are lower than the values simulated for 1971–2000. Four stations were considered with the purpose of evaluating precipitation, which gives 16 total results for potential change in precipitation totals in the future. The projected values were assessed according to the criteria presented in Table 6 in terms of how many results (in %) meet the criteria. In this case, a decrease rate of 5% was considered as a threshold. If projected totals are higher, comparable or slightly lower (<5%) than in 1971–2000, the criterion is not met.

Table 6. Criteria for probability (P) evaluation related to changes in precipitation totals (RR).

P	Criteria Fulfilled	Criteria
1	0%	Projected RR according to W1 < Projected RR for 1971–2000,
2	0–25%	Projected RR according to W2 < Projected RR for 1971–2000,
3	26–50%	Projected RR according to W3 < Projected RR for 1971–2000,
4	51–75%	Projected RR according to W4 < Projected RR for 1971–2000
5	76–100%	

Potential consequences of the impact of climate changes on selected sectors were also classified into five classes depending on the intensity of the effects. Consequences were evaluated separately for each of the sectors. Probability and consequences were the basis for risk evaluation. Probability multiplied by the ratio of consequences is equal to the risk value. A description of potential consequences is presented in Table 7, while dependence between probability and consequences is shown in a risk matrix.

The consequences rate for water resources and hydropower production shows how these sectors can be affected by projected air temperature, sunshine duration and precipitation changes. The range of consequences varies from minor (no impact of these meteorological variables) to very high (changes in climate conditions cause serious problems with water resources and hydropower production).

Table 7. Evaluation of consequences of the impact of meteorological variables on water resources and hydropower production.

Evaluation of Consequences		
1	Minor	No changes in water resources, no impact on hydropower production
2	Low	Low changes in water resources; low impact on hydropower production
3	Medium	Medium changes in water resources; medium impact on hydropower production
4	High	High changes in water resources; high impact on hydropower production
5	Very high	Very high changes in water resources; very high impact on hydropower production

In terms of evaluations of consequences for water resources, two factors were taken into consideration: future changes in mean maximal and minimal discharge, and environmental flow (Table 8). In the case of discharges, a potential decrease in the near and far future in comparison to the reference period was taken into consideration. Changes rate of 5%, 20%, 35% and 50% were considered as the boundary values. The threshold of the highest class (50%) was estimated on the basis of the results for the last decades of the century for other European rivers, according to the RCP8.5 scenario [74]. The impact of climate change on environmental flow was related to the projected number of mean discharges below environmental flow. If over 10% of the projected discharges were below environmental flow (changes over 10th percentile), consequences were classified as 4 or 5, depending on discharge changes.

Table 8. Criteria for the evaluation of consequences (C) for water resources.

C	Discharge Changes	Impact on Environmental Flow
1	Slight decrease (<5%)	No impact
2	Moderate decrease (5–20%)	No impact
3	Noticeable decrease (20–35%)	Minor impact (<10%)
4	High decrease (35–50%)	Noticeable impact (>10%)
5	Very high decrease (>50%)	Noticeable impact (>10%)

The evaluation of consequences for hydropower production was based on its possible changes in the future. In this case, differences (in %) between 2015–2020 and the near and far future were taken into consideration. Previous analysis showed that in the alpine region, where potential for hydropower production is very high, climate change can contribute to a decrease of over 25% in production in the following decades [50,52]. Therefore, for the purposes of this paper, the value of 25% was taken as a threshold for the evaluation of maximal level of consequences. If projected hydropower production in the future was more than 25% lower than nowadays, the maximum level of consequences was given (Table 9).

Table 9. Criteria for evaluation of consequences (C) for hydropower production.

C	Hydropower Production Changes
1	No changes or increase
2	Slight decrease (<5%)
3	Moderate decrease (5–15%)
4	High decrease (15–25%)
5	Very high decrease (>25%)

Based on the evaluated probability and consequences, a risk assessment was carried out. The evaluation of risk was carried out on the basis of the risk matrix (Table 10). The highest risk is noticed when both the probability and consequences are characterized by high values. It especially concerns situations with probability and consequences reaching 4 or 5, which eventually results in "very high" risk. Such a matrix enables risk evaluation for water resources and hydropower production under climate change conditions.

Table 10. Risk matrix presenting the probability of change in meteorological variables and consequences for water resources and hydropower production (red: very high risk; orange: high risk; yellow: medium risk; green: low risk) [27,39].

RISK		**PROBABILITY**				
		1	**2**	**3**	**4**	**5**
	5	5	10	15	20	25
	4	4	8	12	16	20
	3	3	6	9	12	15
	2	2	4	6	8	10
	1	1	2	3	4	5

4. Results

4.1. Changes in Climate Conditions

In the considered multiannual period (1971–2015), the mean annual air temperature in Zielona Góra was equal to 8.9 °C. The year 1996 was the coldest year (6.8 °C), while the highest values were observed in 2014 and 2015. In these years, mean annual air temperature reached 10.4 °C and 10.5 °C (Figure 2). The course of mean annual values for air temperature in the 1971–2015 period was characterized by an increasing, statistically important trend. The rate of changes in air temperature was equal to 0.34 °C/decade. The same rate was observed for mean annual values of maximum air temperature, while the increase in minimum temperature was equal to 0.33 °C/decade. In the considered period, the course for both maximum and minimum air temperature was characterized by statistical importance.

