

Article

Principles for Locating Small Hydropower Plants in Accordance with Sustainability: A Case Study from Slovakia

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Abstract

The present study examines the possibilities for developing the use of small hydropower plants (SHP) in Slovakia, focusing on the principles of sustainability and compliance with European and national legislation. At present, there is a tendency for the construction of hydroelectric power plants to intervene in the river environment, with the potential to exert a substantial impact on the flow of the river and disrupt the surrounding ecosystem. A potential strategy for minimizing environmental impact would be the construction of SHPs, which require less construction work. The Hornád river sub-basin, located in eastern Slovakia, was selected as the study area. The spatial and hydrological data were processed using Geographic Information System (GIS) tools. The hydrological characteristics of the area were determined through the utilization of a digital terrain model (DMR 5.0). The results of the hydrological analyses were then combined with environmental constraints to identify suitable locations for small hydropower plants. The theoretical and technical potential and gradient were calculated for individual sections of watercourses. It is estimated that approximately 61% of watercourse sections have a gradient greater than or equal to 10 m, which represents suitable conditions for the development of small hydropower plants. The presence of a stable flow regime engenders optimal conditions for the utilization of hydropower in the designated location. The study emphasizes the importance of environmental protection of the area, the resolution of property rights issues, and the streamlining of permitting processes. The results of the study contribute to energy planning at the regional level and confirm the effectiveness of using GIS in determining locations for small hydropower plants. Concurrently, emphasis is placed on the necessity to incorporate environmental and legislative imperatives within the overarching strategy for water energy development.

Keywords: small hydropower plant; water energy; hydropower potential



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1. Introduction

The issue of reducing greenhouse gas emissions is one of the important topics addressed by the European Union (EU). At the EU level, many measures have been adopted to transition to sustainable energy, in connection with the sustainable development goals [1]. In 2023, a European Parliament resolution [2] was adopted, emphasizing the importance of advancing these goals. In line with the UN 2030 Agenda and the EU's sustainable development goals, the EU has developed a strategy called the European Green Deal.

In 2021, a key climate regulation was approved: Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021, which sets out a framework for achieving climate neutrality, also known as the European Climate Law. This regulation changes the EU's target to reduce domestic net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, which it plans to achieve through the Fit for 55 package of measures. One of the measures is to increase energy efficiency and the share of renewable energy sources (RES).

According to Eurostat data [3], energy from RES consumed in the EU in 2023 accounted for 24.5% of the total amount, compared to 2004, when it was only 9.6%. Slovakia gradually increased the share of RES to 17.481% in 2022. In 2023, the figure fell to 16.99% in the EU. In terms of the structure of renewable energy sources in Slovakia, hydroelectric power plants play a significant role, accounting for up to 97% of electricity production. Solar power plants account for 1.4% and wind power plants for only 0.1%. As a result of this structure, the volume of electricity produced from RES was relatively stable in 2014–2023 (an average of 5465 GWh) [4]. As stated in the document Energy Security Strategy of the Slovak Republic [5], hydropower is the most widely used renewable energy source for electricity generation in the Slovak Republic.

Renewable energy sources are playing an increasingly important role in electricity generation. In 2024, RES together with nuclear energy accounted for 40% of global electricity generation, with RES alone accounting for 32% [6]. To achieve the set goals, it is necessary to minimize deforestation, develop low-emission technologies, and significantly increase the use of renewable energy sources, which are considered clean sources of electricity generation. Studies [7–9] focused on examining the environmental impacts of RES usability on the surrounding environment.

When evaluating RES, it is possible to distinguish between different types of potential. Theoretical potential represents the total natural energy of a given source, which may, however, remain unused due to certain limitations. The technical potential of a source corresponds to the amount of energy that can be utilized with currently available technologies. Usable potential also takes into account other factors such as various environmental constraints, while economic potential considers the financial viability of the project. Estimates of the technical potential of renewable energy sources vary widely, except for hydropower [10]. The actual energy use of individual sections of watercourses is determined by basic conditions, namely hydrological, geological, topographical, and environmental factors [11,12]. Legislative requirements and established procedures for the preparation of the construction and operation of small hydropower plants, which must be in line with sustainable development, are also important factors [13,14].

When identifying potentially suitable locations for the design of small hydropower plants and their integration into decision-making processes, the use of geographic information systems (GIS) and their tools [15,16] enables a comprehensive assessment of the territory based on several criteria and constraints, including environmental ones, which are usually defined in legislation and other documents. The paper by Sammartano et al. [17] deals with the use of GIS in conjunction with a hydrological model to assess sites for run-of-river power plants. The works [18–21] combine GIS tools and hydrological models to determine the hydroelectric potential of watercourses. The paper by Bayazit et al. [22] emphasizes the possibility of using the results of the study as a basis for regional planning and decision-making by local authorities.

Hydropower, as a renewable source, is one of the proven, predictable, and affordable technologies for electricity generation. Despite relatively high initial investments, their advantages include a long service life and low operating and maintenance costs [23,24]. The article by Ranjitkar et al. [25] highlights the economic and technical challenges, as well

as the often lengthy and complicated administrative and legal procedures [26] associated with the design and construction of hydroelectric power plants. The implementation of hydropower plants is also influenced by legal relations concerning land ownership and public opinion among residents of the affected municipalities [27]. Environmental impact assessments are usually part of the project work when planning the construction of a hydroelectric power plant [28].

Hydropower plant construction projects are unique, and even facilities with the same installed capacity can be completely different, as the design takes into account the specific conditions of the location. Hydroelectric power plants are most often classified according to their installed capacity, which allows them to be divided into small and large, but individual countries and international organizations may set different classification thresholds [29]. Most countries consider small hydropower plants to be those with an installed capacity of up to 10 MW, which is the accepted limit adopted by the European Small Hydropower Association and the European Commission [30]. In India, this limit is set at 25 MW and less [31] and in China at 50 MW and less [32]. In Slovakia, according to the STN 75 0128 Water Management (Nomenclature of Water Power Utilization) standard small hydropower plants are those with an installed capacity of up to 10 MW. There are currently around 25,000 small hydropower plants (installed capacity up to 10 MW) in EU member states, contributing to energy security and the development of local energy sources [33].

The total theoretical hydropower potential of Slovakia's watercourses is 13,682 GWh year⁻¹, and the technical potential is 6683 GWh year⁻¹ [34], which is 55% utilized thanks to large hydroelectric power plants. However, the potential of small hydroelectric power plants is only 25% utilized. There are currently 24 large hydroelectric power plants with an installed capacity of over 10 MW and 253 small hydroelectric power plants in Slovakia (of which 223 are in use, and 30 are built but not in use) [34]. Since hydroelectric power plants can be integrated into the electricity grid during their design and construction, the goal of maximizing the technical potential should be taken into account. Hydropower can be considered the most promising and most widely used renewable energy source in Slovakia [35].

