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Utilization of the Hydroelectric Potential of the Pomorskie Voivodship

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Abstract

One of the sources of electricity used by man is water. Currently the idea of hydroelectric power plants is increasingly appreciated by local governments. Sustainable development and EU directives have required the construction of green power plants. The article outlines the energy situation of the Pomorskie Voivodship. As a result, it was found that more than half of the energy consumed in the region is produced outside its area. Considering the transmission losses, this is a disadvantage. Hydropower installations are increasingly appearing in the voivodship, but there are relatively few of them. The natural and anthropogenic conditions of more than 300 potential hydropower plants have been analyzed. Based on the conducted research, the hydroelectric potential of the voivodship was estimated and the best locations for hydropower were identified.

Keywords: energy, hydropower, ecology, hydroelectric potential estimation

JEL: Q42

Introduction

Pomorskie Voivodship lies in northern Poland. Due to its coastal location it has enormous economic potential. This is connected with water related fields. Important sectors include the shipbuilding industry, port service, and trade. Within the voivodship are located some large, energy-intensive companies such as, for example International Paper Kwidzyn. At the same time, the voivodship is far from Poland's main energy resource — coal. Coal mining is becoming less and less profitable due to renewable energy policy, both in Poland and in the EU. The second reason for the coal crisis is the geological aspect. Mining coal from deeper deposits requires much more labor and financial contribution, which makes it less and less profitable.

Water is one of the main sources of renewable energy. The benefits of using water for energy production were recognized already in ancient Rome. This idea evolved through water mills, up to modern times, when it can be used to produce electricity. Dynamic development of renewable energy sources has been driven by more frequent discussion on limited fossil fuels resources and by introducing EU directives. Initially the sector was dominated by wind turbines, which currently raise a lot of controversy.[1] The falling popularity of wind farms has caused increased interest in hydropower, which more often becomes an important part of the energy policy of local governments (Bajkowski and Górnikowska 2013).

Poland has relatively small hydroelectric potential, which is estimated at 14 TWh per year.[2] For comparison, the power plant Three Gorges Dam in China is able to produce more than 80 TWh per year. Such a difference results from lowland localization and results in the inability to build a large hydro power plant. That is why in Poland "small hydroenergetics" dominate. Despite the significant difference and apparent low potential, it would be possible to cover a large part of

1. See: Raport. Bariery rozwoju energetyki wiatrowej ze szczególnym uwzględnieniem aspektów akceptacji społecznej. Warszawa, sierpień 2013, [@:] http://www.ambiens.pl/pliki/Raport_Bariery_Energetyki_Wiatrowej_2013.pdf.

2. Data published at http://ioze.pl/ [accessed 2015.03.24].

Polish energy demands. Greater use of water to produce energy in the area would cause reduction of energy costs in the region. In addition, the new value does not include the power of pumped-storage plants, which do not count as renewable energy sources.

In Poland there are over 700 hydroelectric dams providing power which exceeds 950 MW.[3] Pumped-storage plants can produce about 1,5 TWh.[4] A lot of power plants co-exist with hydro-technical structures such as flood protection dams, reservoirs, etc. The utilization of hydroelectric potential in Poland is estimated at 12%. Almost half of this potential is located on the Vistula river. Before the political transformation in Poland, there were some ambitious plans which included the construction of a series of cascades on the Vistula river. It was to increase river navigability, as well as to produce energy — twice as much as is produced today by hydroelectric power plants throughout Poland.

Nowadays, the ecological aspect is prevalent in planning such investments. Hydroelectric plants produce clean environmentally friendly energy, although it is forbidden to build in some places due to environmental restrictions. Recent changes in the law introduced the obligation of including fish ladders in the design of hydropower plants, even if the plant uses the latest technology. Power plants that were under construction, when the law changed, were not launched. The restrictive and not quite clear law in this regard often causes investors and local governments to be reluctant.

The main objective of this article is to estimate the level of utilization of hydroelectric potential in Pomorskie Voivodship and indication of the best locations for hydroelectric power plants by analyzing natural and anthropogenic factors.