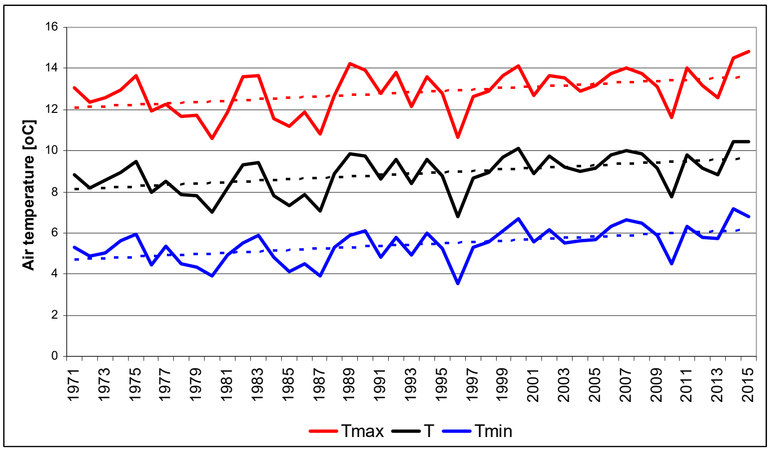


Figure 2. Mean annual values of maximum (Tmax), mean (T) and minimum (Tmin) air temperature with linear trends in 1971–2015 in Zielona Góra.

RCP scenarios project further changes in air temperature in the following decades (Figure 3). In terms of RCP2.6, prognosed data for Zielona Góra show an increase in air temperature for 2015–2100; however it is characterized by low intensity. Comparing the results for the near (2021–2050) and far future (2071–2100) with the reference period (1971–2000), air temperature in the near future in Zielona Góra can increase by about 1 °C. In the following decades, changes in air temperature are minor and are characterized by similar values to those of 2021–2050.

Scenario RCP8.5 is related to quite a different course of thermal conditions. In this case, a constant increase in air temperature is projected during 2015–2100. Air temperature values, calculated for the near and far future, are significantly higher when compared to the reference period. The differences are more noticeable than for RCP2.6. In 2021–2050, mean air temperature is higher than for the reference period by about 1.6 °C. The differences continue to increase for 2071–2100, when they reach 3.6 °C.

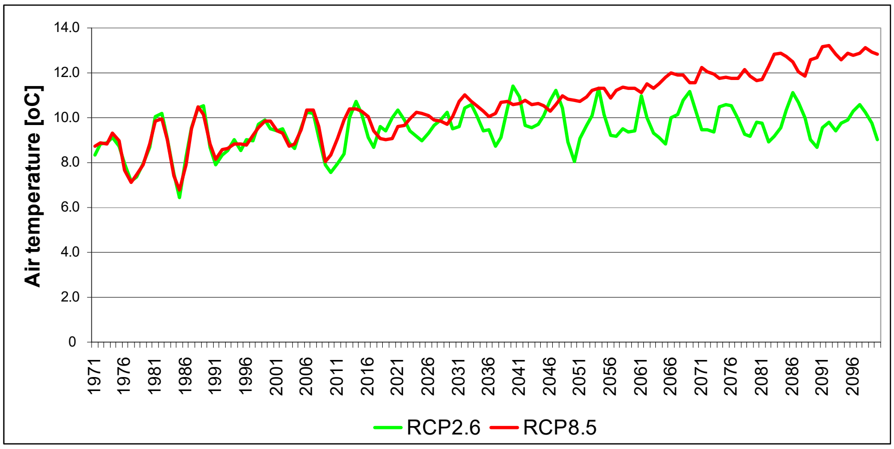


Figure 3. Projected air temperature values for 2015–2100 in Zielona Góra, according to RCP2.6 and RCP8.5 scenarios.

In terms of sunshine duration, the mean annual value in Zielona Góra is equal to 1552 h (hours). Observed changes in annual sunshine duration were comparable with air temperature. In 1971–2015, annual sunshine duration was characterized by an increasing trend with statistical importance. In the considered period, sunshine duration in Zielona Góra increased by about 80 h/decade. The highest sunshine duration was observed in 2015, when its annual value exceeded 2160 h. The lowest values were observed in 1977 (1166 h) (Figure 4).

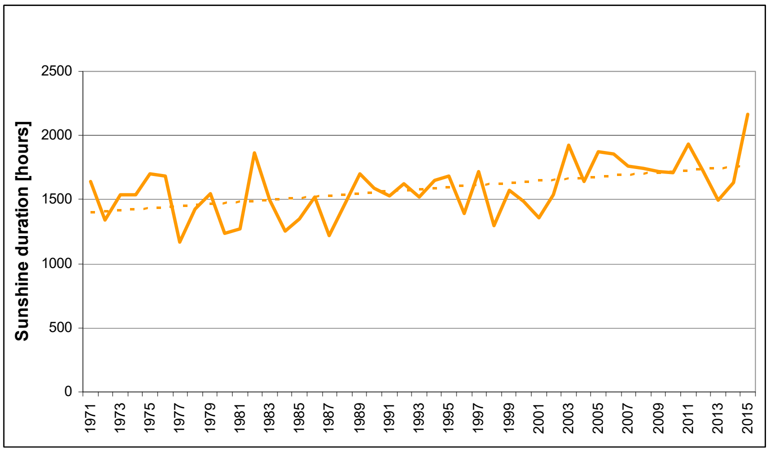


Figure 4. Annual sunshine duration with linear trend in Zielona Góra in 1971–2015.

