

Article

Hydropower Potential Assessment Under Energy Transition: The Case of the Radunia River (Northern Poland)

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Abstract

Progressive climate change and growing energy demand are increasing the importance of renewable energy sources, including hydropower, particularly in regions with favourable hydrological conditions. This study aims to assess development characteristics and the feasibility of determining the hydropower potential of the Radunia River in northern Poland, taking environmental conditions into account. The study employed a hydrological–energy approach based on long-term flow data analysis, the section method, and calculations of water flow power, supplemented by analyses of flow duration curves and differential integral curves. The Radunia River is an example of a lowland watercourse with a relatively high hydroelectric potential for northern Poland, resulting from a favourable combination of hydrological and environmental factors. The results indicate a marked variation in hydropower potential along the river’s course, with the potential concentrated in the middle and lower reaches, where the highest flows and gradients occur. The calculated total potential is approximately 7.07 MW, and annual energy production exceeds 61.9 GWh, with actual production in the existing cascade system of power stations being close to the theoretical values. At the same time, accounting for environmental constraints results in a slight reduction in potential (less than 1%), underscoring the importance of a sustainable approach. The conclusions indicate that the Radunia River is an example of the effective use of water resources, and that the further development of hydropower should be based on the modernisation of existing infrastructure using new environmental technologies, whilst complying with environmental protection requirements.

Keywords: hydropower potential; small hydropower plants; renewable energy; energy transition; Poland

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1. Introduction

Advancing climate change, rising energy demand, and the need to reduce greenhouse gas emissions mean that renewable energy sources are once again becoming a key element of energy and environmental policy, both at national and regional levels [1,2]. The energy transition, aimed at increasing the share of renewable energy sources in the energy mix, highlights the importance of hydropower as a stable and predictable source of renewable energy that can support energy security [3]. In this context, hydropower takes on particular significance [4,5], as it is one of the oldest and most technologically advanced sources of renewable energy, whilst also constituting a key element in the stabilisation of energy systems [6].

In Poland, the direction of development for the renewable energy sector is set out, among other things, in Poland's Energy Policy to 2040 [7] and the Renewable Energy Sources Act of 2015 [8], which highlight the need to modernise existing hydropower facilities and improve energy efficiency whilst maintaining environmental standards. Poland's hydropower sector, despite its relatively small share in the energy mix (1.2%), is characterised by high production stability, a long infrastructure lifespan, and strong links to water management. [9]. It is estimated that Poland's hydropower potential remains largely untapped. The technical potential of hydropower plants in Poland stands at 13.7 TWh, and small hydropower plants (SHPs) could harness as much as 15% of this potential [10]. Furthermore, hydropower is increasingly regarded as 'balancing power' in energy systems. Unlike wind or solar power, it can act as a regulating source within the electricity system, stabilising energy supply, particularly during periods of peak demand, thanks to its flexibility in adjusting generation capacity [11]. In the context of the energy transition, hydropower enhances the stability of the energy system, supports the decarbonization of the economy, and improves countries' energy security [7]. Hydropower is one of the oldest and most reliable renewable energy sources (RES) [12]. Rivers play a strategic role in the energy transition, providing renewable hydropower resources, mainly due to their hydropower potential, whilst also delivering ecosystem services and offering tourism and recreational value [13,14]. Research indicates that hydroelectric power stations can respond quickly to changes in energy demand and compensate for fluctuations in output from other RES, making them a key element of the energy transition [15]. Hydroelectric power stations can maintain high levels of energy production over extended periods and mitigate the risk of so-called 'energy droughts' [5,8].

Poland's hydrological conditions are dominated by lowland rivers with gentle gradients and variable flows; hydroelectric potential is limited both spatially and in terms of volume. In selected catchment areas, particularly in the lake districts of the northern part of the country, there are favourable conditions for its effective and sustainable use [16–19].

One of the most characteristic examples of such a river is the Radunia, a left-bank tributary of the Motława, situated in the Pomeranian Voivodeship in northern Poland [20]. The Radunia stands out from other watercourses in the coastal region due to a combination of a significant total drop in elevation, reaching approximately 160 m, with a relatively short length estimated at 103 km, and the presence of natural retention in the form of the lakes of the Kashubian Lake District [21]. These conditions result in a relatively stable hydrological regime, conducive to the use of hydropower even in lowland conditions. For over a century, the Radunia has been a key component of the water and energy management system of Gdańsk Pomerania, and its development in the form of a multi-stage system of hydroelectric power stations, the so-called Radunia Cascade [22], is one of the best-preserved examples of the comprehensive utilisation of a river's hydroelectric potential in northern Poland. However, the significance of the Radunia is not limited solely to technical and energy aspects. The river plays a vital role in the region's water balance, contributing to water supply, flow regulation, and flood protection for the Gdańsk conurbation. At the same time, its valley, particularly in the middle reaches, is characterised by high natural and landscape values, which are reflected in nature conservation measures and intensive tourism [23].

The coexistence of energy, environmental, socio-economic, and cultural functions makes the Radunia a particularly interesting subject for research into the sustainable use of water resources in lowland conditions, where development pressures must be balanced against the protection of river ecosystems [24]. As a river that is well understood hydrologically and subject to long-term monitoring, the Radunia provides a valuable case study for analyses combining energy, environmental, and socio-economic aspects. The exploita-

tion of the hydroelectric potential of rivers such as the Radunia must be considered within the broader context of global and European energy transition trends [25].

It should be emphasised that the current level of utilisation of Radunia's hydroelectric potential corresponds primarily to technological solutions and energy demand from the early 20th century. A contemporary assessment of the potential should take into account current hydrological data, flow characteristics (including flow duration curves), and the possibilities for modernising turbines and control equipment. Therefore, the existing power stations serve as a reference point for further analysis of the theoretical, ecological, and technical potential across the entire catchment area [24].

Hydroelectric power generated along the Radunia River is renewable in both a physical and functional sense. Its source is a renewable resource—namely, the river flow shaped by the natural water cycle—and its utilisation relies largely on existing hydrotechnical infrastructure, which limits the extent of environmental impact. Unlike many other forms of renewable energy sources, electricity generation at the Radunia hydroelectric power stations is characterized by high predictability and the ability to be controlled on a daily and seasonal basis, which is of significant importance for the stability of local energy systems [26–28]. Furthermore, hydroelectric power stations operating as part of a cascade perform both regulatory and retention functions, influencing flow patterns and mitigating the effects of extreme hydrological events.

In this context, the analysis of Radunia's hydropower potential aligns with current energy and water policy directions, which focus on optimising the use of existing infrastructure rather than on the intensive expansion of new impoundment facilities [23–28]. This approach is consistent with both global trends in sustainable water resource management and national spatial and environmental conditions, where the further development of hydropower requires a precise assessment of the technical and environmental potential of individual catchment areas [27].

In light of the above considerations, the analysis of the Radunia River's hydropower potential is in line with current energy and water policy directions in Poland [7] and the European Union [29,30], which focus on optimising the use of existing infrastructure rather than on the intensive expansion of new damming structures. A review of the literature [31–33] and the results of previous studies [21,34–36] point to the need to develop a concept of integrated and sustainable river management, taking into account hydropower, environmental, and socio-economic aspects simultaneously. Such an approach is particularly important in the context of the energy transition and the growing importance of renewable energy sources, which should be developed in accordance with the principles of sustainable development.

The current energy transition encompasses not only the development of renewable energy sources, but also the improvement of technologies related to energy transmission, storage and management. One example is new solutions utilising hybrid modulation schemes in energy transmission systems, which enable increased energy efficiency and improved stability of system operating parameters. These trends highlight the growing importance of flexibility, reliability and energy efficiency across the entire energy supply chain, in which hydropower, thanks to its ability to regulate output and high operational predictability, can play a significant role in stabilising the electricity system [11,37].

At the same time, increasing attention is being paid to the resilience of water and energy systems to the effects of climate change, particularly to the rising frequency and intensity of extreme events such as hydrological droughts. Recent studies [38] indicate that the effective utilisation of hydropower potential requires a shift away from a sectoral approach to resource management toward integrated models that account for the interdependencies between water management, energy, and the environment. Particular importance is attached to the concept of the water–energy nexus, in which the availability of

water resources directly influences energy production capabilities, while energy infrastructure affects water management practices [39]. Research on hierarchical contingency planning in coupled power and water networks indicates that the increasing variability of hydrological conditions requires the consideration of heterogeneous flexibility resources and the development of adaptive strategies to maintain energy security during periods of limited water availability. In the case of hydropower systems, it is particularly important to analyze the resilience of rivers' energy potential to changes in flow and to identify opportunities for maintaining energy functions while simultaneously meeting environmental requirements and the needs of other water resource users [40]. Thanks to its high predictability of output and the ability to quickly adjust power levels, hydropower is a key component in building resilient energy systems that support the energy transition and adaptation to climate change.

However, assessing the hydropower potential of the Radunia as a renewable energy source requires consideration not only of current hydrological parameters, but also of their variability over time and possible changes in climatic conditions. Forecasting future hydropower potential, based on an analysis of characteristic flows, duration curves, and scenarios for changes in the discharge regime, allows for the determination of the hydropower system's resilience to hydrological variability and the identification of directions for its further adaptation regarding climate change and the planning of various economic needs.