1 Research methods

The level of utilization of hydroelectric potential in the voivodship was determined by the ratio of energy produced by hydroelectric plants to the maximum possible production. Data was collected among the inventory of existing installations and after the deployment projection of new power plants. Proposed locations were indicated on the base of natural and anthropogenic factors. Points were located every 10 km, on each of the analyzed rivers, which symbolize the potential locations of hydroelectric power plants. Each object is assigned with weights for individual factors. In the study, 320 potential locations were analyzed.

Factors taken under consideration were:

- flow rate at the mouth (IMGW) (tab. 1), which were extrapolated to each point; the process was based on the following formula $Q_0 = Q_w \cdot (A_0 A_w^{-1})^n$, where:
  Q_0 — the sought flow value (in the point) (in m^3/s)
  Q_w — flow rate at the mouth (in m^3/s)
  A_0 — area of point catchment area (in km^2)
  A_w — area of the whole catchment area (in km^2)
  n — coefficient; coefficient n equals 1 for young areas, such as Pomorskie Voivodeship[5]
- forms of nature protection or lack of them in a given area (tab. 2)
- distance from transmission network (tab. 3)
- distance from existing hydroelectric power plants (tab. 4)
- size of the market — the number of residents (tab. 5)

For each point, the weights were summed up. On this basis, the most optimal locations for new hydroelectric power plants were chosen.

3. See: Hydroenergetyka w Polsce — obecna sytuacja i perspektywy na przyszłość. By A. Bednarska, [@:] http://www.plan-rozwoju.pcz.pl/dokumenty/konferencja/artykuly/03.pdf.

4. [In the journal European practice of number notation is followed — for example, 36 333,33 (European style) = 36 333.33 (Canadian style) = 36,333.33 (US and British style). — Ed.]

5. See also: Metodyka obliczania przepływów i opadów maksymalnych o określonym prawdopodobieństwie przewyższenia dla zlewni kontrolowanych i niekontrolowanych oraz identyfikacji modeli transformacji opadu w odpływ. Etap I. Określenie jednolitych metod obliczenia przepływów maksymalnych rocznych o określonym prawdopodobieństwie przewyższenia w zlewniach kontrolowanych. Stowarzyszenie Hydrologów Polskich; Ekstrapolacja wartości przepływów rzek [unpublished]. By K. Kowalczyk, Regionalny Zarząd Gospodarki Wodnej Gdańsk, 2015.

Tab. 1. Weight assigned due to flow rate

Flow rate (in m^3/s)	Weight
< 1,0	0
1,0–4,0	1
4,1–7,0	3
7,1–10,0	5
> 10,0	6

Tab. 2. Weight assigned due to the presence of forms of nature protection

Forms of nature protection	Weight
National Parks	exclusion
Other forms of protection	1
No forms of protection	2

Tab. 3. Weight assigned due to distance from transmission network

Distance from transmission network (in km)	Weight
> 7,0	1
3,1–7,0	2
1,0–3,0	3
< 1,0	4

Tab. 4. Weight assigned due to the distance from existing hydroelectric power plants

Distance from power plants (in km)	Weight
< 1,0.	1
1,1–3,0.	2
> 3,0	4

Tab. 5. Weight assigned due to the size of market — the number of residents

The number of residents (in thousands)	Weight
> 3,0.	1
3,0–10,0.	3
> 10,0.	4

The estimation of hydroelectric potential is very difficult. The benchmarking method was used. The power of power plants was compared to their flow. As a result, the indicator was fixed. The research showed that the power of most hydroelectric power plants is about 50 kW per 1 m^3/s of flow. This value was used to estimate the potential of each location. However, there are many power plants in the voivodship that produce less electricity than the fixed indicator. This results from the technology used. Many of the power plants, especially the private ones, were transformed from old mills. Sometimes their power does not exceed 50 kW. Despite their limited power, they are able to supply up to 150 households. On the other hand, there is the Bielkowo power plant. It is a 7 200 kW power plant on the Radunia river, with a flow rate of 5,5 m^3/s. It gives more than 1 300 kW per 1 m^3/s of flow. There are only a few bigger power plants. The result of the chosen approach estimated a "reachable" hydroelectric potential. It does not require the use of the most expensive technologies. Moreover, it will not influence the natural environment significantly. Also, maximal potential was calculated by 100 kW obtained from 1 m^3/s flow rate. The increase of reachable power potential is possible in some places. It requires the use of hydrotechnical constructions such as weirs and dams or modifications of the riverbed. All good and very good locations, indicated based on the sum of weights, have been used to calculate energy potential.