A further increase in sunshine duration is also projected in terms of climate projections. Prognosed changes, similarly to air temperature, strongly depend on climate scenarios (Table 11). The most intensive changes are simulated for RCP8.5. In the case of the near future, predicted annual values of sunshine duration in Zielona Góra in 2021–2015 can be higher by about 180 h in comparison to the reference period. In the case of RCP2.6, the intensity of the changes is almost twice as low.

Simulations for RCP8.5 show that annual sunshine duration can additionally increase in the upcoming decades under RCP8.5 conditions. In 2071–2100, annual values of sunshine duration can be 340 h higher than in 1971–2000. In terms of RCP2.6, simulations show a slight decrease in sunshine duration in comparison to the near future. Therefore, such a tendency is similar to air temperature.

Comparing projected annual sunshine duration with the reference period, the far future is characterized by values exceeding those for 1971–2000 by 66 h.

Table 11. Differences in annual sunshine duration (hours) between the near (2021–2050) and far future (2071–2100) and the reference period (1971–2000) in Zielona Góra.

Scenario	2021–2050	2071–2100
RCP2.6	79.0	66.4
RCP8.5	179.6	339.8

Precipitation is characterized by high year-to-year variety. In the analyzed observation period (1971–2015), mean annual totals varied from 577 mm in Zielona Góra (lowlands) to 736 mm in Bierna (mountain foreland). The highest totals were noticed in 2010, when they exceeded mean values even by 50% (Bierna). On the other hand, 1982 and 2003 were the driest years, with precipitation totals reaching 50–70% of the mean multiannual totals. In the case of the course of annual precipitation totals, a slightly increasing trend was observed for all of the considered stations; however no statistical importance was noticed (Figure 5).

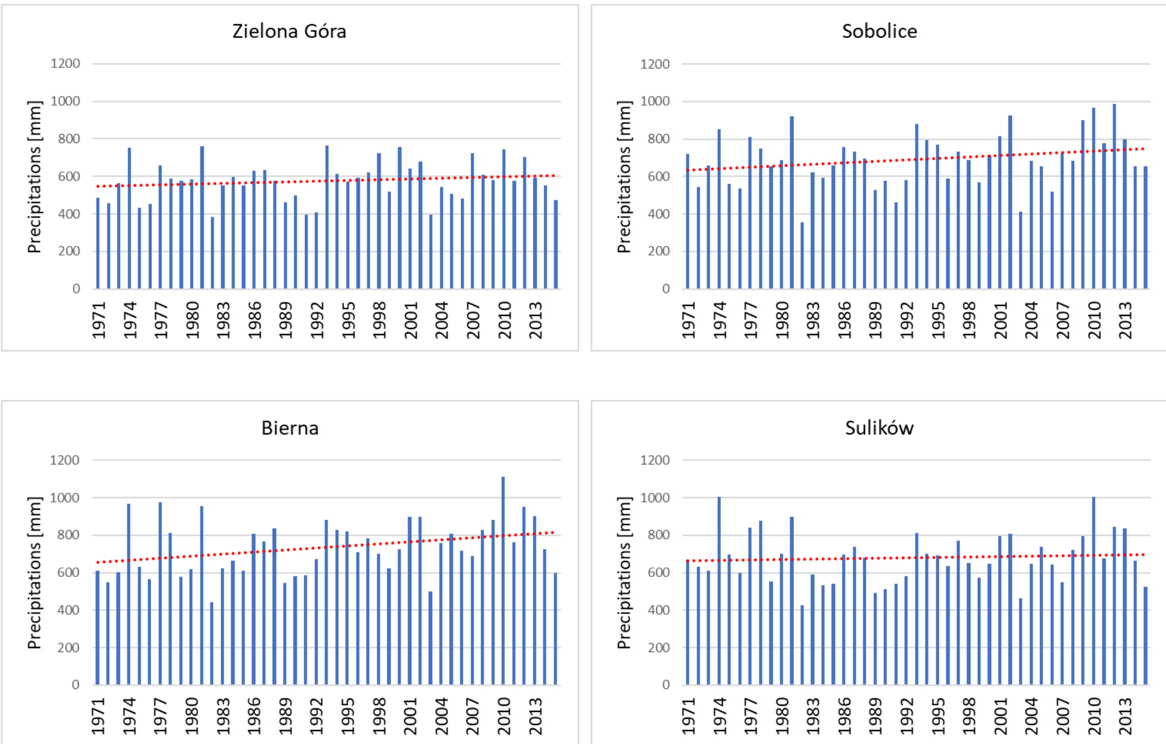


Figure 5. Annual precipitation totals and their trend for 1971–2015 in the Lusatian Neisse river basin.