This research presents a case study focused on the possibility of utilizing water energy through the construction of small hydroelectric power plants, considering the principle of sustainability. The paper consists of two parts: the first part is devoted to calculating the potential of hydropower in a selected area in a GIS environment, and the second part is devoted to the specific conditions in Slovakia. In this study, we focus on a comprehensive approach to small hydropower plant projects, from site selection using GIS tools to project preparation, taking into account the legislative restrictions of the current legislation in Slovakia. The process from the presentation of the intention to build a small hydropower plant to its commissioning is a complex one, influenced by administrative, legislative, and environmental factors arising from Slovak and EU legislation.

2. Materials and Methods

2.1. Study Area

The study area (Figure 1) consists of the Hornád sub-basin and belongs to the international Danube basin. The area of the Hornád sub-basin is 4420 km². The total length of the Hornád river in Slovakia is 178.8 km [36]. The Hornád sub-basin is covered by forests, with an area of 2142 km² (forest cover 48.5%) [37].

There are three climatic regions in the Hornád sub-basin. The first is characterized as warm and moderately dry to humid with cold winters (average annual air temperature is 8–10 °C, average annual precipitation is 600 to 700 mm). The second district is characterized as moderately warm, moderately humid to humid, valley, and hilly to mountainous

(average annual temperatures are 6–8 °C, average annual precipitation is 700–900 mm). The third district is in the northern and western parts and is slightly cold (average annual air temperature is 4–5 °C, average annual precipitation is 700–900 mm) [37].

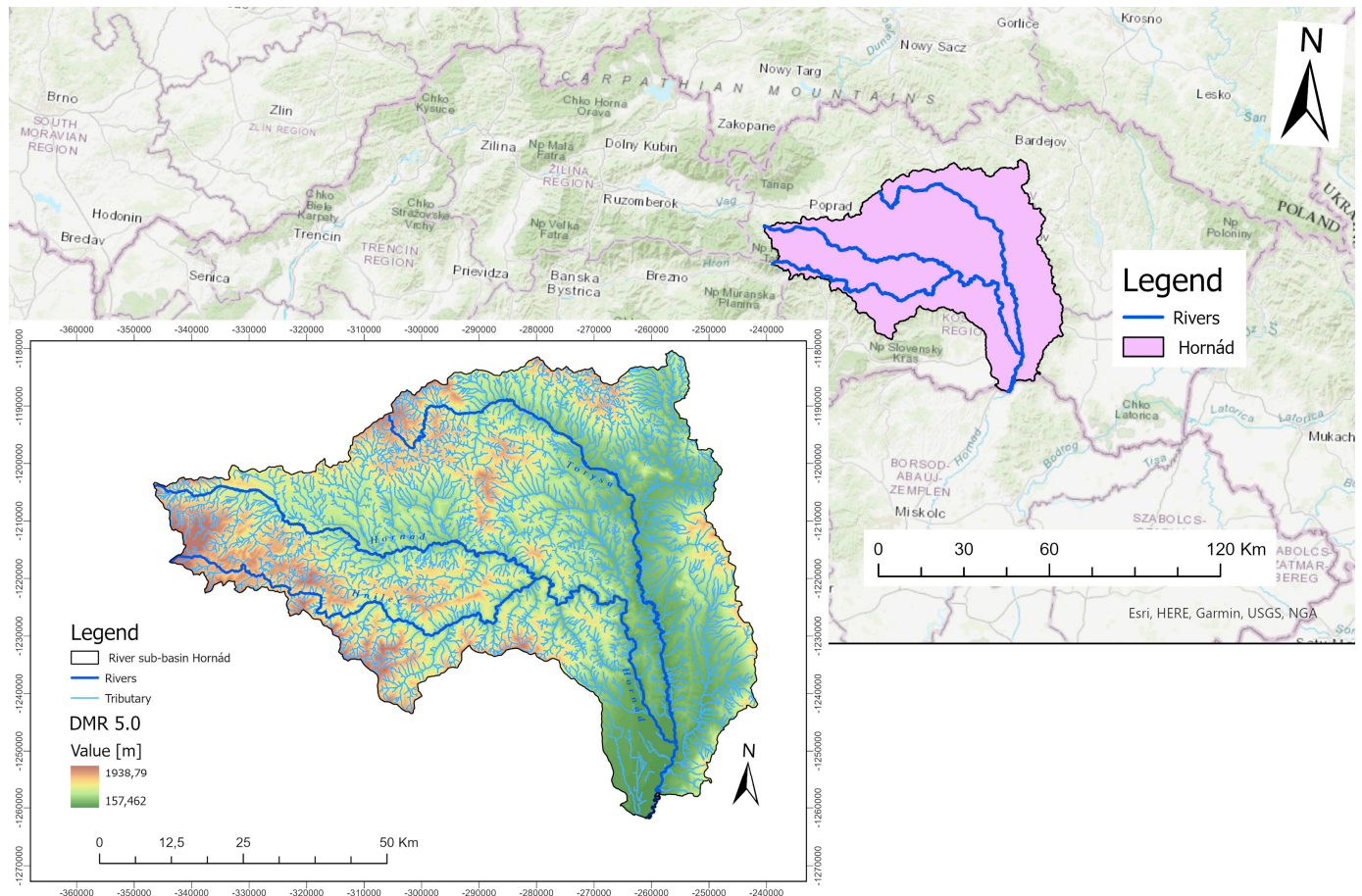


Figure 1. Hornád river sub-basin.

2.2. Methodology

The methodology can be divided into four main steps, which are closely linked to each other. The first step includes the study of the legislative basis related to the issue of hydropower use in the conditions of Slovakia. The second step consists of the collection and preprocessing of input data into GIS. The next step is the estimation of hydropower potential on watercourses. The last step is the addition of other criteria and factors influencing the selection of a site for a hydroelectric power plant based on legislative requirements. These steps are illustrated in the following Figure 2.

2.2.1. The Legal Background

The first step of the research focuses on a detailed analysis of all relevant documents and professional publications concerning the the legislative framework (Legal and information portal. www.slov-lex.sk/, accessed on 1 October 2025) and conditions for the construction and operation of hydroelectric power plants in Slovakia, including an assessment of the potential for hydropower use. In addition to the professional literature, we also focused on studying strategic and conceptual materials from government and ministerial institutions. These documents are available through the open government portal (Open Government Portal. available at: <https://rokovania.gov.sk/>, accessed on 3 October 2025) and the websites of individual ministries.