2 Energy consumption in Pomorskie Voivodship

The electricity consumption in Pomorskie Voivodship is 7 150 GWh (status for 2009). The largest share of energy consumption is in the industrial sector. Almost 60% of energy is delivered by the national power system from sources outside the region. The first reason for the lack of energy independence of the voivodship is the small production potential in relation to demand. Within the region there are no energy resources mined. Also, there is no big, navigable river, which would allow for the transport of coal, thereby enabling the construction of a coal-fired power plant, as was the case with the Dolna Odra power plant. However, the area has very favorable conditions for the location of power plants based on renewable energy sources. The voivodship has the best conditions to develop wind energy power plants. Also, the hydroelectric sector has been developing more dynamically in recent years. Other energy sources which can be used are biomass, biofuel, and biogas. Photovoltaic energy is used in limited ways. The least used energy source is geothermal energy, due to the weak conditions within the voivodship. The second reason is the short time when installed power can be fully used. Windmills generate energy when the wind is strong enough — about 26% of the time in a year. Photovoltaic cells can work when the sun is shining — 10% of the time in a year, while hydroelectric power plants work on average 46% a year (Hajdrowski 2012). A power plant that can work the most of time in a year is nuclear power plant — 91%. They can work almost all the time, excluding 1 month a year for fuel replacement. Coal, gas and biomass-fired power plants use only 80% of their power.[6] Malaczewski (2017), estimated that over 80% of energy is generated by unrenewable sources. The cost of production of 1 MWh in a coal-fired plant is PLN 282 and it is currently the cheapest in Poland. Due to the high CO_2 emissions and EU policy, thermal power plants have a lower share in electricity production, but it is still significant, over 70% of total production. Nuclear power plants can work almost the whole year, produce less waste, and the energy is quite cheap, compared to other sources. Nevertheless, it provokes great controversy among the general public. The cost of one MWh produced by windfarm is PLN 466 and by hydroelectric plant PLN 484. The difference is not significant. The most expensive energy in our climate zone is energy produced by solar panels (tab. 6).

Tab. 6. Cost of electricity production (PLN/MWh)

Windmills (land)	Windmills (sea)	Hydroeletric plant	Biomass	Photo-voltaics	Coal	Gas	Nuclear plant
466	713	484	487	1091	282	314	313

CHPs (Combined Heat and Power) plants have the largest share in electricity production. The biggest among them are: the CHP plant in Gdańsk, Gdynia, Kwidzyn — in International Papers, Starogard Gdański — Polfarma and in Gdańsk Refinery. Total production in these 5 CHP plants is 2300 GWh, which covers 32% of demand for electricity of the inhabitants of the voivodship (status for 2009). They are located near large manufacturing facilities and use production waste. In the paper mill in Kwidzyn remnants of wood are used, the CHP plant in Gdańsk Refinery uses petroleum. Within the Pomorskie Voivodship there are numerous wind power plants. Their power in 2008 was estimated at 145 MW, and electricity production at 363 GWh — about 5% of demand. They are located mostly in the coastal belt, where wind conditions are good or very good — 1st and 2nd class. In Pomorskie Voivodship there are more than 80 small hydroelectric power plants. 31 of them supply the central energy network. Produced energy is estimated at 11 GWh (status for 2008). Also, gas is used to produce electricity. Władysławowo is the most famous place in terms of using natural gas to produce energy. The city is supplied in energy, which is produced 100% by gas. It is possible thanks to its coastal location and nearby drilling platform. At the bottom of the Baltic Sea, there is a gas pipeline connecting the shore with a platform from which the town benefits.

6. See: Plan zagospodarowania przestrzennego województwa pomorskiego 2009 (nieobowiązujący). Załącznik do uchwały nr 1004/XXXIX/09 Sejmiku Województwa Pomorskiego z dnia 26 października 2009 r., Gdańsk, październik 2009, [@:] https://pbpr.pomorskie.eu/pzpwp2009; Raport dla województwa pomorskiego. By M. Bastian, Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej, Gdańsk 2012.