The main objective of the study was to assess the hydroelectric potential of the Radunia River as a renewable energy source in the context of sustainable development. The study focuses on a section-by-section assessment of hydroelectric potential and includes a comparison of river flow during different phases of decline and increase. The innovative approach of the study involved:

- Determining the measure of hydropower potential in relation to the falling and rising phases of river flow;
- Defining and applying the concept of ecological hydropower potential for the Radunia River;
- Assessing the synergy between the river's energy function and its ecological role.

The research findings enabled the formulation of recommendations for further research and for introducing changes to renewable energy management in the Radunia River basin.

2. Literature Review

2.1. Hydropower in the Context of Sustainable Energy Systems

Hydropower is one of the oldest and most stable sources of renewable energy, and in many countries, it is a key component of the energy transition and the diversification of the energy mix. The literature [29–36] emphasizes that hydropower can contribute to enhancing energy security and stabilising the electricity system, particularly in the context of the growing share of intermittent energy sources such as wind and solar power [23]. In many European countries, the development of hydropower is based primarily on the modernization of existing hydropower plants and the utilisation of the potential of small hydropower plants (SHPs), which can operate with relatively little environmental impact [16].

Rivers are not only a source of energy but also natural systems providing a wide range of ecosystem services. Studies [17–20] on the impact of hydropeaking show that the development of hydropower often involves trade-offs between energy production and the regulatory and cultural services provided by rivers. At the same time, river ecosystems provide many ecosystem services, including climate regulation, water retention, mainte-

nance of biodiversity, and socio-cultural services [18–20]. The literature [41–43] emphasises that the development of hydropower can lead to conflicts between energy objectives and environmental protection, as well as the preservation of the landscape values of rivers. The construction of dams and hydroelectric power stations can affect changes in the hydrological regime, fish migration, and the structure of river ecosystems. For this reason, contemporary research approaches focus on finding solutions that reconcile the energy, ecological, and social functions of rivers within the framework of Integrated Water Resources Management.

The efficient and sustainable utilisation of the potential of rivers and water reservoirs for energy purposes, as well as the regulation of water resources, can only be achieved through the interdependent functioning of both sectors. Efficiency in both areas can only be guaranteed through the coordination of plans, particularly long-term ones. All water structures are very costly, although the share of energy infrastructure construction costs in the total investment costs associated with riverbed adaptation is approximately 10–20%, depending on the size of the power plant. When analysing the interdependencies between hydropower—in particular energy security and energy potential—and water management, several aspects must be borne in mind. These include:

- The energy potential of water resources, which refers to the possibility of using flowing water (water flow) to drive a water turbine and, consequently, to generate electricity. The energy potential of water resources is most often assessed in terms of three values: theoretical, technical, and economic.
- The hydrological safety of river and reservoir water resources, which concerns the impact of hydroelectric power plant structures on the shape of the river channel and changes in flow, the hydrological regime, and fluvial processes [44–46].

2.2. Legal Framework for Hydro Energy Policy

Globally, hydropower remains the largest source of renewable energy in the electricity sector, accounting for over half of global renewable energy production and playing a key stabilising role in the energy systems of many countries, including the European Union [47–51]. This significance is reflected in the strategic documents of international organisations, including actions implemented under the UN Sustainable Development Goals [52] (SDG 7—Affordable and Clean Energy), as well as in climate policies aimed at achieving carbon neutrality by the middle of the 21st century. In Poland, hydropower policy is based on national and EU legislation governing the use of water for energy production. Of key importance are the Water Framework Directive [48], the Water Law, and the Act on Renewable Energy Sources [8], which imposes an obligation to protect water resources and restricts interference with rivers. In the European Union, the development of renewable energy sources is regulated, inter alia, by Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (RED II), updated as part of the Fit for 55 package, which aims to increase the share of RES in gross final energy consumption and reduce greenhouse gas emissions. The development of hydropower in Member States must comply with the provisions of Directive 2000/60/EC (the Water Framework Directive), which imposes an obligation to achieve good water status and to reduce hydromorphological pressures. This means that hydropower investments must not lead to a deterioration in water quality or disrupt the functioning of river ecosystems [7,29].

In summary, the legal framework seeks to balance renewable energy development with environmental protection: on the one hand, it promotes the development of renewable energy; on the other, it imposes numerous restrictions aimed at protecting the aquatic environment. In practice, this means that a compromise must be sought between energy production and the preservation of the natural functions of rivers.

3. Materials and Methods

3.1. Study Area

The Radunia River in Poland, a left-bank tributary of the Motława located in the Pomeranian Voivodeship, was selected as a case study for this research. It constitutes a system of great hydro-energy significance, with existing small-scale hydroelectric power plants. The Radunia River is one of the most important rivers in Pomerania in northern Poland and plays a significant role both in the energy system, due to the presence of a cascade of hydroelectric power stations, and in shaping the landscape and recreational values of the Kashubian Lake District and the Gdańsk conurbation. The river possesses valuable natural habitats and fulfils important social, tourist, and recreational functions (Figure 1).

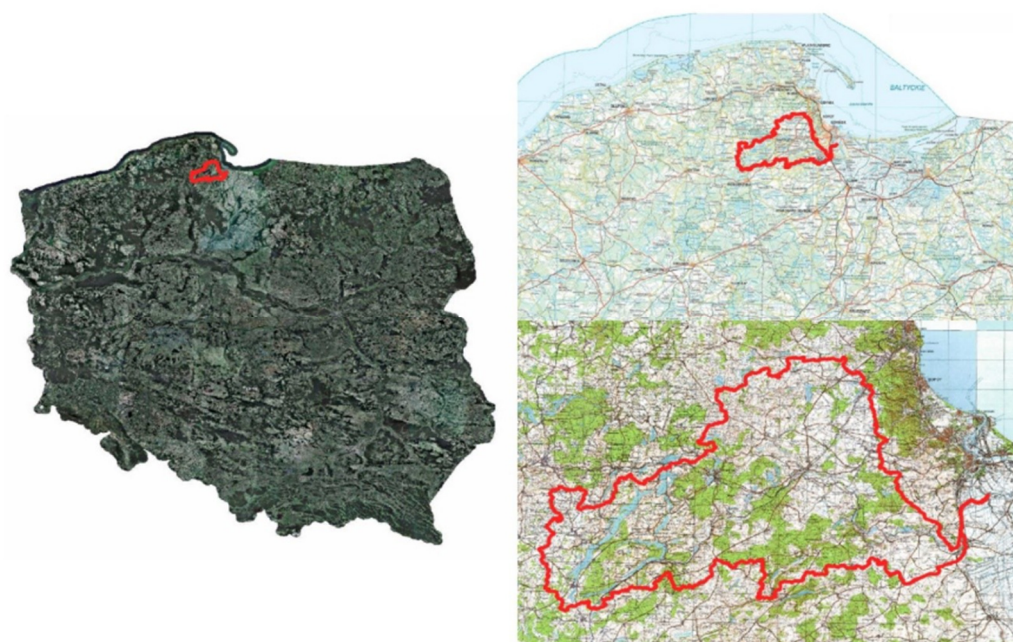


Figure 1. The geographic location of the Radunia River in Poland. Source: own elaboration.

The Radunia River is fed mainly by groundwater and is of an alpine nature, characterised by a fast current. The average annual unit discharge for the Radunia catchment area ranges from 8 to 10 dm³ s⁻¹ km⁻² [25].

As has already been demonstrated, the Radunia River stands out from other water-courses in the coastal region due to a combination of a significant total drop in elevation, reaching approximately 160 m, with a relatively short length estimated at 103 km, and the presence of natural retention in the form of the lakes of the Kashubian Lake District. The catchment area of the Radunia River is approximately 837 km². It is a catchment located in northern Poland, covering parts of the Kashubian Lake District and flowing into the Motława River in the Gdańsk area (Figure 2).

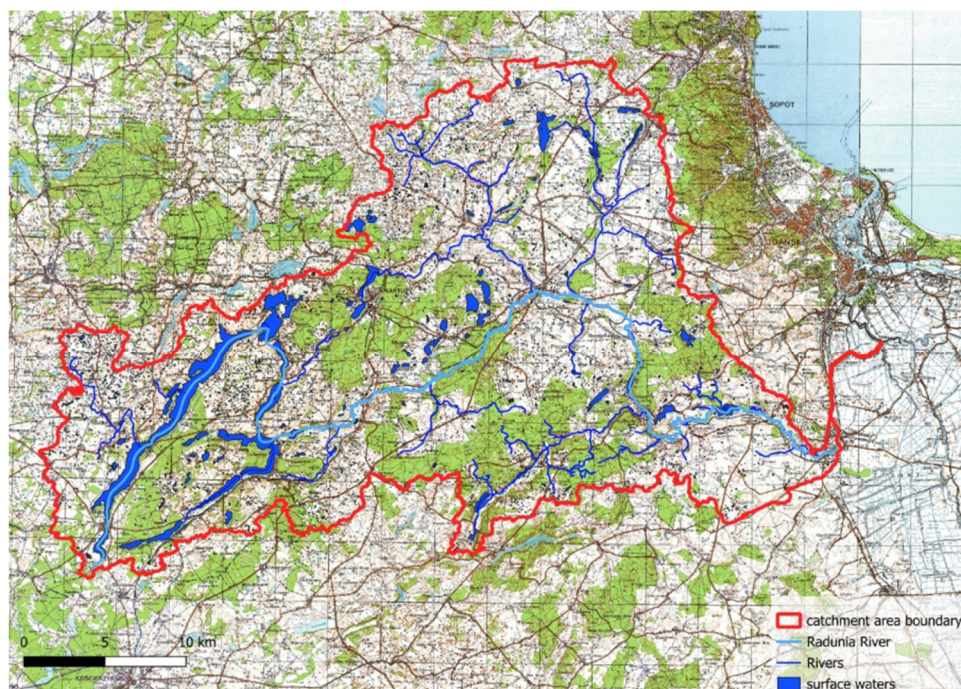


Figure 2. Radunia's river catchment area boundary. Source: own elaboration.