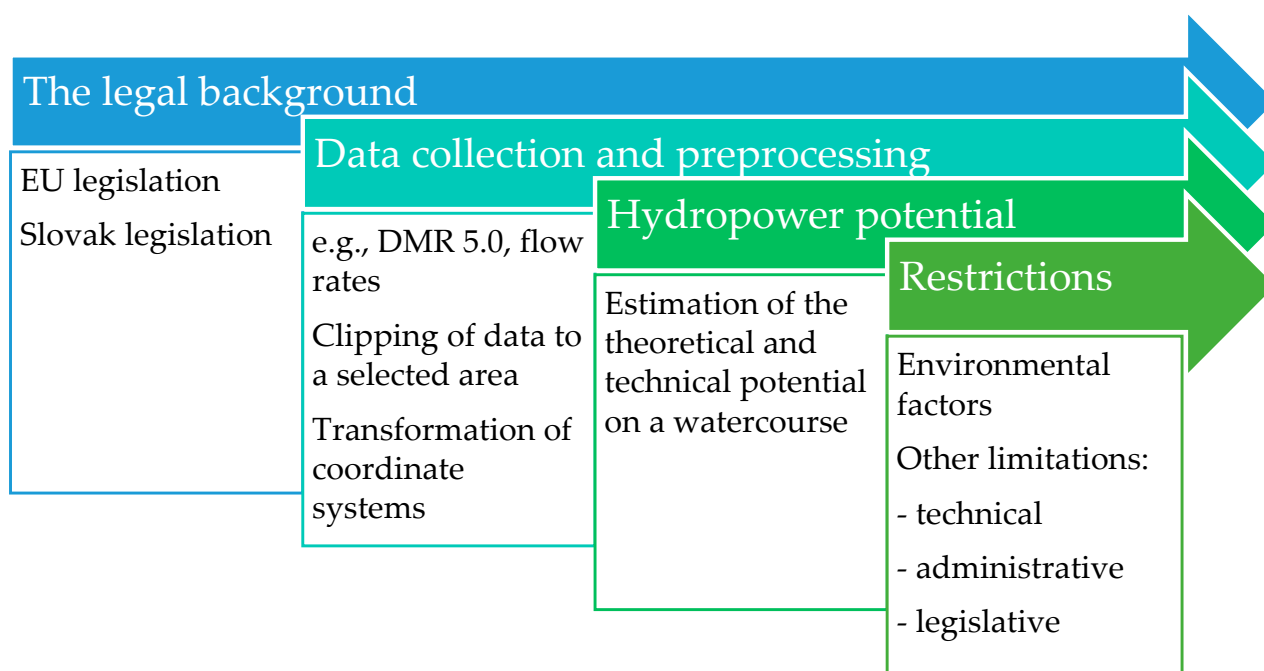


Figure 2. Methodology flowchart.

2.2.2. Data Processing Overview

The data used in the study are from freely available sources and are processed in ArcGIS Pro 3.5.0. in the coordinate system of the Unified Trigonometric Cadastral Network S-JTSK (EPSG:5513) and the Baltic Elevation System after alignment (EPSG:8357). The data in other coordinate systems are transformed to the chosen coordinate system by means of transformation keys.

The digital elevation model for the selected area was derived from the DMR 5.0 digital elevation model, which was created by interpolating the classified point cloud of the airborne laser scanning. The raster is in TIFF + TFW format with a resolution of $1\text{ m} \times 1\text{ m}$. For use in this study, the raster was resampled to $5\text{ m} \times 5\text{ m}$. The source of the product is the Office of Geodesy, Cartography and Cadastre of the Slovak Republic (www.skgeodesy.sk/gku/produkty-sluzby/na-stiahnutie/zbgis.html, accessed on 1 October 2025). The accuracy of the DMR affects the hydropower potential values of the watercourse [38]. According to Leitmann and Gál [39], DMR 5.0 elevation accuracy values have reached values ranging from 0.02 m to 0.16 m.

The ArcHydro extension in ArcGIS Pro 3.5 was used to create maps of the basic hydrological characteristics of the Hornád sub-basin. In the initial phase of processing, the digital relief model was modified with the Fill Sinks command to ensure that it was hydrologically correct. The modified DMR was then used to derive values for runoff direction, runoff accumulation, and uninterrupted length (Flow direction, Flow accumulation and Flow length commands). The D8 algorithm was used to calculate the flow direction, which creates a raster where each cell is assigned a value ranging from 8 to 128, with each value representing one direction. The output raster was used as input for the flow accumulation calculation. This was followed by analyses of the river network and catchment area delimitation.

To calculate the surface runoff volume, we used the Curve number (CN) method, which was developed by the US Soil Conservation Service (SCS). CN values were constructed by combining soil type data obtained from soil-ecological rating units, land use/land cover data, and, in the case of forested areas, data from the forest soil unit map.

Data on the surface water quantity in the selected watercourses were obtained from the hydrological yearbook published by the Slovak Hydrometeorological Institute (SHMI), which monitors the surface water quantity [40] through a state-of-the-art hydrological network. The study used values from 34 water gauging stations located in the Hornád sub-basin for 2019–2023. Figure 3 shows the location of the water gauging stations with their database numbers.