3 Hydroenergy in the Pomorskie Voivodship

Altitude differences in the voivodship are small, which results in low slopes (Marcinkowska et al. 2013). It influences the flow rates of rivers, which is the key factor for hydroelectric plant location. In Pomorskie Voivodship, small hydroelectric plants dominate — with power less than 5 MW. The power of only two of them exceeds 4 MW (fig. 1). The first one, with the power of 4 160 kW, is located on the Słupia river, the second with the power of 7 200 kW on the Radunia river. In total, 89 hydroelectric plants exist in the voivodship (according to RZGW Gdańsk data).[7] Due to the characteristics of these rivers, most objects utilize dams and weirs to produce electricity. The biggest power plants are located on the Radunia. There are 9 power plants — power in total of over 14 MW. Also, energy production on the Słupia river is significant — 7,5 MW. The third important river is Wierzyca, its power plants produce over 2 MW.

Electricity production on other river is relatively small and generated energy is used rather locally. Many stations are located on Reda, Liwa, Łupawa and Nogat rivers. On the Łupawa river, 5 plants were located with total power of 900 kW. Eight stations were located on the Łeba. Most of them are small, only two of them have data about its power. The power of generators on the Liwa is barely over 200 kW.

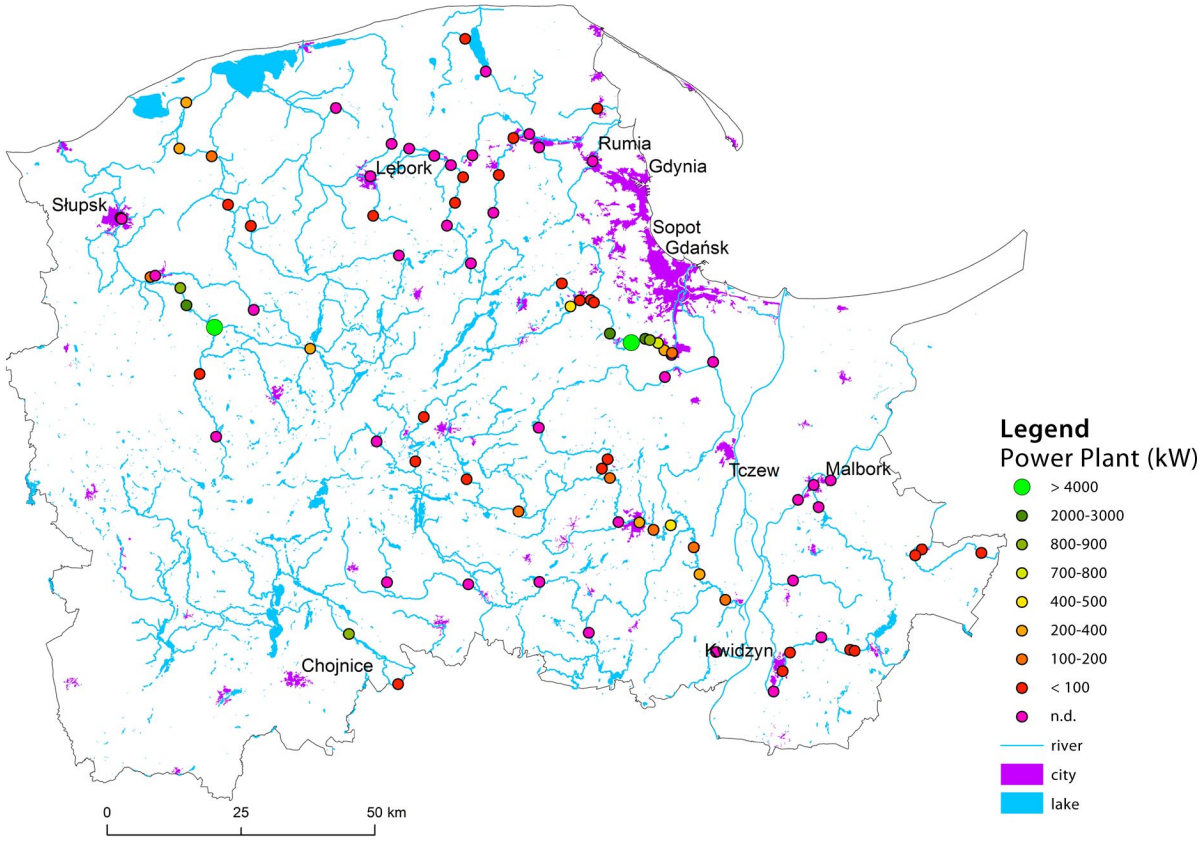

Fig. 1. Hydroelectric power plants existing in Pomorskie Voivodship

Source: Own elaboration on the basis of the data of the Regional Water Management Board