Projections for precipitation, according to RCP2.6, do not show any significant changes in annual totals (Table 12). In the case of the considered stations, a slight increase (Zielona Góra and Sulików) or decrease (Bierna) were simulated for 2021–2050. However, the changes do not exceed 1%. The prognosis for the far future (2071–2100) does not indicate major changes either. Annual precipitation totals can be a little lower (Zielona Góra) or comparable (Sulików, Sobolice) to the values simulated for 1971–2000. The highest change was noticed for Bierna (for 2071–2100), where projected precipitations can be 2% lower than in the reference period.

More noticeable changes were modeled for RCP8.5. In this case, all the stations were characterized by lower precipitation totals. The most significant decrease was modeled for the station of Bierna, located in the southern part of the region, in the mountain foreland. The projections indicate that annual precipitation totals can be lower by about 5% in 2021–2015. An even higher decrease is simulated for the far future, when mean values in Bierna can be 13% lower than at the end of the 20th century. The remaining stations are also characterized by decreasing precipitation, especially for 2071–2100. In Sobolice and Sulików the totals can be lower by 5–8% in comparison to the reference period, while in Zielona Góra they are comparable with the near future.

Table 12. Projected changes in annual precipitation totals (%) between the near and far future (2021–2050; 2071–2100) and the reference period (1971–2000) in Zielona Góra (ZG), Sulików (SUL), Sobolice (SOB) and Bierna (BIE), according to the RCP2.6 and RCP8.5 scenarios.

Period	RCP2.6				RCP8.5			
	ZG	SUL	BIE	SOB	ZG	SUL	BIE	SOB
2021–2050	1	1	−1	0	−2	−1	−5	−1
2071–2100	−1	0	−2	0	−2	−8	−13	−5

4.2. Changes in Hydrological Conditions

One of the most important tasks concerning water resources is determining hydrological conditions. In this case, river discharges were projected for the 1971–2100 period. Similarly to the meteorological variables, simulations for hydrological conditions were carried out for three periods: 1971–2000 (reference period), 2021–2050 (near future) and 2071–2100 (far future).

The results showed that the direction and intensity of hydrological changes are dependent on changes in particular meteorological variables. In terms of the RCP2.6 scenario, negative changes in discharges are prognosed for the future periods. The changes concern a decrease in discharges, which consequently leads to a lower amount of water resources. In terms of the reference period, mean simulated discharges varied from 12.4 m^3/s to 13.4 m^3/s. In the near future, projected discharges reach 10.2–11.5 m^3/s, whereas for the far future, hydrological conditions seem to be a little more optimistic if compared to the near future—the mean discharge rate amounts to 10.4–12.3 m^3/s.

The results for RCP8.5 show that the discharge rate in the future can significantly fall, especially in the latest decades of the century. Basing on the models' principles, mean discharges for the reference period were classified into 11.2–13.5 m^3/s. In the case of the future periods, the simulations for 2021–2050 show that the values can be equal to 9.8–11.3 m^3/s. In the far future, a further significant decrease can occur. In this case, mean discharges can amount to 7.0–8.6 m^3/s. Therefore, minimum and maximum values of mean discharges, according to RCP8.5, can decrease by about 36–38% when compared to 1971–2000 (Table 13).

Table 13. Simulated maximum and minimum values for mean annual discharges [m^3/s] for the Przewóz gauge in the reference period (1971–2000), near future (2021–2050) and far future (2071–2100).

Period	RCP2.6		RCP8.5	
	Min	Max	Min	Max
1971–2000	12.4	13.4	11.2	13.5
2021–2050	10.2	11.5	9.8	11.3
2071–2100	10.4	12.3	7.0	8.6

The consequence of the changes in discharge rates in the future is also a modification of unitary runoff. The predicted tendency for unitary runoff is similar to the discharge changes presented above, and can vary depending on type of scenario. Simulated unitary runoffs for the most pessimistic realizations of RCP2.6 and RCP8.5 are presented in Figures 6 and 7.