Based on a historical map of the Radunia River dating from 1898, it can be concluded that its northern section was partially straightened in order to improve water flow (Figure 3). The meandering river channel was straightened, deepened, and reinforced, and in places its course was also altered. These measures were primarily aimed at improving flood protection, enhancing water drainage, and adapting the land to economic and settlement needs. At the same time, the regulation restricted natural fluvial processes, such as meandering and periodic flooding, which led to the transformation of the environment, changes in habitat conditions, and a reduction in biodiversity in the river valley [20,25].



Figure 3. An old topographic map (Messtischblätter) on a scale of 1:25,000 from 1900 showing the meandering course of the River Radunia. Source: Berlin State Library, Germany [49].

3.2. Methods

In the scientific literature and research practice, a wide range of methodological approaches is employed to assess the hydropower potential of rivers, encompassing both global-scale and regional analyses [32,45,53–56]. Methods that integrate hydrological data with the morphometric parameters of river channels play a particularly important role, as they enable a quantitative and spatially differentiated evaluation of available energy resources. In studies focusing on European rivers, including those located in Eastern Europe, methodological frameworks have also been developed that take into account hydro-ecological conditions as well as the principles of sustainable water resource management [33,57–60].

The present study was conducted in three stages:

Stage 1: Assessment of hydropower potential

It is noted that the most accurate and objective results are obtained using the distributed calculation method, which is based on an analysis of individual river sections, thereby allowing for the capture of local variations in hydrological conditions and terrain gradients.

The assessment of the hydropower potential of the Radunia River was carried out using a hydrological–energy approach, based on:

- An analysis of average annual water flows;
- The section-by-section assessment method [61–63].

When calculating the theoretical hydropower potential of the river, the arithmetic mean of the water flow rates between the two hydrological stations was used ($Q_{avg} = 0.5 (Q_1 + Q_2)$), which is in line with the general methodological principles for determining this value [36,58].

This method involves linking the watercourse's hydrological parameters with its morphometric characteristics, enabling the determination of both the theoretical, ecological, and technical energy potential across the entire catchment.

The equation for the theoretical hydropower potential of a river is presented in this article in a simplified form, without taking into account the density of water, which is assumed to be constant. This approach is commonly found in many publications [33,64,65].

The basis for the calculations is the equation defining the power of a water jet, derived from the potential energy of the flow:

$$P = g \cdot Q_{mean} \cdot \Delta H, P = g \cdot Q_{sr} \cdot H, \quad (1)$$

where

P —power [W];

g —acceleration due to gravity [m/s^2];

Q_{mean} —average water flow in the river section [m^3/s];

ΔH —difference in elevation in the section under analysis [m].

The total power of all river sections that could potentially be used for energy generation is estimated. For each section, its total power (N , kW) is determined using Equation (1). The total power of all sections constitutes the river's total energy potential (CGP) and is defined as:

$$CGP = N_1 + N_2 + N_3 + \dots N_n = \sum N_i, \quad (2)$$

where

N_1, N_2, N_3 —the power of each river section.

It is also worth noting that potential hydropower reserves can be identified for each section of the river *Erew* (kWh):

$$E_{rew} = T \cdot g \cdot Q_{mean} \cdot \Delta H, \quad (3)$$

where

T —the number of hours in a year.

The value of T in the estimated potential hydropower reserves is taken as 8760, i.e., the number of hours in a year [63].

In order to calculate the hydroelectric potential of the Radunia River, in accordance with the methodology, it was necessary to divide its length into sections for the purposes of the calculations. In this context, hydrological stations on the river were used to calculate the corresponding water flows. Where there are no hydrological stations on the river, or only a small number of them, river sections are defined using other indicators (uniform gradients, river sections without tributaries, etc.) and with the use of modular river flow maps.

The overall distribution of stations ensures that the number of calculated sections corresponds to the length of the river [21]. These cover the upper, middle, and lower reaches of the river, allowing for an analysis of flow changes and highlighting significant hydrological variation along its course.

Stage 2: Assessment of river flow rate

Assessing the river flow rate is crucial for determining the overall hydroelectric potential, as it is one of the key parameters used in such calculations.

To this end, based on data from the aforementioned hydrological stations, the average, maximum, and minimum long-term water flows Q_{mean} , Q_{max} , and Q_{min} should be calculated. In this study, the flow value Q was not treated as a single average value, but was determined on the basis of an analysis of long-term hydrological data.

To this end, the long-term average flow (Q_{mean}) was calculated, and the deviations of individual values from this average ($K = Q_{mean}/Q_i$) were then determined; these were used to calculate the cumulative sum of deviations $St = \sum (K_i - 1)$ [17,34]. Analysis of the St values enabled the identification of periods of increased and decreased water availability, allowing for a more realistic assessment of the conditions for hydropower utilisation [64]. The analysis of long-term observational series to identify the cyclical nature of long-term fluctuations in river flow characteristics boils down to identifying groups of years with increases and decreases in flow values.

$$K_i = Q_{mean}/Q_i, \quad (4)$$

$$St = \sum (K_i - 1). \quad (5)$$

The analysis utilised hydrological data from a long-term observation period, covering annual flows (average, maximum, and minimum) for each of the gauging stations analyzed, which made it possible to account for variations in the hydrological regime. In addition, an analysis of flow duration curves was applied; these form the basis for assessing the availability of river water resources as a function of time and allow the determination of available flows for energy purposes. In accordance with the methodological approach, flows with a specified probability of exceedance form the basis for estimating energy production under real-world conditions [62,66–68]. Since 2019, all hydrological stations have been in a declining phase. We are observing a decline phase at all hydrological stations. Based on the analysis of time series, this may last 8–12 years. Therefore, in line with earlier forecast estimates, the duration of the decline phase may extend to 2030.

Stage 3: Identification of energy reserves

An important element of the methodology is also the consideration of environmental constraints, including the need to maintain an undisturbed flow, which is essential for the functioning of aquatic ecosystems [68,69]. In practice, this means that only a portion of the

total flow can be used for energy production, which results in a reduction in technical potential relative to theoretical potential. The scientific basis for the ecological threshold criteria for hydropower potential was first proposed in the study by [36] and adapted for our research on the Raduń River. The ecological criteria for this potential set out in the text allow us to maintain the hydromorphological quality of this river in accordance with Directive 2000/60/EC. The 45% indicator of the total capacity of small hydropower plants corresponds to typical operating conditions for small hydropower plants in Poland [62]. The approach adopted in this study is consistent with the provisions of Directive 2000/60/EC, which introduced a fundamental change in water resource management in Europe, moving away from an administrative division of space in favor of an approach based on river basins. Under this Directive, the basic planning and management unit is the river basin, which allows for a comprehensive consideration of the hydrological, ecological, and socio-economic processes occurring within the river system.

The application of the catchment approach is of particular importance in the analysis of hydropower potential, as it allows for a holistic assessment of water resources, taking into account tributaries, natural and anthropogenic retention, as well as pressures resulting from economic use [46,70]. In the case of the Radunia River, which is characterised by significant morphological diversity and the presence of a cascade system, this approach enables a proper interpretation of the spatial variation in hydropower potential and its links to the functioning of the entire catchment area.

The application of the section-by-section assessment method to the Radunia River is particularly justified due to its varied morphology, the presence of natural and artificial retention features, and the existing cascade system of hydroelectric power stations. This methodology enables not only an assessment of the current level of utilisation of hydropower potential, but also the identification of energy reserves and an analysis of the possibilities for its optimisation under conditions of a changing hydrological regime [46,70,71].

4. Results

4.1. Characteristics of Flows and Their Variations at Hydrological Gauging Stations

An assessment of the hydrological conditions of the Radunia River was carried out based on data from seven gauging stations located in various parts of its catchment area (Figure 4). The distribution of the stations covers the upper, middle, and lower reaches of the river, enabling an analysis of the spatial variation in flows along the entire length of the Radunia.