4 Location of hydroelectric power plants

The choice of a hydroelectric location is a complicated process. It is based on the Water Law Act. The law was amended 50 times in 12 years and in 2017 is going to be greatly changed. The most important natural conditions to select optimal location of hydroelectric power plants are terrain

7. RZGW — Regionalny Zarząd Gospodarki Wodnej.

slope and flow rates. Pomorskie Voivodship is characterized by little terrain slopes and rivers by low flow rates (Jankowska 1985). Currently turbines installed in hydroelectric power plants allow us to "bypass" this problem VHL turbines are able to function at terrain slope less than 25° and a flow of 10 m^3/s. Similarly, there are screw turbines, which are effective at terrain slope 22°–36° and a flow of 1–10 m^3/s. These turbines are friendly to fish due to their slow rotation. Their power is 500 kW. One turbine is capable of producing almost 4 380 MWh. The value of produced energy is almost PLN 2,5 million per year. Energy obtained from one installation would be enough to cover the demand of 1 200 households — with average consumption of 3 600 kWh per year.[8] It should be emphasized that a power plant may have more than one turbine that can produce energy for a particular municipality or locality.

The second natural factor is the flow rate. It greatly influences the possible power of a planned installation and consequently — the cost-effectiveness of the construction. Hydroelectric power plants can function with flow rate greater the 1 m^3/s. It is a value high enough to install screw turbines. Flow rate which does not exceed 4 m^3/s enables us to build a 1 000 kW power plant. Flow rate of 7 m^3/s and less allows us to locate a 7 000 kW power plant — the power plant Bielkowo on Radunia river. Flow rate greater than 10 m^3/s enforces other technologies. The turbines used have to withstand higher pressures (e.g., Kaplan turbine) (Warać, Wójcik, and Kołacki 2010). The problem that occurs when it comes to a bigger river is the width and depth of the riverbed. In such cases, carrying out the investment usually requires the modification of the riverbed to ensure that the actual flow in the turbine is enough. It results in much higher costs of construction.

Another important factor which might influence the choice of best location is the existing form of nature protection in the area. Within the voivodship there are 321 protected areas. Most of them are nature reserves — 131. There are also 2 National Parks (fig. 2). Their presence results in excluding these areas from further analysis (fig. 3).