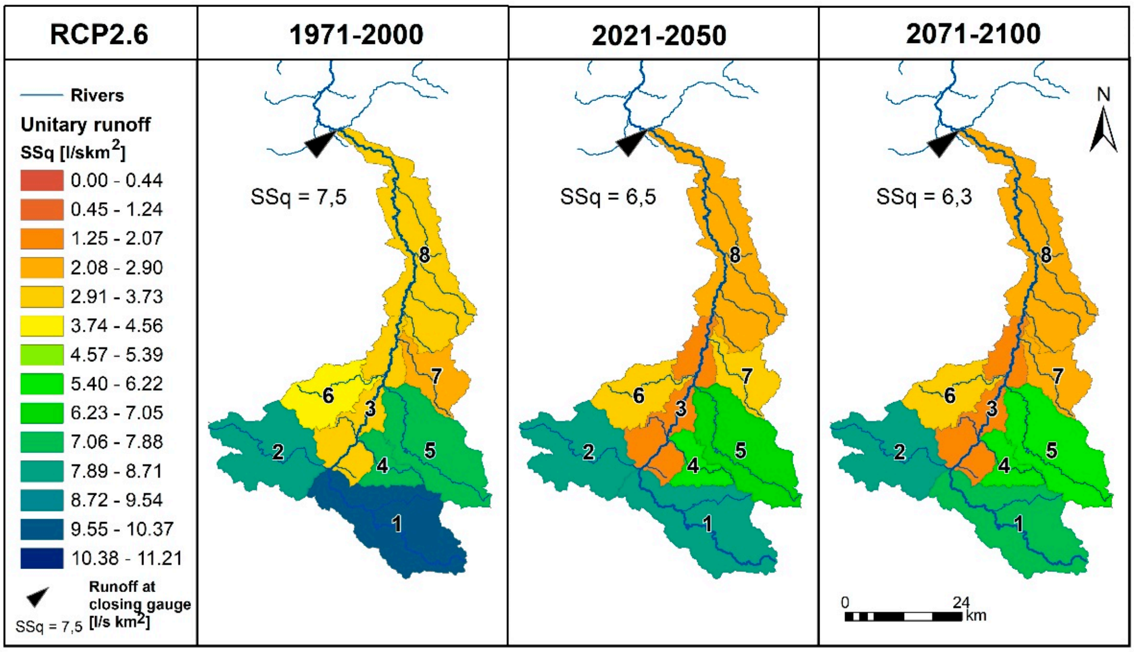


Figure 6. Simulated unitary runoff for the eight sub-basins of Lusatian Neisse river basin, according to a realization of R09 of the RCP2.6 scenario.

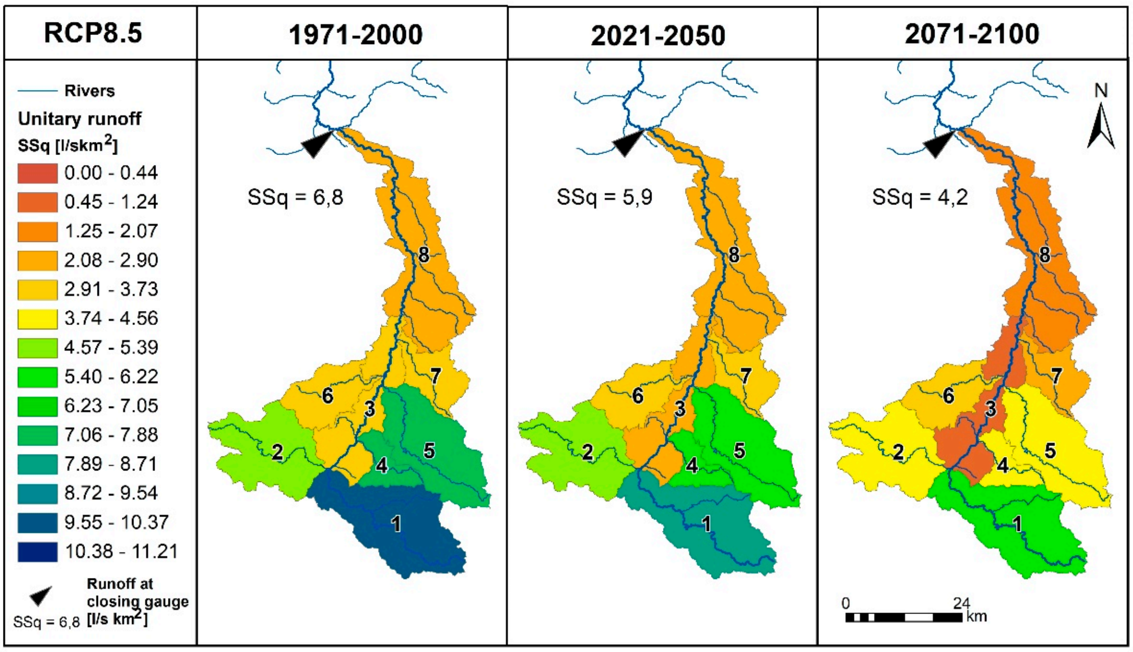


Figure 7. Simulated unitary runoff for the eight sub-basins of Lusatian Neisse river basin, according to a realization of R08 of the RCP8.5 scenario.

A decrease in discharges in the future can contribute to an increase in the number of situations when discharge rates can be lower than environmental flow. According to Kostrzewa's formula, the value of environmental flow for the Przewóz gauge is equal to 3.17 m^3/s. Thus, considering projected discharge rates, calculations of frequency of mean monthly discharges below environmental flow for all of the considered scenarios and future periods were carried out. The results showed that a very high number of such situations can occur in the case of the RCP8.5 scenario, especially in the far future. The simulated mean frequency of mean monthly discharges that are below environmental flow for 2021–2050 is equal to 2.1% (RCP2.6) and 3.3% (RCP8.5). In the case of RCP8.5, for some of the runs of the scenario, it even amounts to over 6%.

For the period of the far future, the frequency of such discharges, in terms of RCP8.5, dramatically increases. The simulations project that over 10% of the mean monthly discharges can be below 3.17 m^3/s. Some of the runs for RCP8.5 show that the number of discharges below environmental flow can exceed 18% of all calculated discharges. In these terms, RCP2.6 is definitely a more optimistic scenario, as it projects the frequency of such critical discharges in the far future to be below 2% (depending on the runs, the increase in such a frequency can rise from 0.3% to 3.1%). That shows that in the context of water resources in the future, it is very important to keep climate change within the level considered in RCP2.6.