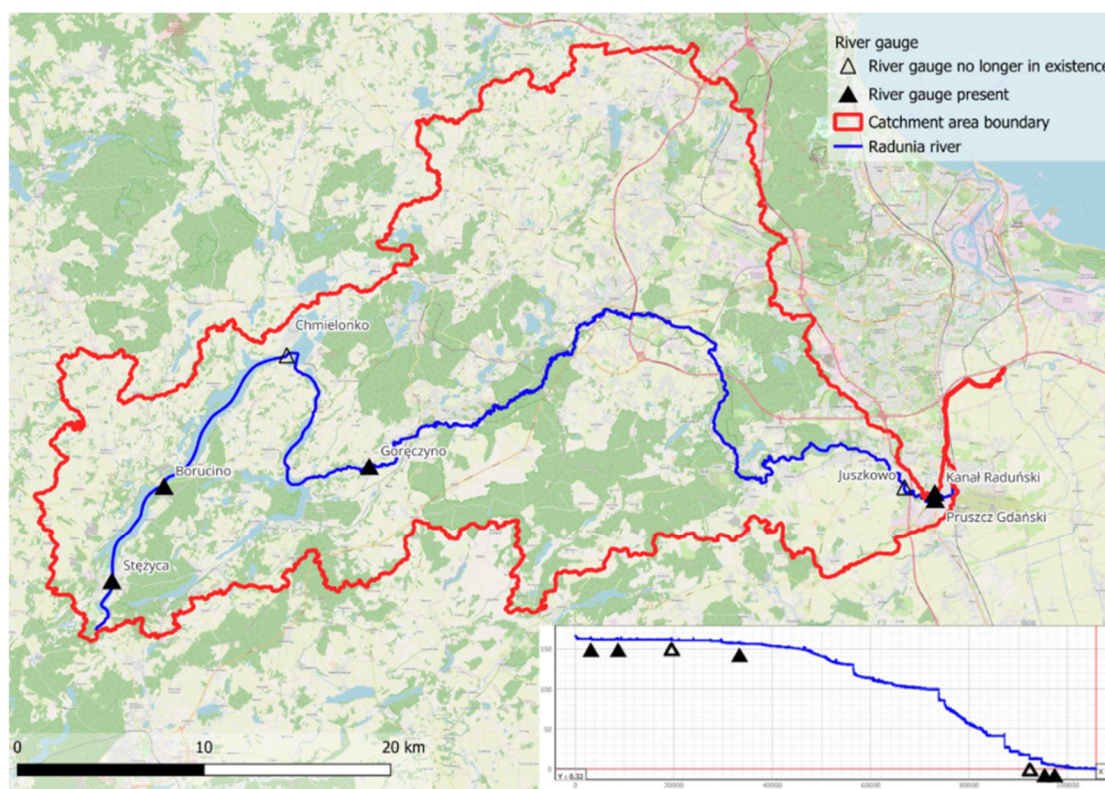


Figure 4. Location of hydrological stations along the river and its longitudinal profile, as well as the distribution of hydrological stations along the Radunia River. Source: own elaboration.

An analysis of average flows at hydrological stations indicates a gradual increase in the water resources of the Radunia River towards its lower course. This is primarily due to the increasing catchment area and the inflow of water from numerous tributaries and the system of ribbon lakes [42,72].

The lowest flow rates are observed in the upper reaches of the river, whilst in the lower reaches of the Radunia, there is a marked increase in flow (also taking into account the river's gradient), which also translates into greater potential for harnessing hydro-power. At the same time, the presence of lakes and retention reservoirs helps to stabilise flows, limiting extreme values of floods and low water levels [46].

Long-term average flows show a marked increase towards the lower reaches of the river (Table 1). In the upper part of the catchment, the average flow at the Stężycza cross-section is approximately $0.193 \text{ m}^3/\text{s}$, whilst at Borucino it reaches $0.795 \text{ m}^3/\text{s}$. In the middle reaches of the river, at the Goręczyno section, this value rises to $2.887 \text{ m}^3/\text{s}$. The highest flows are observed in the lower reaches of the Radunia: in Pruszcz Gdański, where the average flow is $4.582 \text{ m}^3/\text{s}$, and in Juskowo, where it is $6.252 \text{ m}^3/\text{s}$. An analysis of flow variability also indicates a marked variation in the hydrological regime along the river's course [62,69]. In the upper reaches of the Radunia, the flow amplitude is relatively small, and the flow irregularity coefficient $Q_{\max}/Q_{\min}$ takes values below 2. This indicates a relatively stable nature of the flows, resulting from the presence of numerous lakes in the Radunia catchment, which act as natural retention reservoirs.

In the lower reaches of the river, flow variability is significantly greater. At the Pruszcz Gdański section, the flow amplitude exceeds $21 \text{ m}^3/\text{s}$, and the $Q_{\max}/Q_{\min}$ ratio for the Juskowo gauging station reaches a value of over 10. The high variability of flows in this part of the river results from the accumulation of water from the entire catchment area and the impact of hydrotechnical infrastructure [46,73–75].

Similar trends of increasing flow towards the river mouths were also observed in analyses conducted for other rivers in the Pomeranian Voivodeship, where flow rate and

river gradient are the primary factors determining the hydroelectric potential of water-courses [33].

Table 1. Data from hydrological stations on the Radunia River.

Water Level Station	River Course	Q_{mean} (m ³ /s)	Q_{max} (m ³ /s)	Q_{min} (m ³ /s)	Q Max/Q Min
Stężycza	top	0.193	0.275	0.142	1.94
Borucino	top	0.795	1.050	0.555	1.89
Chmielonko	middle	1.380	2.508	1.070	2.34
Goręczyno	middle	2.887	5.676	1.481	3.83
Juszkowo	bottom	6.252	23.671	2.258	10.49
Kanał Raduński	bottom	1.572	4.500	0.410	10.97
Pruszcz Gdański	bottom	4.582	19.896	0.918	21.67

Source: own elaboration. Water level gauging station.

In the Radunia river catchment area, lakes play a significant role, acting as a natural retention feature and influencing the hydrological regime. Of the 11 natural lakes through which the Radunia flows, the most important are Upper and Lower Raduńskie, Wielkie Brodno, Upper Łapino, and Lake Bielkowskie. The total volume of these lakes is 146.765 million m³. Consequently, the natural regulation of the Radunia's average flow by the lakes amounts to over 38%. The presence of numerous lakes helps to even out flows, reduce extreme water levels, and increase natural retention. Consequently, this contributes to the stabilisation of flows in the upper reaches of the river, which is reflected in lower hydrological variability observed at gauging stations located in this part of the catchment.

An important element of Radunia's hydrological system is the cascade of retention reservoirs associated with the operation of hydroelectric power stations [20,76]. The largest reservoirs are located at the Łapino, Bielkowo, and Straszyn power stations (Table 2).

Table 2. Capacity of retention reservoirs at hydroelectric power stations on the Radunia River.

Tank	Capacity (m ³)
Rutki	300,000
Łapino	1,550,000
Bielkowo (derywacyjna)	2,453,000
Straszyn	3,400,000
Prędzieszyn	-
Kuźnice	-
Juszkowo	221,000
Pruszcz Gdański	-
Total storage capacity	7,924,000

Source: own elaboration on: [77].

The Radunia catchment area features a system of retention reservoirs linked to a cascade of hydroelectric power stations, which play a significant role in shaping the river's hydrological regime and in harnessing its hydroelectric potential. Based on literature data, the capacity of the five main reservoirs has been determined, with a total capacity of 7.92 Mm³, indicating the relatively limited retention capacity of the entire system. Overall, artificial regulation of the river's flow amounts to just over 5%. The Bielkowo and Straszyn reservoirs play the most significant role, accounting for over half of the total storage capacity of the system under analysis. Smaller reservoirs, such as Rutki and Juszkowo, serve a supplementary function, contributing locally to flow regulation [76–78].

It should be noted that the Radunia hydrotechnical system also includes other reservoirs for which no data on capacity are available. It can be assumed that these are small-scale structures whose impact on the retention balance of the entire catchment is limited, which is why they have not been included in the literature reviews.

The relatively small total capacity of the reservoirs indicates that the scope for regulating river flow is limited, which has a direct impact on the operation of hydroelectric power stations. Limited storage capacity means that energy production is more dependent on current hydrological conditions, including seasonal flow variations and the occurrence of floods and low water periods. On the other hand, the cascade system of reservoirs allows for partial equalization of flows and improves the operating conditions of power stations through their sequential use.

A similar role for retention reservoirs in hydropower systems is also indicated by analyses of other rivers in the Pomeranian Voivodeship, where their primary function is to stabilise the operation of hydroelectric power stations and to regulate flows in the river channel [33,79].

An analysis of the integral curves of mean flows for the hydrological stations on the Radunia River, compiled on the basis of cumulative deviations from the long-term mean flow, allowed for the detailed identification of periods with varying water availability and an assessment of their impact on the river's hydropower potential (Figure 4).

The analysis of flow variability was carried out using difference curves (integral curves), as illustrated in Figure 5, defined as the cumulative sum of the deviations of annual flows from the long-term mean, in accordance with the relationship given by Equation (5).

As shown in Figure 5, in the case of the Goręczyno station, for which the longest and most continuous data series from 1961 to 2023 is available, a prolonged downward phase is clearly evident, spanning the period from the early 1960s to the mid-1980s, during which the values of cumulative deviations decrease from around 0 to minimum values of approximately -3.0 . This period corresponds to a predominance of flows below the long-term average and indicates reduced water availability in the catchment. Subsequently, a gradual transition to an upward phase is observed, particularly evident after 2000, leading to positive values after 2015, which indicates an increase in water resources in the final years of the analysed period.

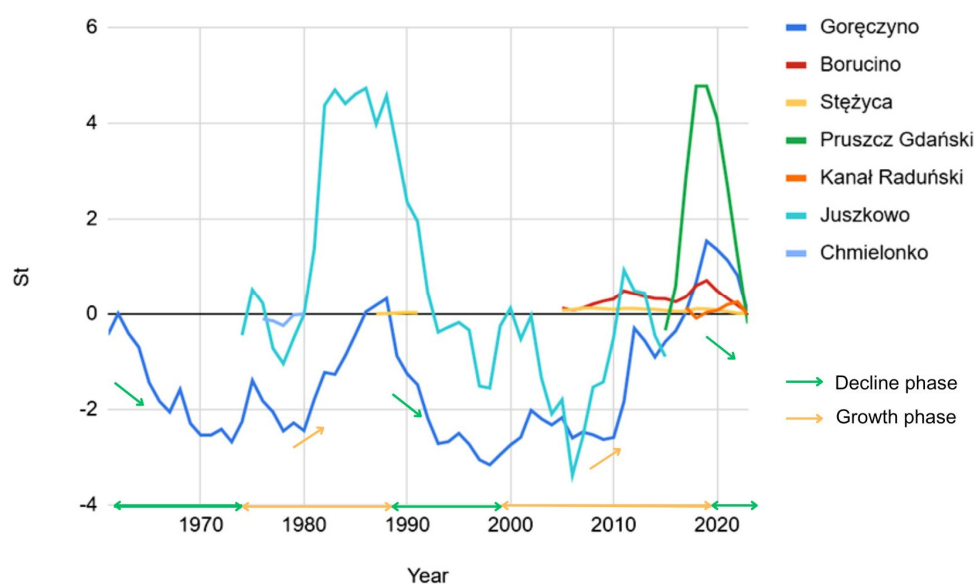


Figure 5. Curves of the differential integrals of mean flow rates. Source: own elaboration.