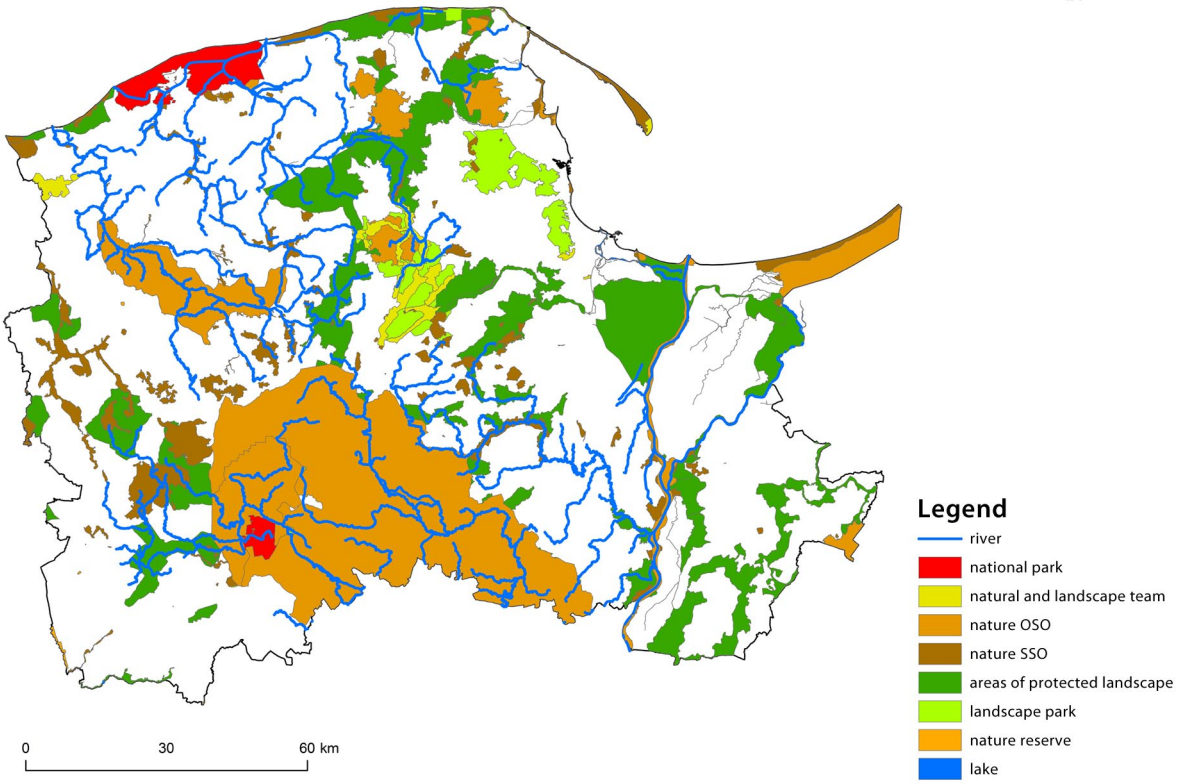

Fig. 2. Forms of nature protection in Pomorskie Voivodship

Source: Own elaboration on the basis of General Directorate for Environmental Protection