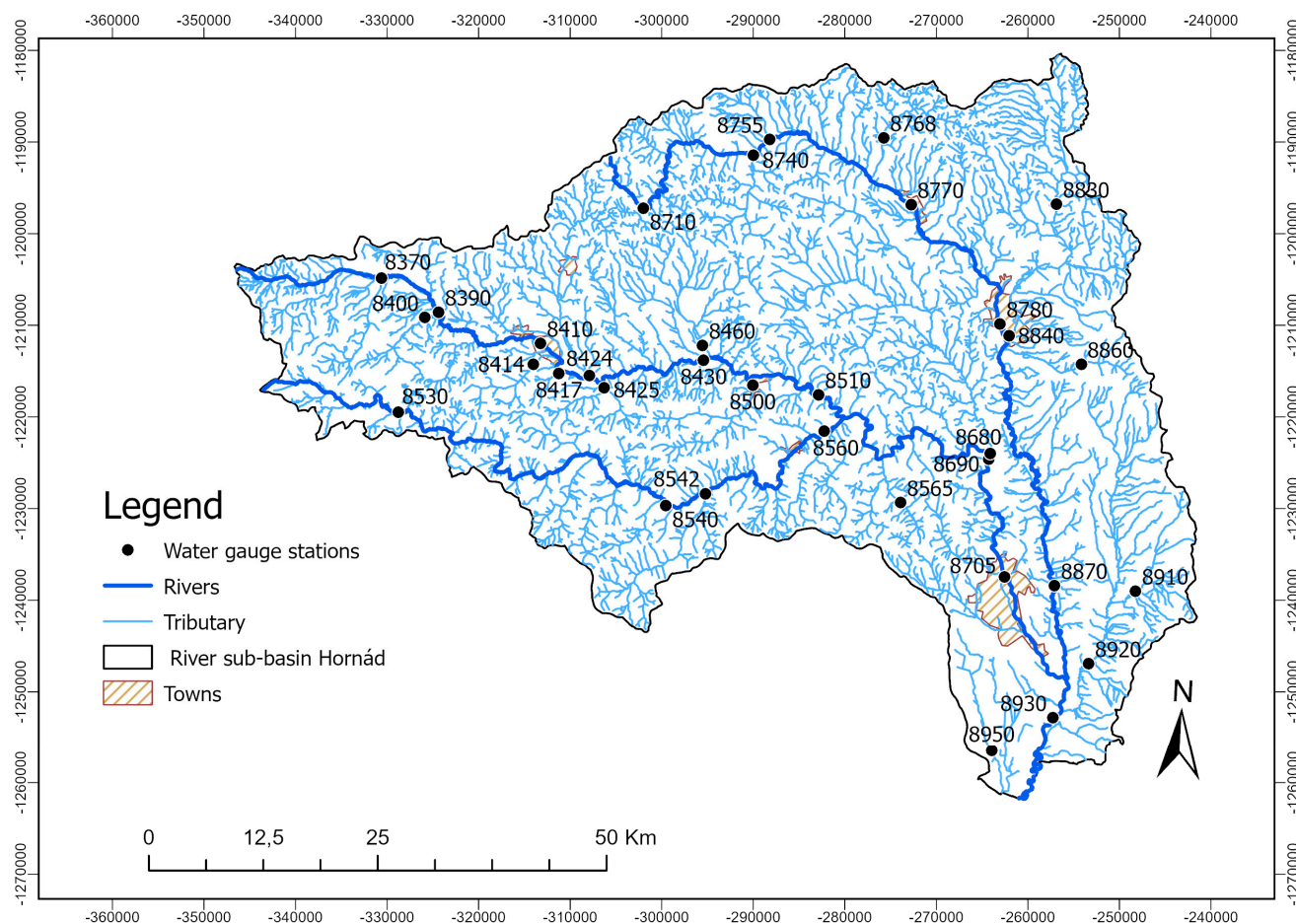


Figure 3. Location of water gauging stations in the Hornád sub-basin.

The data include values in $\text{m}^3 \text{s}^{-1}$ of the average monthly flow, the average annual flow, the highest peak flow, and the lowest average daily flow each year. Operational data from stations that allow online transmission are available on the SHMU website.

The suitability/unsuitability of a site with a technically viable hydropower potential for the construction of small hydropower plants is also limited by other factors such as natural and environmental protection activities and interests, watercourse management, etc.

Important environmental factors include the level of nature protection and protected areas, nature reserves, natural monuments, protected areas, protected landscape features, protected areas zones, and the Natura 2000 network of protected areas. Data are available through the National Geoportal (<https://geoportal.gov.sk/>).

2.2.3. Estimation of Hydropower Potential

The hydropower potential is influenced by the water flow rate Q , the gradient H , and the turbine efficiency η . It is estimated according to the following formula:

$$P = \rho \times g \times Q \times H \times \eta, \quad (1)$$

where P is the theoretical power (W), ρ is the density of water (1000 kg m^{-3}), g is the gravitational acceleration (9.81 m s^{-1}), Q is the average flow rate ($\text{m}^3 \text{ s}^{-1}$), H is the gradient (m), and η is the efficiency.

An efficiency value of η equal to 1 is considered in the calculation of the theoretical potential. On the other hand, the technical potential already takes into account the limitations of the technology, the efficiency of the turbines, and the availability of water under realistic conditions. The streamflow gradient was derived from DMR 5.0.

3. Results

3.1. Legislative Framework—Requirements and Principles for the Realization of SHP

Slovakia is bound by EU law and national law. The Slovak legal system ensures compliance with European standards, which are either directly applicable to or implemented in national legislation. The use of hydropower and the design of hydropower plants (including small hydropower plants) fall under the remit of the Ministry of Economy (covering energy, including renewable energy sources) and the Ministry of Environment (covering Slovakia's water management policy). Table 1 below provides an overview of the strategic and legal documents relating to the use of hydropower.

Table 1. Documents and legal norms concerning the construction and operation of small hydropower plants.

Level	Name
EU	Directive (EU) 2018/2001 [41]
EU	Directive 2000/60/EC [42]
EU	Directive 2001/42/EC [43]
EU	Council Directive 92/43/EEC [44]
SR	Energy Policy [45]
SR	Energy Security Strategy of the Slovak Republic [5]
SR	Act No. 364/2004 Coll. [46]
SR	Decree No. 211/2005 Coll. [47]
SR	Decree No. 433/2005 Coll. [48]
SR	Act No. 309/2009 Coll. [49]
SR	Act No. 24/2006 Coll. [50]
SR	Act No. 25/2025 Coll. [51]

Directive [41] on the promotion of the use of energy from renewable sources was revised and supplemented in 2024. Directive [42] establishes a framework for Community action in the field of water policy. This directive resulted in a requirement for a comprehensive approach to the protection and use of water and related ecosystems. Based on this approach, a basic unit for assessing water status was created—the water body [52].

The basic strategic document in Slovakia is the Energy Policy of the Slovak Republic [45], which defines the main objectives and priorities of the energy sector. When setting targets, it draws on the pillars of the EU Energy Policy and emphasizes the optimization of domestic energy resources and low-carbon technologies, such as renewable energy sources.

In 2008, the Energy Security Strategy of the Slovak Republic [5] was adopted, which defined the objective of achieving a competitive energy sector and ensuring safe, reliable, and efficient supply of all forms of energy. One of the sub-objectives is to increase the share of electricity from renewable energy sources.

Act No. 364/2004 Coll. on Water (Water Act) [46], among other things, determines the conditions for the use of watercourses for energy purposes and stipulates the obligation to obtain a permit for water abstraction and the change in the flow regime of a watercourse. In connection with this Act, Decree No. 211/2005 Coll. [47], which determines the list

of watercourses of hydro-economic importance and watercourses for water supply, and Decree No. 433/2005 Coll. [48], which determines the details of the use of the hydroenergy potential of watercourses, were issued.

Act No. 309/2009 Coll. on the Promotion of Renewable Energy Sources [49] establishes rules for the promotion of the construction and operation of renewable energy sources and for small hydroelectric power plants up to 10 MW guaranteed purchase prices for electricity. The obligation to carry out an environmental impact assessment for hydropower plants above a certain capacity results from Act No. 24/2006 Coll. on Environmental Impact Assessment (EIA) [50]. Act No. 25/2025 Coll., the Construction Act [51], regulates the procedures for the preparation, construction, operation, and removal of structures.

The process of constructing a small hydropower plant consists of several interrelated steps, as shown in Figure 4. In all individual phases, it is necessary to ensure consultation and cooperation with the participants in the proceedings and all affected entities.



Figure 4. Schematic diagram of the small hydropower plant design process.

The preparatory phase consists of selecting a suitable location for the SHP and assessing the technical and hydrological conditions.

3.2. Hydrological Analyses and Estimation of the Theoretical and Technical Hydropower Potential

To estimate the theoretical and technical hydropower potential in the studied area, analyses such as runoff modeling, accumulation, and slope determination from a hydrologically correct DMR were performed.

A river network was derived from a hydrologically accurate terrain model, which is shown in Figure 5. The Strahler method [53] was used to classify river channels (Figure 4). The derived river network was compared with the Hydrography layer (ESRI geodatabase, ETRS89 coordinate system (EPSG:4258)), obtained from the portal operated by UGKK. The data were published, based on the INSPIRE Directive. The comparison showed the adequacy of the derived river network.