At the other hydrological stations, the trends in the cumulative difference curves (Figure 4) show a similar pattern, albeit with smaller fluctuations. At the Borucino and Stężycza stations, the values of cumulative deviations remain relatively close to zero for a significant part of the analysed period, indicating greater flow stability in the upper part of the catchment, due to the presence of lakes and natural retention. In the lower reaches of the river, represented by the Pruszcz Gdański and Kanał Raduński stations, a more pronounced transition to a positive phase is observed after 2015, with values in Pruszcz Gdański exceeding 1.0, indicating increased water abundance in the recent period.

A different curve is observed for the Juszkwowo station, where a clear upward phase (positive values up to around 4.5) occurred in the 1970s and 1980s, followed by a prolonged downward period lasting until around 2010, with minimum values of around −4.7. This indicates significant variability in hydrological conditions at this section, resulting from both natural factors and the impact of hydrotechnical regulation.

A comparison of the differential integral curves for individual gauging stations reveals a marked spatial variation in the hydrological regime of the Radunia. In the upper reaches of the river, flow variability is mitigated by lake retention, which results in a more stable curve, whereas in the lower reaches, greater dynamics of change are observed, resulting from the accumulation of flows and the impact of the hydroelectric cascade system [69]. The identified phases of high and low flows have a direct impact on the river's hydropower potential. Prolonged periods of water deficit, observed particularly in the second half of the 20th century, led to a reduction in available flow energy and, consequently, a decrease in electricity generation capacity [26,58]. In turn, the upward trend observed since 2000, particularly evident in the lower reaches of the river, indicates an improvement in conditions for utilising the hydroelectric potential. At the same time, significant flow variability, particularly at the Juszkwowo section, may affect the stability of energy production and must be taken into account in forecasting analyses.

Currently, at the present stage, starting from 2019, a decline phase has been observed at all hydrological stations. Based on a time series analysis of the curves, this phase may last 8–12 years. Therefore, in line with earlier forecast estimates, the decline phase could continue until 2030.

A significant feature of the analysed data is the systematic predominance of values corresponding to the rising phase over those of the falling phase of the flow. These differences are relatively small for lower flows (e.g., Stężycza, Borucino), but increase markedly with rising flow, reaching their highest values at stations with the highest flows (Pruszcz Gdański, Juszkwowo). This pattern indicates an asymmetry in the runoff process—the rising phases are characterised by greater dynamics of change than the falling phases. This may result from the hydrological conditions of the catchment, such as lake retention, the presence of reservoirs, and varied conditions of infiltration and surface runoff [62,80].

In the upper part of the catchment (lower flows), the differences between the rising and falling phases are small, indicating a more balanced hydrological regime. In contrast, greater discrepancies are observed in the lower reaches of the river, which may be related to the accumulation of runoff and the impact of anthropogenic activities, including river channel regulation and the operation of a cascade of hydroelectric power stations.

In addition, differential integral curves were plotted for maximum and minimum flows, which were used as an auxiliary tool in interpreting hydrological variability; however, mean flows formed the essential basis of the analysis.

Based on the differential curves developed for mean flow values (Q_{mean}), the progression of the rising and falling phases of water flow was analysed for selected gauging stations in the Radunia catchment. Figure 6 illustrates the relationship between mean flow and the values of the differential curves for the rising and falling phases. A clear upward trend is evident for all analysed gauging stations—as flow increases, both the values for

the rising and falling phases increase. Analysis of the relationship between average flow and the values of the integral difference curves for the falling and rising phases indicates a clear variation in the river's hydropower potential depending on the water abundance phases. In all the cross-sections analysed, the rising phases achieve higher values than the falling phases, which indicates greater dynamics in the process of water resource replenishment within the catchment. This phenomenon is confirmed by the calculated percentage differences between the phases, which increase with rising flow, from approx. 12–20% in the upper part of the catchment to over 30% in its lower reaches.

In practice, this means that Radunia's hydroelectric potential increases during periods of rising water levels, whilst it decreases during periods of falling water levels. Periods of falling water levels correspond to times of water scarcity in the catchment area and reduced energy generation capacity at hydroelectric power stations. Conversely, rising phases favour the maximum utilisation of potential, which is reflected in higher energy production and more stable operating conditions for the cascade of power stations. This phenomenon is particularly evident in the lower reaches of the Radunia (Pruszcz Gdański, Juskowo), where the greatest phase asymmetry is observed due to the accumulation of outflow and the influence of hydrotechnical infrastructure (Figure 6).

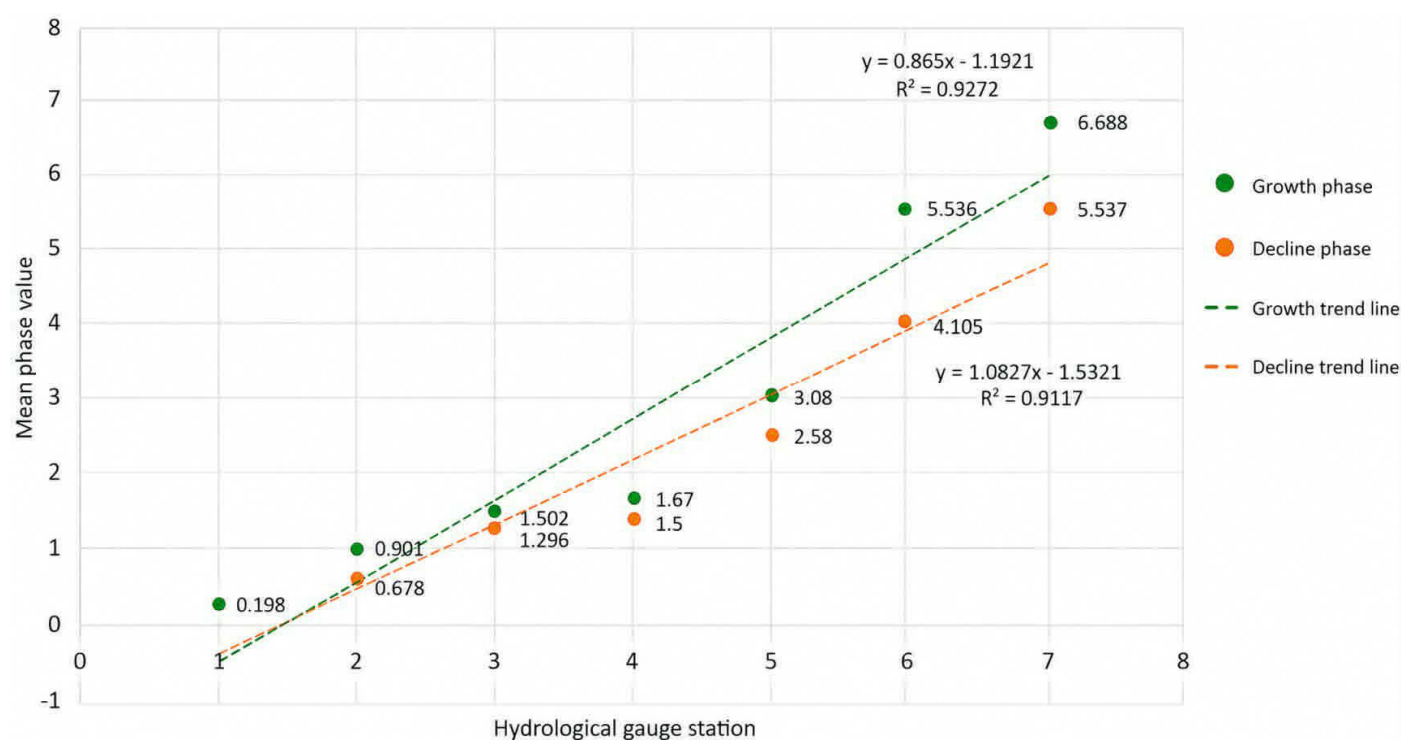


Figure 6. Trend line showing the relationship between rising and falling phases for the average flow at the Radunia water gauge stations. Source: own elaboration.

The analysis carried out revealed clear variations in water flow rates during the rising and falling phases. At all the gauging stations analyzed, flow rates during the rising phase are higher than during the falling phase; however, the extent of these differences varies spatially.

The largest relative differences in flow were recorded in the lower reaches of the river, where at the Pruszcz Gdański section, the flow during the rising phase is approximately 34.8% higher, and at Borucino, 33.7% higher, compared to the falling phase. Conversely, the smallest differences occur at the Raduński Canal (11.3%) and Stężycza (12.5%) sections, indicating a more even flow pattern in these parts of the catchment.