8. Data published at https://energiadirect.pl/ [accessed 2015.03.25].

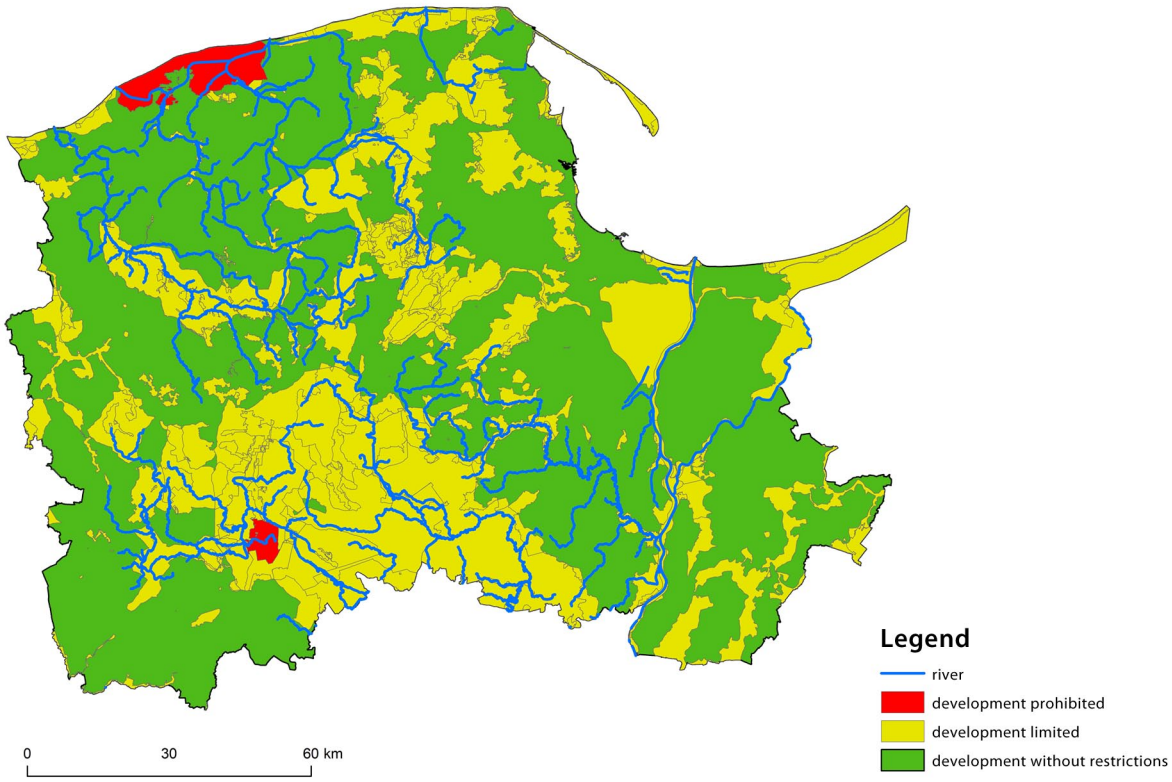

Fig. 3. Construction restrictions resulting from existing protected areas

Source: Own elaboration on the basis of figure 2

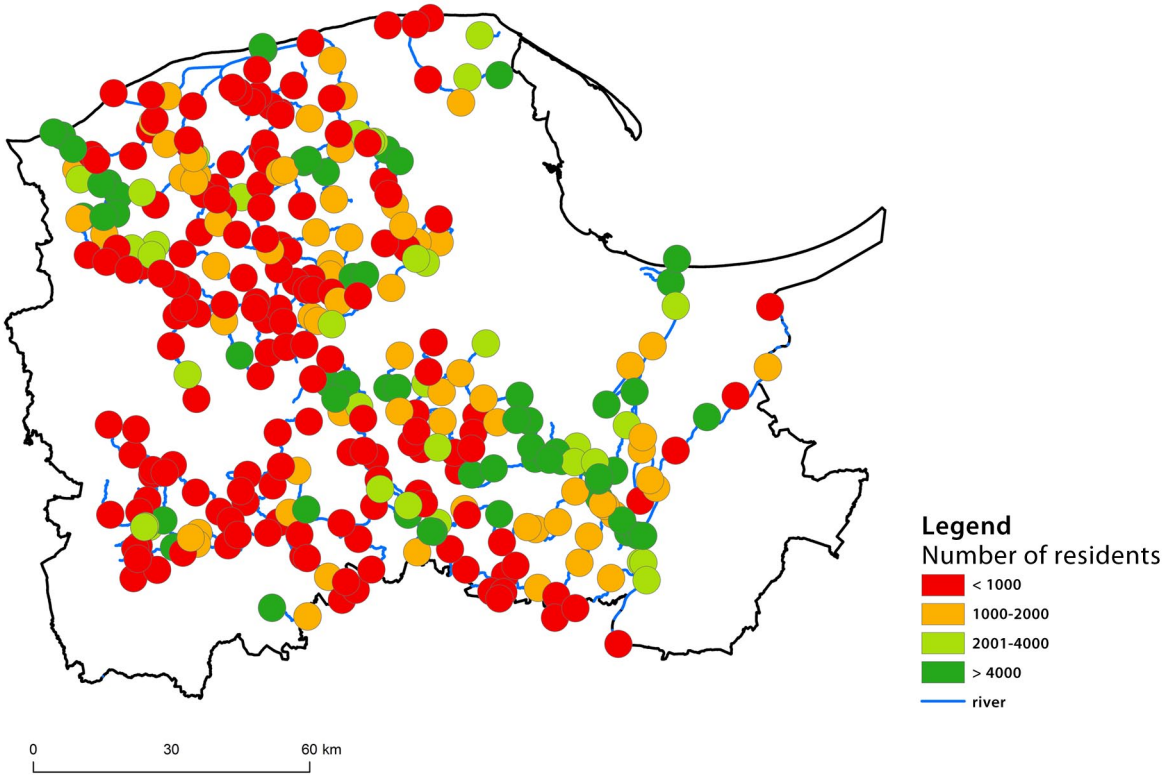

Fig. 4. Number of inhabitants 3 km away from the potential location of the power plant

The anthropogenic factors include: the size of the market (number of inhabitants in adjoining areas) and the distance from the transmission network. The first is especially important for locating small hydroelectric power plants, which are characterized by low power. It would not be cost-efficient to build long energy lines, due to their cost and energy loss. Areas with the largest market are located near big cities: Tricity, Starogard Gdański, Kwidzyn, Malbork, Lębork, Słupsk, and Wejherowo. The most profitable areas for hydroelectric power stations are those with more than 1 400 households, so the number of inhabitants must exceed 4 000. However, the area of the voivodship is dominated by villages, where population does not exceed 1 000 (fig. 4). The second anthropogenic factor is the distance from the transmission network. Within the voivodship, there are only four 400 kV high voltage energy lines. For this reason, the number of potential locations for utility power plants is limited. Also, the localization of one power plant close to another would be problematic. They would be direct competitors fighting for the market, such localization would be illogical. Most of the voivodship's area is more than 3k from existing hydroelectric power plants (fig. 5). Regions with a higher density of hydroelectric installations are located near rivers the Radunia, Reda, Łeba and cities Kościerzyna, Kwidzyn, and Starogard Gdański.