4.3. Changes in Hydropower Production

One of the most important issues related to water resources is hydropower production. Both German and Polish hydropower stations located on the Lusatian Neisse River play a crucial role in hydropower production. Calculations of potential annual hydropower production were carried out for current conditions and for the future. They were based on modeled discharge values for the periods of 2015–2020, 2021–2050 and 2071–2100 for two considered climate scenarios.

Taking into account changes in discharges evaluated on the basis of RCP2.6, hydropower production in the future can be equal or even higher than it is currently. In the near future, hydropower production at the power plants with large turbine gullets can increase by up to 5% in comparison to 2015–2020. In 2071–2100, it can additionally increase by 1–2% (Table 14). Quite different conditions are simulated for RCP8.5 (Table 15). In this case, a significant decrease in hydropower production is modeled, especially for the last decades of the century. In 2021–2050, the production can fall by 4–9% in comparison to 2015–2020, while for the far future (2071–2100) it can additionally decrease by even 25%. In the case of the last period, the hydropower stations with large turbine gullets can be characterized by energy production reaching only 34% of the nominal potential (Nieder-Neundorf, Lodenau). In Table 16 we present the projected values of hydropower production for particular hydropower stations and the ratio of its decrease between 2015–2020 and 2071–2100 for RCP8.5. According to these projections, almost all hydropower stations are characterized by a decrease of 31–34%. The hydropower station of Obermühle is the only one with a relatively low decrease, reaching 16%. This shows that in the case of the RCP8.5 scenario, potential energy supply by the hydropower stations can be seriously limited.

Table 14. Projected annual hydropower production in 2015–2020, 2021–2050 and 2071–2100 and its share [%] in nominal hydropower production at German and Polish hydropower plants on the Lusatian Neisse River, on the basis of mean discharges for the RCP2.6 scenario.

Hydropower Station	2015–2020		2021–2050		2071–2100	
	kWh/year	%	kWh/year	%	kWh/year	%
Obermühle	948,522.78	100	948,522.78	100	948,522.78	100
Vierradmühle	1,560,487.37	78	1,718,204.79	86	1,760,447.08	88
Ludwigsdorf	1,486,323.25	37	1,636,544.95	41	1,676,779.62	42
Pieńsk	2,694,622.68	87	2,966,966.40	96	3,039,909.65	98
Nieder-Neundorf	2,445,238.00	38	2,692,376.57	42	2,758,569.00	43
Bremenwerk	2,045,497.89	41	2,252,235.00	45	2,307,606.49	47
Lodenau	3,216,438.51	39	3,541,521.80	42	3,628,590.57	44
Sobolice	2,301,401.41	42	2,534,002.52	47	2,596,301.30	48
Bukówka	3,882,551.23	48	4,274,958.09	53	4,380,058.49	54

Table 15. Projected annual hydropower production in 2015–2020, 2021–2050 and 2071–2100 and its share [%] in nominal hydropower production at German and Polish hydropower plants on the Lusatian Neisse River, on the basis of mean discharges for the RCP8.5 scenario.

Hydropower Station	2015–2020		2021–2050		2071–2100	
	kWh/year	%	kWh/year	%	kWh/year	%
Obermühle	948,522.78	100	948,522.78	100	798,329.41	84
Vierradmühle	1,856,466.85	93	1,675,587.65	84	1,233,678.00	62
Ludwigsdorf	1,768,235.93	44	1,595,953.24	40	1,175,045.90	29
Pieńsk	3,103,993.87	100	2,893,375.85	93	2,130,293.90	69
Nieder-Neundorf	2,909,029.17	45	2,625,596.75	41	1,933,137.29	30
Bremenwerk	2,433,469.89	49	2,196,372.14	44	1,617,113.85	33
Lodenau	3,826,504.19	46	3,453,680.38	41	2,542,827.00	31
Sobolice	2,737,910.93	50	2,471,150.89	45	1,819,424.07	33
Bukówka	4,618,959.30	57	4,168,925.03	52	3,069,437.23	38

Table 16. Projected nominal hydropower production [%] at German and Polish hydropower plants on the Lusatian Neisse River and its decrease between the 2015–2020 and 2071–2100 periods, according to the RCP8.5 scenario.

Hydropower Station	Nation	2015–2020 [%]	2071–2100 [%]	Decrease [%]
Obermühle	Germany	100	84	16
Vierradmühle	Germany	93	62	33
Ludwigsdorf	Germany	44	29	34
Pieńsk	Poland	100	69	31
Nieder-Neundorf	Germany	45	30	33
Bremenwerk	Germany	49	33	33
Lodenau	Germany	46	31	33
Sobolice	Poland	50	33	34
Bukówka	Poland	57	38	33

4.4. Risk Analysis

In terms of probability of changes in air temperature and sunshine duration in the future, climate scenarios usually indicate an increase in their values. Previously discussed differences in air temperature and sunshine duration between the future and current period showed that projected values for the future are in all cases higher than simulations for the reference period.