In the remaining profiles, these values are 15.7% (Chmielonko), 19.7% (Goręczyno), and 20.7% (Juszkowo), respectively. The average difference between the rising and falling phases for all analyzed stations is approximately 21.2%, which confirms the significant asymmetry of the Radunia River's hydrological regime.

The results obtained indicate that flows during the rising phase are, on average, more than a fifth higher than during the falling phase, which is of significant importance for assessing hydrological variability and the potential for utilising water resources, including hydropower potential.

From the perspective of hydropower potential, greater differences between the rising and falling phases at higher flow rates may indicate greater variability in the operating conditions of hydroelectric power stations. A more stable flow pattern (smaller differences) is more conducive to the efficient use of energy, whereas high variability can make it difficult to manage energy production optimally.

4.2. Electricity Generation at the Radunia Hydroelectric Power Stations

The Radunia River is one of the most extensively developed watercourses for hydroelectric power in the Pomerania region. A cascade of hydroelectric power stations operates along its course [78,81], including facilities in Łapino, Bielkowo, Straszyn, Kuźnice, Przędziszyn, Juszkowo, and Pruszcz (Figure 7).



Figure 7. Location of hydroelectric power stations on the Radunia River (Radunia Cascade). Source: own work.

The total installed capacity of these power stations exceeds 15 MW, with the Bielkowo power station, at approximately 7.2 MW, being the largest facility in the system (Table 3). The Straszyn and Łapino power stations also play a significant role, whilst the remaining facilities are smaller run-of-river power stations with a capacity ranging from several dozen to several hundred kilowatts.

The operation of the cascade of hydroelectric power stations on the Radunia indicates that the river's energy potential is being utilised to a significant extent [82]. However, the

amount of energy produced depends on the variability of river flows and the operating conditions of individual hydrotechnical facilities.

Table 3. Hydropower plants on the Radunia River and their electricity generation characteristics.

Name of the Power Station	Opening Date	Installed Capacity	Power (kWh)	
			at 100% Capacity Utilisation	at 45% Capacity Utilisation
Pruszcz	1921	100 kW	876,000	394,200
Straszyn	1910	3.5 MW	30,660,000	13,797,000
Bielkowo	1925	7.2 MW	63,072,000	28,382,400
Juszkowo	1937	232 kW	2,032,320	914,544
Łapino	1927	2.907 MW	25,465,320	11,459,394
Prędzieszyn	1937	436 kW	3,819,360	1,718,712
Pruszcz II	2005	250 kW	2,190,000	985,500
Rutki	1910	560 kW	4,905,600	2,207,520
Kuźnice	1934	781 kW	6,841,560	3,078,702
Total power		15.966 MW	139,862,160 kWh	62,937,972 kWh

Source: own elaboration based on [75].

In order to determine the volume of electricity generation at individual hydroelectric power stations on the Radunia River, estimates of annual energy production were carried out. This figure was determined based on the installed capacity of individual power stations and their theoretical annual operating time of 8760 h, assuming a capacity utilisation factor of 45%, which corresponds to typical operating conditions for small hydroelectric power stations in Poland, according to Formula (6) [62,83,84].

$$E = P \cdot 8760 \cdot k, \quad (6)$$

where

E —energy (kWh);

P —installed capacity (kW);

8760—number of hours in a year;

k —capacity utilisation factor (0.45).

The calculations are estimates and represent the maximum possible energy production assuming continuous operation of the power stations throughout the year. The results of the calculations for individual facilities are presented in Table 3.

Analysis of the results indicates that power stations with the highest installed capacity account for the largest share of electricity generation, in particular those in Straszyn, Bielkowo, and Łapino. The remaining power stations play a supplementary role, yet their combined output constitutes a significant component of the local energy system [40].

A comparison of the river's theoretical hydropower potential with the actual energy production at existing hydroelectric power stations indicates that the Radunia is among the watercourses with a relatively high degree of energy utilisation [27]. The cascade of hydroelectric power stations operating on the river enables the utilisation of a very significant portion of the available energy potential [22,82,85], with the largest share of energy production coming from the largest hydrotechnical facilities located in the middle and lower reaches of the river.

In the analysis of the Radunia River's hydropower potential, two hydrological parameters are of key importance: the volume of water flow and the difference in elevation between individual sections of the river [83,86]. These factors determine the amount of power that can be obtained from the water flow, which has been calculated in this study in accordance with Equations (1) and (3).

4.3. The Hydroelectric Potential of the Radunia River

In assessing the river's theoretical hydropower potential, long-term average flows and their variation patterns were utilised. These were determined using differential integrals derived from the cumulative deviations from the long-term average flow. Furthermore, differential integrals were determined for maximum and minimum flows. A similarity was found between the differential integrals for average and minimum flows. This indicates a certain predominance of lower flows over time, which may be related to significant regulation of water flow in the Radunia River. Based on the above Equation (1), the hydroelectric potential of individual sections of the Radunia River between the hydrological stations (3) was calculated (Table 4).

Table 4. Hydroelectric potential between hydrological stations on the Radunia River.

Name of the River Section	Elevation Difference (m)	Average Flow (m ³ /s)	Total Potential (P) (kW)	Production Capacity over Time (E) (kWh)
Riverhead – Stężyca	1.04	0.80	8.16	71,481.6
Stężyca- Borucino	4.43	0.43	18.68	163,636.8
Borucino-Goręczyno	1.48	1.89	27.44	240,374.4
Goręczyno- Juskowo	148.15	4.57	6641.82	58,182,311.3
Juskowo-Kanał Raduński	3.92	3.91	150.36	1,317,153.1
Kanał Raduński – Pruszcz Gdański	1.71	3.61	51.50	451,140.0
Pruszcz Gdański-Ujście	3.25	5.33	169.93	1,488,586.8
P total power (kW)			7067.89 kW	
E total energy (kWh)			61,914,716.4 kWh	

Source: own elaboration.

The calculated hydropower potential of the Radunia River shows marked variation along its course. The highest potential values are observed in sections with greater elevation differences and higher average annual flows. Both the hydrological conditions and the morphometric characteristics of the river channel change along the course of the river, which affects the amount of available energy potential [69,84,87–89].

An analysis of hydrological conditions and existing hydropower infrastructure indicates that the Radunia River possesses significant energy potential, which is largely utilised by a cascade system of hydropower stations. The greatest potential for energy production is concentrated in the middle and, to some extent, the lower reaches of the river, where the highest flows and river gradient are found (Figure 8). Over 95% of the river's total hydroelectric potential is concentrated in its middle and, to some extent, lower reaches, between the Goręczyno and Raduński Canal hydrological stations (Figure 8). The largest hydroelectric power stations are located in this section.

This approach is commonly used in analyses of the hydroelectric potential of rivers, where the assessment is based on the theoretical hydropower capacity derived from the hydrological and morphometric parameters of the watercourse [33].

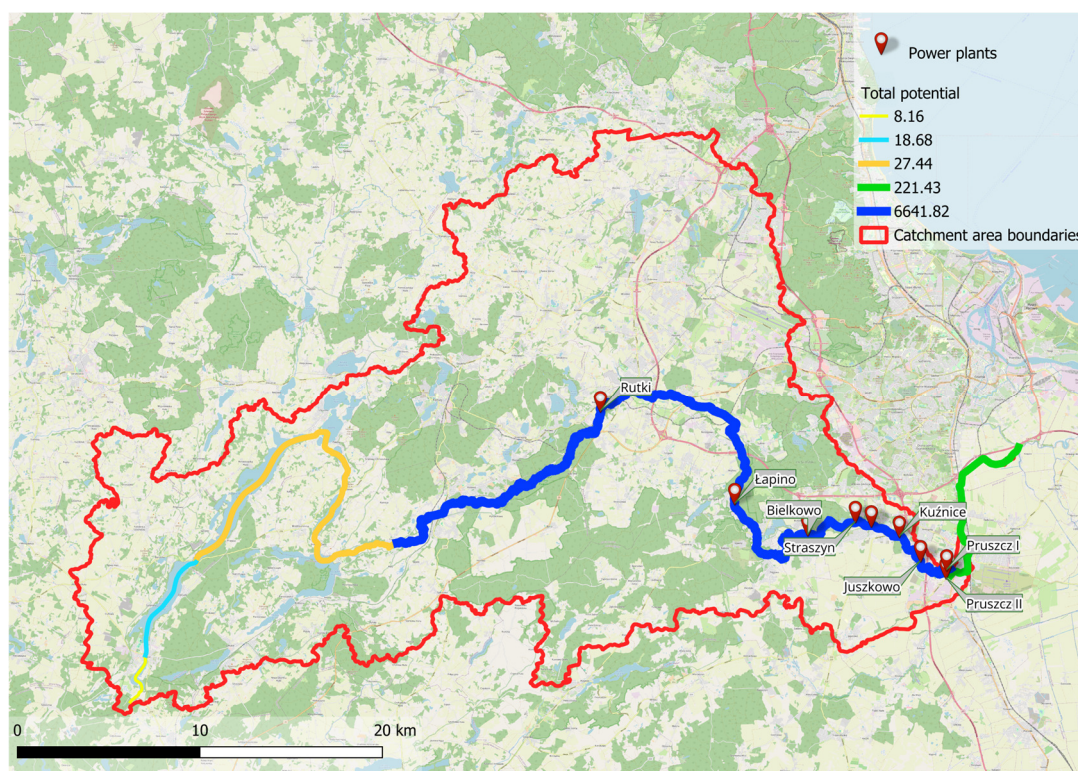


Figure 8. Assessment of the hydroelectric potential of the Radunia River across its various sections. Source: own work.