To calculate the surface runoff using the SCS-CN method, runoff maps were created by combining vector layers of BPEJ and forest soil units and land use according to Corine Land Cover for 2018 (Figure 6). The currently available data are for 2018. The data show that forest and semi-natural areas are the most significant in the Hornád sub-basin, accounting for 53.31%, with deciduous forests covering approximately 775.6 km², coniferous forests covering 709.2 km², and mixed forests covering 657.6 km². Agricultural areas account for 39.46% of the total area.

To assess the potential hydropower of the site under investigation, it is necessary to know the river flow data. Based on a hydrological analysis of the area, discharge points from the catchment area were determined, for which theoretical values of average flow in m³ s^{−1} were calculated for a selected precipitation value (average value for the last 5 years). The estimated values were compared with the flow values at nearby measuring stations (Figure 7a).

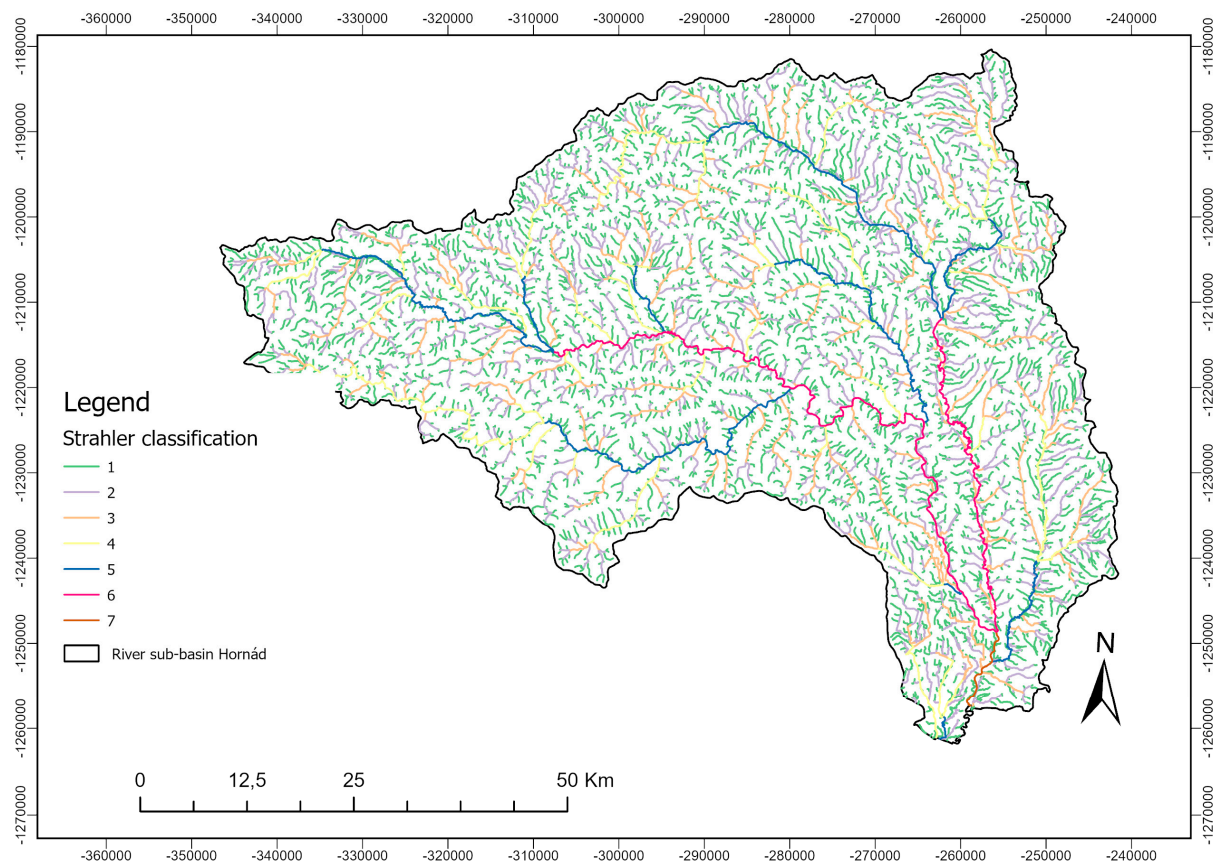


Figure 5. Stream order of each channel in the river network.

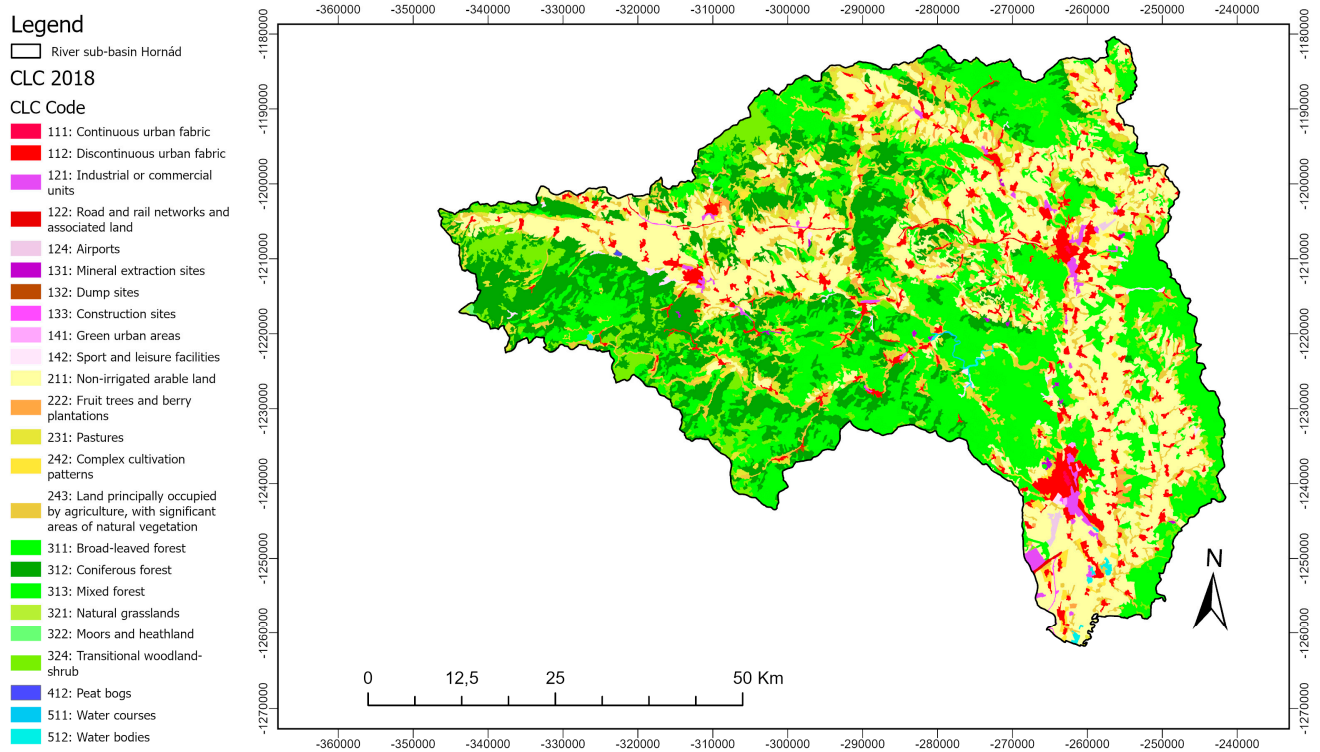


Figure 6. Land cover in the Hornád sub-basin in 2018.