Mean projected annual air temperature for 1971–2015 for both RCP2.6 and RCP8.5 is equal to 8.8 °C. In case of future thermal conditions, projected mean annual air temperature for 2021–2050 and 2071–2100 amounts to 9.8 °C (for both periods) for RCP2.6 and 10.4 °C and 12.4 °C for RCP8.5. Thus, the level of local warming in all cases is characterized by positive values (Table 17). Considering the criteria presented in Table 4, it is equal to 1.0 °C (W1 and W3), 1.6 °C (W2) and 3.6 °C (W4). Consequently, the variable of air temperature, according to the criteria presented in Table 5, was given the highest (5) probability rank. It should be emphasized that an additional factor that confirms the high probability of changes in air temperature is its course for the observation period of 1971–2015. It is characterized by a noticeably increasing, statistically important trend. Furthermore, if such a trend continues, mean annual air temperature in the future will be similar to projected values in terms of RCP8.5. Thus, the current tendency of air temperature suggests a realization of the pessimistic scenario, related to a constant and high increase in air temperature by the end of the century.

Table 17. Projected levels of changes in air temperature in the future against 1971–2000, on the basis of the data for Zielona Góra.

Level of Changes in Air Temperature	[°C]
W1	1.0
W2	1.6
W3	1.0
W4	3.6

In case of sunshine duration, its mean annual values for 1971–2000, assessed on the basis of simulated data, are similar for both scenarios (1511–1519 h), whereas the projected annual sunshine duration for the near and far future is equal to 1590 and 1577 h for RCP2.6 and 1699 and 1859 h in the case of RCP8.5. Thus, similarly to air temperature, all of the levels of local changes in sunshine duration are characterized by positive values and vary from 66 h (W3) to 340 h (W4) (Table 18). Thus, the probability of changes in sunshine duration was also given the highest rank (5). Similarly to air temperature, sunshine duration, in terms of observation data for 1971–2015, was also characterized by an increasing, statistically important trend, which additionally proves that this variable can still increase in the future. If the current trend continues, an increase in this variable in the future can be even higher than simulated within the climate scenarios.

Table 18. Projected levels of changes in sunshine duration in the future in comparison to 1971–2000, on the basis of the data for Zielona Góra.

Level of Changes in Sunshine Duration	Hours
W1	79
W2	180
W3	66
W4	340

In the case of precipitation totals, predicted changes are not as significant as for air temperature and sunshine duration. Table 19 presents the changes for the stations representing the lowlands (Zielona Góra, Sobolice) and the mountain foreland (Sulików, Bierna) of the discussed region. In most cases, changes in precipitation are related to a decrease in relation to projected totals for 1971–2000. In the case of W4, changes reaching or exceeding 5% are expected for Sobolice, Sulików and Bierna. Additionally, the value of 5% is also reached for W2 in Bierna. Therefore, four of 16 results for the considered stations are characterized by a decrease in precipitation totals reaching at least 5%. As a result, the probability of negative changes in precipitation totals was given the rank of 2 (25%). Unlike air temperature and sunshine duration, the current increasing trend of precipitation totals (without statistical significance) for 1971–2015 does not correspond to the future projections. It confirms that future trends for precipitation are difficult to assess and are not as obvious as in the case of air temperature and sunshine duration.

Table 19. Projected levels of changes in precipitation totals in the future compared to 1971–2000, on the basis of data for Zielona Góra, Sobolice, Sulików and Bierna.

Level of Changes in Precipitation Totals	Zielona Góra [%]	Sobolice [%]	Sulików [%]	Bierna [%]
W1	1	0	1	−1
W2	−2	−1	−1	−5
W3	−1	0	0	−2
W4	−2	−5	−8	−13

Taking into consideration changes in air temperature, sunshine duration and precipitation, consequences for water resources availability and hydropower production were evaluated. Based on criteria presented in Table 8, mean maximal and minimal discharges projected within RCP8.5, especially for 2071–2100, can be more than 35% lower than in 1971–2000. Therefore, the total consequences rate for water resources was estimated at 4. In the case of future hydropower production, most of the hydropower plants in 2071–2100 can be characterized by a decrease in comparison to 2015–2020 exceeding 30% (Table 16). Thus, the rate of consequences for hydropower production, according to criteria presented in Table 9, is equal to 5. Considering the highest probability of changes in air temperature and sunshine duration in the future and potential consequences for water resources and hydropower (production, the risk value was estimated at 20 for water resources and at 25 for hydropower production (Table 20). Therefore, the highest risk rank was given to the considered sectors, which means that appropriate measures should be implemented in order to mitigate the effects of climate change for water resources and hydropower production. The potential impact of precipitation changes on both water resources and hydropower production is characterized by medium risk (8 for water resources and 10 for hydropower production) due to there being no significant changes simulated for the future periods.

Table 20. Risk matrix for consequences for water resources and hydropower production under the probability of changes in air temperature and sunshine duration.