A comparison of the calculated hydroelectric potential of the Radunia River with the actual energy production at existing hydroelectric power stations shows that these figures are similar; in some cases, energy production may reach levels comparable to, or even higher than, the theoretical potential determined on the basis of average flows.

This phenomenon stems primarily from the specific nature of the river's hydrotechnical development. The presence of retention reservoirs plays a key role, as they enable flow regulation and temporary water storage. This makes it possible to increase the flow rates directed through the turbines during periods of high energy demand, leading to a more efficient use of water resources than would be indicated by average values.

Another significant factor is the hydrological regime of the Radunia catchment area, which is characterised by relatively high humidity and the occurrence of periodic floods. During high water levels, flows significantly exceed average values, which—as demonstrated in the analysis of the rising and falling phases—can increase the available potential by as much as over 20%. Under such conditions, hydroelectric power stations can generate greater amounts of energy than would be indicated by the average hydrological parameters.

The analysis is based on hydrological data and focuses on assessing the current hydropower potential of the Radunia River. However, in the context of the energy transition and projected climate change, the impact of future changes in the hydrological regime on the potential for hydropower remains a key issue. Climate projections for Central Europe indicate an increase in the frequency and intensity of extreme events, including periods of hydrological drought interspersed with episodes of heavy rainfall. These events may lead to increased variability in river flows, thereby affecting the stability of electricity generation at hydroelectric power stations. In the case of the Radunia River, a potential factor limiting the use of hydropower resources in the future may be a decline in water availability during low-flow periods and the need to maintain ecological flow.

At the same time, the presence of flow-through lakes, retention reservoirs and a cascade system of hydropower plants may partially increase the system's resilience to short-term hydrological fluctuations. A detailed analysis of the impact of climate scenarios and an assessment of the uncertainty surrounding future water resources are beyond the scope of this study; however, they represent an important direction for further research into the long-term role of hydropower in the energy transition.

Furthermore, the cascade arrangement of hydroelectric power stations on the Radunia River is of significant importance. Water used for energy generation at one power station is subsequently reused at subsequent facilities located downstream. This results in the repeated use of the same volume of water, which in practice increases the total energy production within the system.

Based on the spatial analysis (Figure 8), it can be seen that the greatest potential and concentration of power stations are found in the middle and lower reaches of the river, where the highest flows and greatest gradients are also found. This facilitates the intensive exploitation of hydropower potential and explains the high energy efficiency of this section.

In the case of the Radunia River, the differences between actual electricity generation (assuming 45% utilisation of the operational potential of hydroelectric power stations) and the estimated theoretical potential stem primarily from the significant degree of alteration to the river system, resulting from both natural processes and human activity, as well as from the cascade arrangement of hydroelectric power stations operating in the catchment area. The presence of lakes and retention reservoirs, which accumulate water resources and enable the regulation of flows over time, is also of significant importance.

The cumulative water resources stored in lakes and reservoirs, combined with the cascade arrangement of hydroelectric power stations, create the possibility of controlling flow and redistributing electricity generation depending on hydrological conditions. As a result, it is possible to increase the efficiency of water resource utilisation and optimise energy production during specific periods of the year.

A comparison of theoretical potential with actual energy production indicates that appropriate hydrotechnical development, flow regulation, and a cascade arrangement of power stations enable the very efficient use of the Radunia River's water resources, leading to energy production at a level similar to or higher than the values resulting from simple calculations of potential.

It is also important to highlight the risks associated with extreme hydrometeorological events on the Radunia River, given that this area is closely linked to the urban and energy infrastructure of the Gdańsk conurbation. Consequently, future assessments of hydropower development on the Radunia River should take into account climate-related risks associated with extreme rainfall and flooding. Heavy rainfall can lead to sudden increases in flow rates, local flooding, and the overloading of hydrotechnical and energy infrastructure [86]. Extreme rainfall events can reduce the operational reliability of hydroelectric power stations and increase the vulnerability of the associated power infrastructure. In the case of the Radunia River, Table 1 shows that the upper and, to some extent, the middle reaches of the Radunia River, due to significant natural regulation by lakes, may be characterised by a lower infrastructure risk compared to the lower reaches of the river, where regulation by hydroelectric power stations is significantly lower.

4.4. Protected Areas and Opportunities for Harnessing Hydropower Potential

The scope for further exploitation of the Radunia's hydropower potential is limited by both hydrological and environmental factors [25,73,82]. A significant portion of the

river valley is covered by various forms of nature conservation, including Natura 2000 sites and landscape parks (Figure 9).

An analysis of the distribution of protected areas in the Radunia catchment indicates a significant concentration in the upper and middle parts of the catchment, where extensive forms of protection predominate, including Natura 2000 sites and landscape parks.

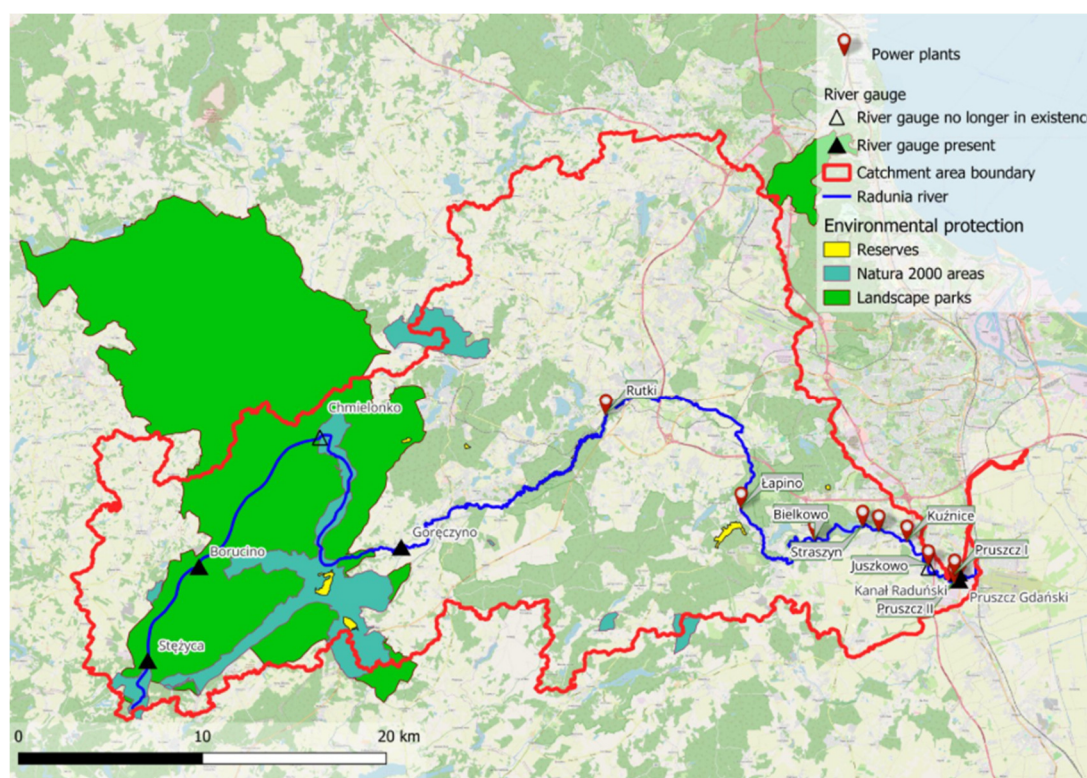


Figure 9. Protected areas in the Radunia catchment area and the potential for hydroelectric power generation. Source: own work.

A particularly large network of protected areas covers the region of the trough lakes and the headwaters of the river, and this plays a significant role in shaping natural water retention and stabilising runoff. In the lower reaches of the Radunia, the proportion of protected areas is significantly smaller and more scattered, which partly favours the location of existing hydroelectric facilities (Figure 10).

Such spatial variation in nature conservation measures has a direct impact on the potential for harnessing the river's hydropower. In areas with a high level of protection, the implementation of new projects is significantly restricted due to the need to preserve natural hydrological processes and the integrity of aquatic ecosystems and river valleys. These restrictions stem directly from the need to meet the environmental objectives set out in the Water Framework Directive, in particular the achievement of good water status and the maintenance of the ecological continuity of watercourses (Directive 2000/60/EC) [47]. At the same time, the presence of protected areas helps maintain a more stable flow regime, which indirectly affects the operating conditions of existing hydropower plants. In view of the above, it is possible to introduce the category of ecological hydropower potential; this forms part of the overall hydropower potential and is relevant and necessary for rivers within a specific catchment area outside the boundaries of protected areas, subject to certain limitations on the river's hydrographic and hydrological indicators.

Concerning our study site (the Radunia River), the following environmental conditions can be proposed for the exploitation of its ecological hydropower potential.