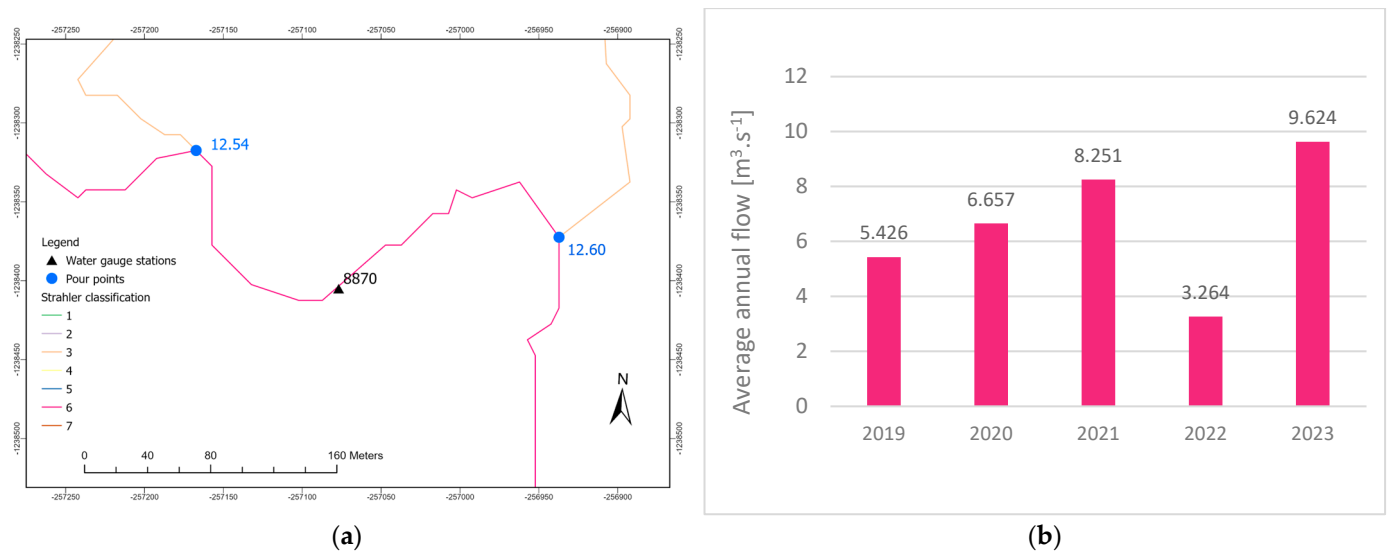


Figure 7. Average annual flow values at water meter station 8870: (a) spatial location of points of interest with water meter station; (b) average annual flow values at station 8870 in 2019–2023.

For the purposes of this study, data from water gauging stations for the years 2019–2023 were processed. At station 8870 (Figure 7b), the maximum measured flow rate in the selected period was $202.6 \text{ m}^3 \text{ s}^{-1}$ in 2021. The lowest measured flow rate was in 2022, reaching $0.685 \text{ m}^3 \text{ s}^{-1}$. From the long-term measurements (1931–2022) of the flow rate in the given section of the Torysa river, the maximum flow rate was measured in 2006, when it reached $359 \text{ m}^3 \text{ s}^{-1}$, and the lowest recorded flow rate was in 1968, when it reached $0.540 \text{ m}^3 \text{ s}^{-1}$.

Based on the analysis of the measured flow data, watercourses in the Hornád sub-basin show seasonal variability, with winter and spring months bringing increased flows, due to higher precipitation and snowmelt at higher elevations. The middle course of the Hornád river is characterized by a stable flow regime, which creates optimal conditions for small hydropower plants with lower sensitivity to seasonal flow fluctuations. The middle and lower parts of the Hornád river exhibit stable flows, and these locations are suitable for the construction of small and micro hydropower plants, as evidenced by the number of hydropower plants already built, 24 of which are in operation (Figures 8 and 9). The upper sections of the Hornád river and its tributaries are characterized by conditions suitable for the construction of small hydropower plants that can also consider seasonal changes in flow caused by local precipitation and snowmelt.

The theoretical and technical hydroelectric potential was calculated for individual sections of watercourses based on the estimated flow values. A turbine efficiency value ($\eta = 0.85$) was selected for the calculation of the technical potential. Values obtained from the DMR were used to determine the gradient. The estimated theoretical hydropower potential of watercourses is shown in Figure 8 and the technical hydropower potential in Figure 9.

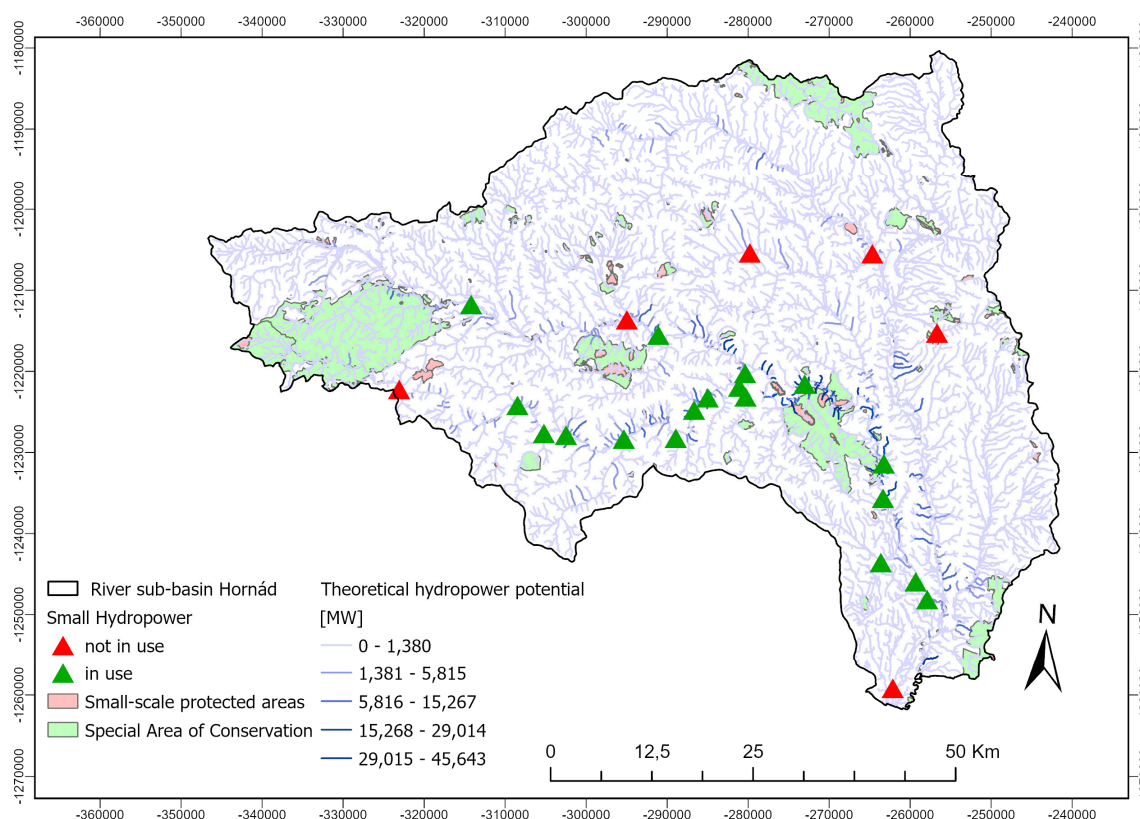


Figure 8. Estimation of the theoretical hydropower potential of watercourses in the Hornád sub-basin.