Sector	Air Temperature			Sunshine Duration			Precipitation Totals		
	P	**C**	**R**	**P**	**C**	**R**	**P**	**C**	**R**
Water resources	5	4	20	5	4	20	2	4	8
Hydropower production	5	5	25	5	5	25	2	5	10

5. Discussion

Presented results on the water resources problems under climate change conditions show that significant changes are expected in the future in terms of water-related conditions. The analysis showed that a considerable increase in air temperature and sunshine duration in the remaining decades of the 21st century in the Lusatian Neisse river basin could be accompanied by a decrease in river discharges. In the near future (2021–2050), projected discharges for both scenarios amount to 13–17% and are about 2–5% higher in comparison to some projections for Swiss regions [53]. Projections for the far future (2071–2100) indicate a very high decrease in mean maximum and minimum discharges (36–38%), which would significantly contribute to limits in water availability. Projected discharges for the Lusatian Neisse River can be even lower than environmental flow, which may contribute to serious ecological problems. As much as 18% of discharges could be below environmental flow, especially according to RCP8.5. Therefore, the results for both water resources and ecology at the end of the century can be very noticeable. On the other hand, RCP2.6 shows a more optimistic scenario, with only 2% of discharges lower than environmental flow. Similar results were noticed for other regions, where effects related to environmental flow vary from negligible to disastrous [47].

A similar situation is observed for hydropower production by hydropower plants located on the Lusatian Neisse River. Under RCP2.6, hydropower production will still be kept at a normal level or even increase, while RCP8.5 indicates a significant decrease of as much as 34% of nominal production (in 2071–2100). The results for the near future (2021–2050) are comparable to some alpine regions for 2031–2050 [51]. In the Alps, hydropower production could increase by about 5% (the most optimistic scenario) or decrease by 7% (the most pessimistic scenario). In the region of the Lusatian Neisse river basin, huge energy problems can occur in the region at the end of 21st century if the pessimistic scenario of RCP8.5 is realized. Hydropower production between 2015–2020 and 2071–2100 can drop by over 30%, which is a higher rate than, e.g., in case of the Rhone River, where the maximal projected decrease between 2001–2010 and 2090–2100 reaches 25% [50].

Taking into consideration climate projections carried out for the RCP2.6 and RCP8.5 scenarios, it should be emphasized that results for these scenarios (especially for RCP8.5) are currently under discussion [75]. RCP8.5 was considered to be an extreme scenario, representing the 90th percentile of no policy baseline scenarios. It assumes an increase in coal use to become a major source of power generation; however the use of coal in the recent years has decreased [76]. Thus, the probability of RCP8.5 scenario realization seems to be smaller than was previously assumed. Nevertheless, current trends of some meteorological variables in the region of the Lusatian Neisse river basin (e.g., for air temperature) show similar tendencies to those modeled for RCP8.5. In the case of the discussed region, values simulated for future periods (on the basis of 1971–2000 data series) are comparable with the results of the trends carried out for measurement data for 1971–2015. Therefore, considering potential climate change in the future, the results of the extreme scenarios cannot be neglected. On the other hand, one of the latest reports of the IPCC [77] assumes a limitation of global warming to 1.5 °C in comparison to the preindustrial era, which is more optimistic than the limitation implemented for RCP2.6 (2 °C). Thus, taking into consideration the low probability of RCP8.5 realization and new opportunities related to a stronger limitation of global warming, the risks for water resources and hydropower production in the discussed region could be lower than presented in the paper.

6. Conclusions

The development of future conditions related to water resources and hydropower production is strongly dependent on climate scenarios. Current trends indicate that today's changes in discussed meteorological variables are more similar to the RCP8.5 scenario. Taking into consideration the presented results, increasing air temperatures and sunshine durations can negatively affect water resources in the future, even though precipitation projections do not show significant trends. The results of the analysis and current low water resources in Poland indicate that appropriate measures should be undertaken in order to use water resources in accordance with sustainable water management. Based on the presented results on meteorological and hydrological conditions as well as on climate projections, the following recommendations can be given in order to mitigate the impact of climate change on water resources in the region:

- Analysis of legal regulations and their adaptations. The most important adaptations measures refer to legal aspects, i.e., verification of legal water permits and their adaptation to a new Water Law. The permits should also consider pond economy and the aspect of hydropower stations.
- Water retention and sustainable use of water resources. Aspects of retention capacity of the basin and coordination of the flooding of former opencast mine pits should be taken into consideration. Furthermore, development of "green-blue" and "grey" water infrastructures would contribute to significant water savings.
- Changes in river valleys. In these terms, actions focused on the creation of buffer zones and reclamation of river valleys and riverbeds should be undertaken. In the reclamation process, the very important problem of invasive species should be considered.
- Changes in strategic documents of the local governments. The documents should consider the aspects of climate change in the context of their impact on the inhabitants and the economy. Such documents should be systematically updated. Strategies on sustainable water use should also be developed.
- Improvement in cooperation between bodies dealing with water management and water energy production. Such cooperation would enable the development of a common approach towards water management in terms of hydropower plants. Furthermore, an improvement in power plant technical measures would contribute to a higher efficiency of hydropower production.
- Increasing awareness in terms of current and future water resources. These types of measures concern promotional actions focused on the transfer of information to inhabitants, local authorities and persons dealing with water management in the region.

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