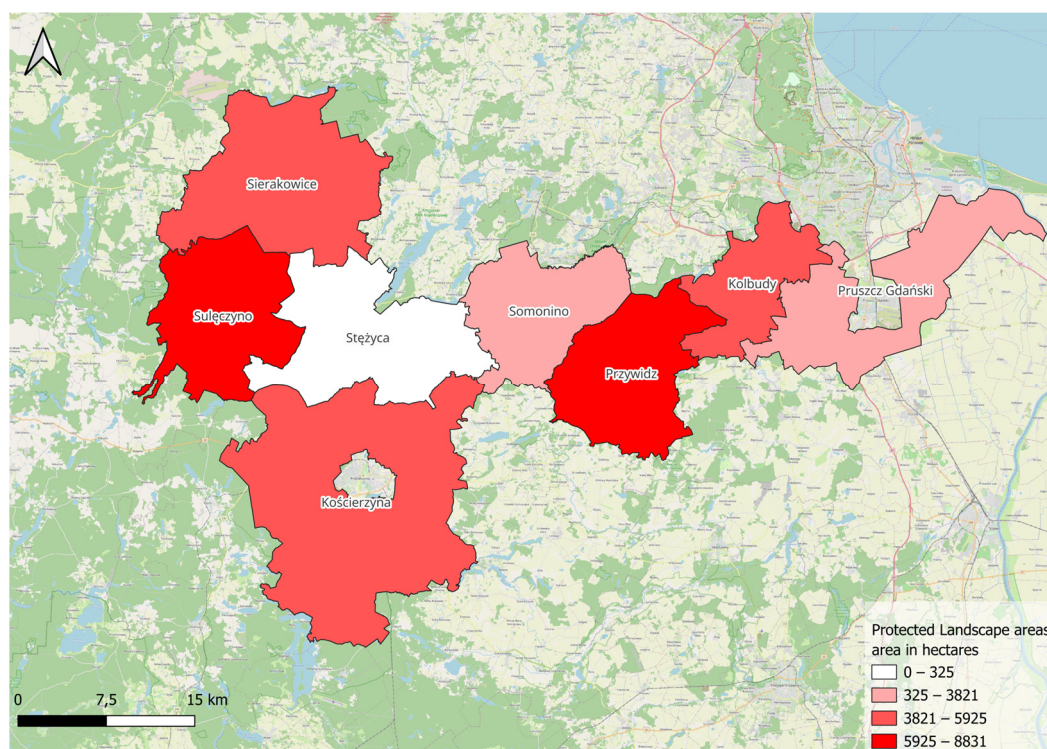


Figure 10. Protected landscape area in the Radunia River basin according to LAU 2. Source: own work.

It is not possible to utilise the hydroelectric potential in the upper reaches of the river from its source over a stretch of at least 10 km or with a catchment area of at least 50 km². This is where the river originates, and any disruption to its hydrological regime and water content may lead to rapid silting of its channel. This also applies to excessive ploughing and the afforestation of hydrotechnical structures within this catchment area, which may lead to a significant intensification of erosion processes (sheet erosion) and the excessive runoff of their products into the river channel. Taking such criteria into account will contribute to the preservation of river sections located near their sources, which generally have reference operating conditions, a factor of paramount importance in determining the ecological status of the river (Directive 2000/60/EC, Water Framework Directive [26,90–92]).

The presence of areas with different protection categories within the river basin, including nature reserves, landscape parks, and Natura 2000 sites, is of great importance. About this criterion, when determining ecological potential, excluding protected areas from the overall assessment will contribute to the preservation of the river's natural ecosystem, ensure less anthropogenic over-regulation, preserve its hydrological regime, and minimize natural losses in the river system.

Taking the hydrological regime into account, the threshold criteria for determining the ecological hydropower potential could be an average annual water flow of at least 0.3 m³/s, and the minimum average annual water flow should be at least 0.1 m³/s. Consequently, most upper river sections, which are very low in water flow (streams), as well as very small rivers in terms of water flow, cannot be used for hydropower purposes. Taking the above indicators into account, for the construction of even small hydroelectric power stations, the minimum water flow required for their operation should be

approximately 0.1 m³/s gross (Principles of the construction and operation of small hydroelectric power stations/Geothermal and Hydropower. 13 December 2025 [89].

The above criteria enable the determination of the ecological hydropower potential of the Radunia River, taking protected areas into account. To this end, it is necessary to exclude the two upper sections of the river (Riverhead–Stężyca and Stężyca–Borucino) from the calculations. The total potential will decrease by 54.28 kW (475,492.8 kWh), i.e., by less than 1%, which is an insignificant figure, but one of great importance in the ecological assessment of this renewable energy source and its value. The ecological potential of the Radunia River for hydropower will then amount to 7013.61 kW, or 61,439,223.6 kWh.

Similar criteria can be applied when determining the ecological hydroelectric potential of other lowland rivers in Poland, which will undoubtedly strengthen the ecological component of the economic use of hydropower within the framework of renewable energy sources. Furthermore, similar studies have been carried out for rivers in Ukraine and have yielded positive ecological results [93–95].

Consequently, the development of new hydropower projects must take into account the requirements for the protection of aquatic ecosystems, in particular the maintenance of undisturbed flow and the preservation of the river's ecological continuity [48,67]. In many cases, the energy potential of rivers in the Pomeranian Voivodeship is already largely utilised by existing hydropower installations, and the construction of new power stations is hampered by low river gradients and environmental constraints [33,96].

In the case of the Radunia, further development of hydropower should focus primarily on modernizing existing facilities, improving their efficiency, and optimising the operation of the cascade of power stations [48,78,97]. The results of the analysis indicate that the Radunia River constitutes a significant element of the regional renewable energy system. The utilisation of its hydropower potential contributes not only to electricity generation but also to the development of the local economy and recreational functions associated with the development of the river valley. In the context of the growing importance of renewable energy sources in the energy policy of the European Union [49] and globally [11,98,99], the rational use of the hydroelectric potential of rivers such as the Radunia may constitute an important element of the region's sustainable development [97,100–104].

Furthermore, it is possible to partially harness the hydroelectric potential of the middle section (Figure 9) of the Radunia River through the operation of new, highly environmentally friendly small hydropower plants (EFSHP) [66,104]. Under such conditions, the use of the river's water resources for energy production is minimized, without significant changes to the river's ecosystem. This, in turn, can go a long way towards meeting local electricity demand, particularly for socio-economic and recreational purposes.

5. Conclusions

The analysis conducted indicates that the Radunia River constitutes a lowland watercourse with a relatively high hydropower potential in the context of northern Poland. This potential results from the combined influence of hydrological and geomorphological factors, including relatively favourable flow conditions, significant cumulative head differences, and the presence of natural and artificial water retention systems.

A noteworthy aspect of the study is the integration of a section-by-section analysis of the river with a catchment-based approach. This methodology enabled the identification of spatial differences in hydrological and morphometric conditions along the river course and provided a more detailed assessment of hydropower potential than approaches based

solely on averaged river parameters. The results indicate that the middle and, to a lesser extent, lower reaches of the Radunia are characterized by the highest estimated hydropower potential due to the coexistence of relatively high flows and substantial elevation gradients.

The application of differential integral curves allowed the identification of periods of increasing and decreasing average annual discharge. The observed differences between these phases exceeded 30%, highlighting the importance of long-term hydrological variability for both hydropower potential assessments and the operation of existing hydroelectric facilities.

The comparison between the estimated theoretical potential and current energy production suggests that the river is already substantially utilised for hydropower generation. The existing cascade system facilitates repeated use of the same water resources, while retention reservoirs contribute to flow regulation and may reduce the effects of seasonal discharge fluctuations.

The study also incorporated environmental considerations through the concept of ecological hydropower potential. The results suggest that excluding environmentally sensitive river sections from further energy development would reduce the estimated total potential only to a limited extent. However, this assessment should be treated as indicative, as it is based on generalized environmental criteria and does not replace detailed ecological analyses at the local scale.

The findings presented should be interpreted in light of several limitations. First, the hydrological analysis was based primarily on available long-term flow records, which may not fully reflect recent changes associated with climate variability and land-use transformations within the catchment. Second, the estimation of hydropower potential relied on simplified calculations using average flow and head parameters and did not account for all technical, operational, and economic constraints affecting energy production. Third, the assessment of ecological hydropower potential was conducted at a general level and should be complemented by site-specific environmental studies before any management decisions are considered.

Within these limitations, the results provide an overview of the spatial distribution of hydropower potential along the Radunia River and may contribute to comparative analyses of lowland river systems. Future research could focus on incorporating higher-resolution hydrological data, detailed hydraulic modelling, and comprehensive ecological assessments to improve the accuracy of hydropower potential evaluations. From a practical perspective, the results suggest that modernization of existing hydropower infrastructure and optimisation of flow management may warrant further consideration alongside broader environmental and socio-economic objectives.

In summary, the Radunia River serves as a prime example of the sustainable utilisation of hydropower potential in lowland conditions. The results of the research conducted may form the basis for further comparative analyses and be utilised in the planning of water resource management in other catchment areas with similar physical and geographical conditions.

Recommendations

Given the results of the research conducted on the Radunia River, it is considered important to undertake further in-depth studies into its socio-economic and tourism potential. The analyses carried out to date do not fully exhaust the possibilities for utilising the river in the context of local development, particularly in the areas of the economy, society, and tourism and recreation. It is necessary to carry out comprehensive studies taking into account both natural conditions and infrastructural and social aspects, which will enable the identification of optimal directions for the development of the Radunia

River. It is also important to take into account the principles of sustainable development, so that any use of the river does not lead to the degradation of the natural environment. Furthermore, it is advisable to extend the analyses to include an assessment of the river's tourism potential, including opportunities for the development of water-based, educational, and recreational tourism. Future research should also take into account the resilience of infrastructure under extreme hydrometeorological conditions. Combining assessments of hydropower with analyses of infrastructure resilience would contribute to sustainable river basin management in a changing climate. The results of such studies could form the basis for developing a strategy for the development of the entire region, taking into account the multifunctional use of the river's resources.

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