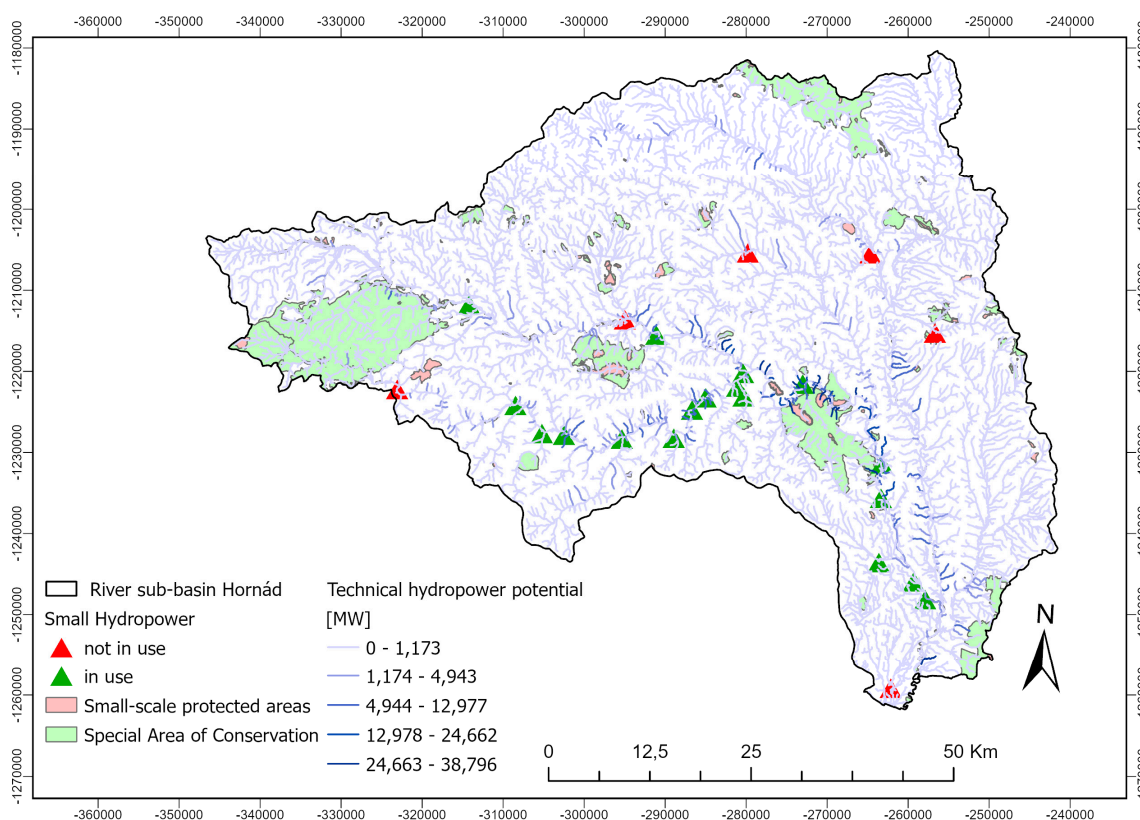


Figure 9. Estimation of the technical hydropower potential of watercourses in the Hornád sub-basin.

4. Discussion

The construction of small hydropower plants expanded mainly in the 1990s (after 1989). Some facilities from this period are still in operation, but they only partially utilize the available hydropower potential and may no longer meet the requirements for sustainable operation. Since 1989, Slovak legislation has changed significantly, and another important factor was the country's accession to the EU. Significant changes have occurred, particularly in environmental requirements, which have also been incorporated into legislation. The need to revise the policy on the use of small hydropower plants is also emphasized in the contribution by Novikau et al. [54], which points to the need to take local socio-political contexts into account when developing energy policy.

The selection of suitable locations for small hydropower plants and thus the use of water energy is based on analyses and the determination of the basic hydrological characteristics of the river basin [55]. More complex hydrological modeling is needed for reliable assessment of watercourses [56,57]. In our study, we measured the flow values to compare with our estimated values. The accuracy of the calculation is also influenced by the quality of the digital terrain model. For our study, DMR 5.0 with a resolution of 1 m was available, but the calculations were time-consuming. Therefore, we chose to resample the model to a resolution of 5 m. The spatial resolution of the DMR determines the details of the relief, and it is necessary to choose a resolution that sufficiently covers the topography without losing interpretation and processing capabilities [58].

Small hydropower plants use a relatively low head to generate electricity, which can be less than 10 m [59]. This head is naturally available in watercourses. In our study, we considered a head equal to or greater than 10 m. Given the nature of the Hornád sub-basin, according to the DMR, the lowest value is 157.9 m, the highest is 1938.2 m, and approximately 61% of watercourse sections have a head greater than or equal to 10 m.

For individual sections of watercourses, the theoretical and technical potential was calculated from the estimated flow values based on the selected procedure. When analyzing the measured flow values (an example of one station is shown in Figure 7b), 2022 was an exceptionally dry year. Electricity production fell year-on-year from 2076 to 1831 GWh, a decrease of −11.84% [60]. The study in [61] reports the finding of statistically significant correlations between the course of meteorological drought and the dynamics of theoretical hydropower potential in the studied river basins in Central Europe. The impact of climate change on the hydroelectric potential in the Topľa River basin is discussed in contribution [62], which points out that the hydroelectric potential of small hydroelectric power plants is strongly related to the distribution of runoff throughout the year and can therefore be strongly influenced by changes in precipitation, i.e., runoff.

For hydroelectric power plants with storage capacity (reservoirs, dams), changes in water levels affect the energy (volume $\times$ head) available for electricity generation. Data from remote sensing of the Earth [63,64] are used to estimate changes in water levels in reservoirs and dams, which can also provide a quantification of seasonal changes.

The actual technical potential may differ from the values stated in reports and documents, as the estimated values are based on mathematical models, long-term average flows, and precipitation and may not consider current conditions and limitations (e.g., changes in legislation). The technical potential may be influenced by the development of new technologies in the field of hydropower. The paper by Thakur et al. [65] describes the Archimedes Screw Turbine and its use in locations with a small head. This means that even parts of watercourses that were previously excluded may become suitable for hydropower use in the future.

In connection with efforts to increase electricity production through small hydropower plants, it is necessary to consider Slovakia's commitments and objectives, particularly in the

areas of water protection, preventing biodiversity loss, etc. In his paper, Landy [66] proposes environmentally compatible potential, which allows for the exclusion of sources that do not comply with legal requirements and the subsequent assessment of sources, including related infrastructure (e.g., connection to the electricity grid) and its impact on ecosystems (such as connection to the distribution network) and the environment. The selection of individual alternative solutions should consider environmental factors for successful assessment—the EIA process [67]—with the aim of achieving a successful solution.

Another important factor is the assessment of property rights to the land, including from the perspective of the accessibility of the selected location. In order to obtain a building permit, it is necessary to prepare project documentation, which also includes the construction plan. In terms of property rights, a condition for this phase is also the conclusion of a lease agreement with the owner of the land where the SHP will be built. The lease agreement is concluded between the future owner of the SHP and the watercourse administrator, the Slovak Water Management Company, in the case of state ownership, or another owner. This phase is carried out in the process of proceedings on the construction plan for the implementation of the reserved SHP construction. After a legally binding decision on the construction project has been issued, the implementation of the reserved SHP construction project is carried out in accordance with the Building Act [39]. The result of the completed construction process is implementation and operational documentation, with an issued occupancy permit. If the lease agreement for the land on which the reserved small hydropower plant construction is located is concluded for more than 5 years, it is subject to registration in the real estate cadaster information system in accordance with the Cadastre Act [68].

Figure 10 shows an example of a water structure recorded in the real estate cadaster information system. The water structure with inventory number 3385 is registered as a small hydroelectric power plant (Figure 10a) with an orthophoto image in Figure 10b. Part B of the title deed lists the owner with the title of acquisition by a 50-year lease agreement.



Figure 10. Water structure with descriptive number 3385: (a) spatial location of the water structure in the real estate cadaster information system; (b) orthophoto image of the water structure.

Since the entire process of constructing waterworks is essentially an administrative procedure, it is possible to estimate that, in the case of a small hydroelectric power plant, the time from submission of the application to the start of operation will be 2–4 years. This

timeframe may be affected by legislative, environmental, and technical factors, as well as by the administration on the part of the state authorities.

To facilitate investment, by state authorities representing the Slovak Republic and selected public administration entities, Act No. 142/2024 Coll. [69] was passed in 2024. Its aim is to facilitate and streamline the settlement of property rights to land and accelerate approval processes and public procurement. As stated in the article [70], based on modeling the economic efficiency of investments, the construction of small hydropower plants in the Košice region is feasible while complying with all the rules and restrictions imposed on this type of construction.

In June 2022, the Slovak government approved the Water Policy Concept until 2030 with a view to 2050 [71], which emphasizes the use of the hydroelectric potential of watercourses with minimal negative impact. The measures are aimed at reconstructing and modernizing hydroelectric power plants in order to mitigate negative impacts on the environment. It recommends the creation of a new concept for the use of the hydroelectric potential of watercourses, directly identifying sections where the construction of new facilities will not be permitted and setting criteria for minimizing negative impacts. Small hydroelectric power plants will no longer automatically be considered a higher public interest.

In the future, the task will be to develop tools that would enable automated evaluation of the suitability of sites for small hydropower plants based on changing input data. This approach would enable simulation and creation of alternatives and would help streamline and shorten the first phase of the preparation process (Figure 8). In their paper, Bódis et al. [72] proposed a GIS-based method for estimating the hydroelectric potential in Europe based on the use of existing databases. The development of a methodology, including recommendations for the quality of output data, would enable the application of machine learning, which would contribute to smarter decision-making in the planning and construction of small hydropower plants.

The system could also include monitoring of technical parameters, environmental factors, and possibly economic indicators, which would enable a faster response to changes and optimize the process of determining hydropower potential and locations for small hydropower plants.

5. Conclusions

The results obtained in this study show that hydropower is the most important renewable energy source in Slovakia, accounting for approximately 97% of total electricity production from RES in the long term. The total theoretical hydroelectric potential of watercourses in the Slovak Republic reaches 13,682 GWh year⁻¹, with the technical potential representing approximately 6683 GWh/year. However, only 55% of this potential is used in large hydroelectric power plants and approximately 25% in small hydroelectric power plants, which points to significant opportunities for further development of the sector.

In the case of the studied area—the Hornád river sub-basin—analyses derived from the DMR 5.0 digital terrain model and hydrological data showed that approximately 61% of watercourse sections have a gradient greater than or equal to 10 m, which represents suitable conditions for the development of small hydropower plants. The results of hydrological measurements in the period 2019–2023 showed a stable flow regime, which creates favorable conditions for the efficient and sustainable use of hydropower, especially in the middle and lower reaches of the Hornád river.

The study also confirmed that geographic information systems (GIS) are an effective tool for modeling hydroelectric potential, determining gradients, and identifying suitable locations for small hydroelectric power plants. The combination of data on flows, relief,

precipitation, and environmental constraints made it possible to create a comprehensive and spatially accurate picture of the possibilities for exploiting water potential.

From a legislative point of view, the need to harmonize the construction of small hydropower plants with national and European legislation has been confirmed, in particular with Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources, the Water Framework Directive 2000/60/EC, as well as Act No. 364/2004 Coll. on Water and Act No. 24/2006 Coll. on Environmental Impact Assessment (EIA). Compliance with these regulations is essential to ensure sustainable development and minimize negative impacts on watercourse ecosystems.

Overall, it can be said that the potential for the development of small hydropower plants in Slovakia is considerable, but its implementation requires a comprehensive approach that integrates technical, environmental, legislative, and socio-economic aspects. The document approved by the Slovak government [69] recommends modernizing and reconstructing existing hydroelectric power plants and related water structures, taking into account the expected impacts of climate change and drought. The text also proposes to repeal the Concept for the Use of the Hydroelectric Potential of Watercourses in the Slovak Republic until 2030 [34] and to develop a new document, the Program for the Sustainable Use of Hydroelectric Potential, which will be a basic document in accordance with the Integrated National Energy and Climate Plan for 2021–2030. The program will take into account the protection of waters, ecosystems, smooth navigation, and protected areas, including an assessment of the impact on the environment and the health of the population. “No-go” zones will be defined where the construction of new facilities will not be permitted, and a set of criteria for construction with minimal impact on watercourses will be established. At the same time, existing water use permits will be reviewed in accordance with EU requirements and, if necessary, amended or revoked to achieve environmental objectives.

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Abbreviations

The following abbreviations are used in this manuscript:

GCC SR	Geodesy, Cartography, and Cadastre Authority of the Slovak Republic
GCI	Geodetic and Cartographic Institute Bratislava
RES	Renewable energy sources
SHP	Small hydropower plant
GIS	Geographic information system
EIA	Environmental impact assessment

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