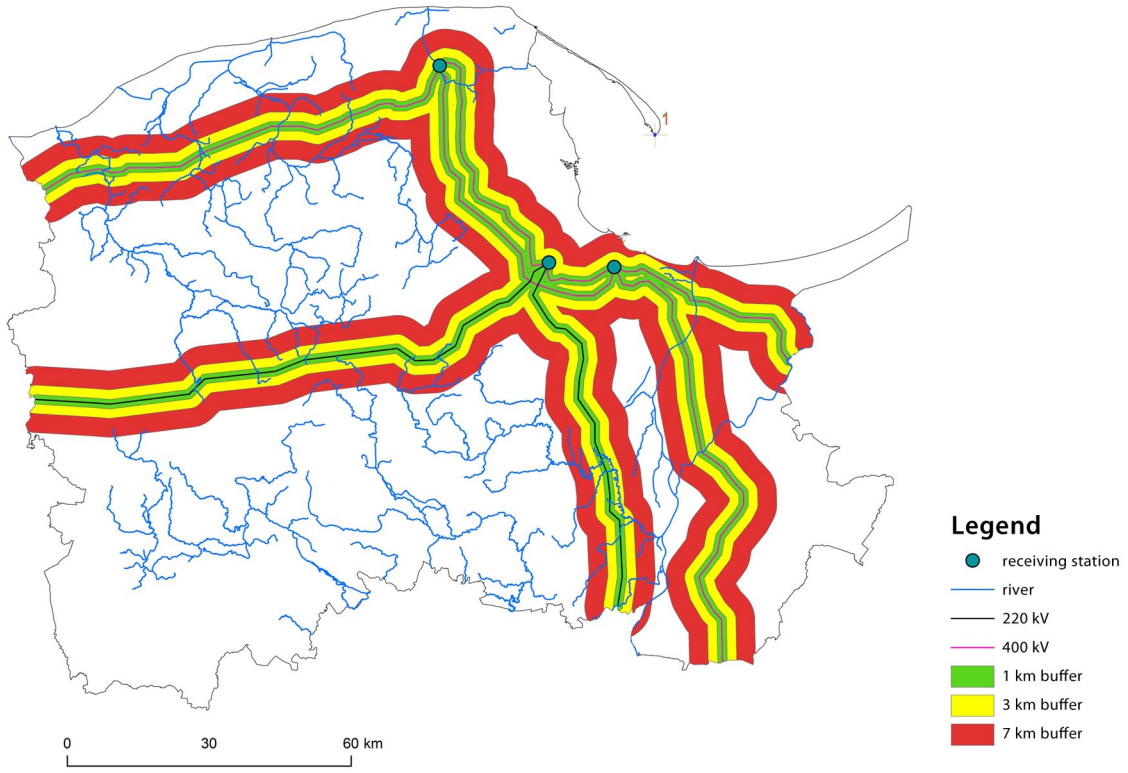

Fig. 5. The location of high voltage energy lines and sites predisposed to the building of utility power stations

Source: Own elaboration based on Raport dla województwa pomorskiego. By M. Bastian, Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej, Gdańsk 2012

5 Results. Hydropower development in Pomorskie Voivodship

After analyzing the 320 potential locations for hydroelectric power plants. 107 good or very good location were indicated. Four locations were excluded due to the presence of the National Park. 82 areas were identified as sufficient for this type of investment. Areas with inadequate natural and anthropogenic conditions were also indicated. There were 127 of them (tab. 7). The sums of weights for potential locations of hydroelectric power plants were presented on figure 6.

Locations of hydroelectric facilities with insufficient potential account for 39,7% of all sites. They are mainly concentrated around tributaries of larger rivers. It is caused mainly by low flow rate and population of surrounding areas. The worst conditions are near the Kłodawa's mouth. This

Tab. 7. Number of locations of given quality

Location	Sum of weights	Number of locations
Excluded	0	4
Not sufficient	0,1–9,0	127
Sufficient	9,1–12,0	82
Good	12,1–17,0	92
Very good	17,1–19,0	15
Total		320

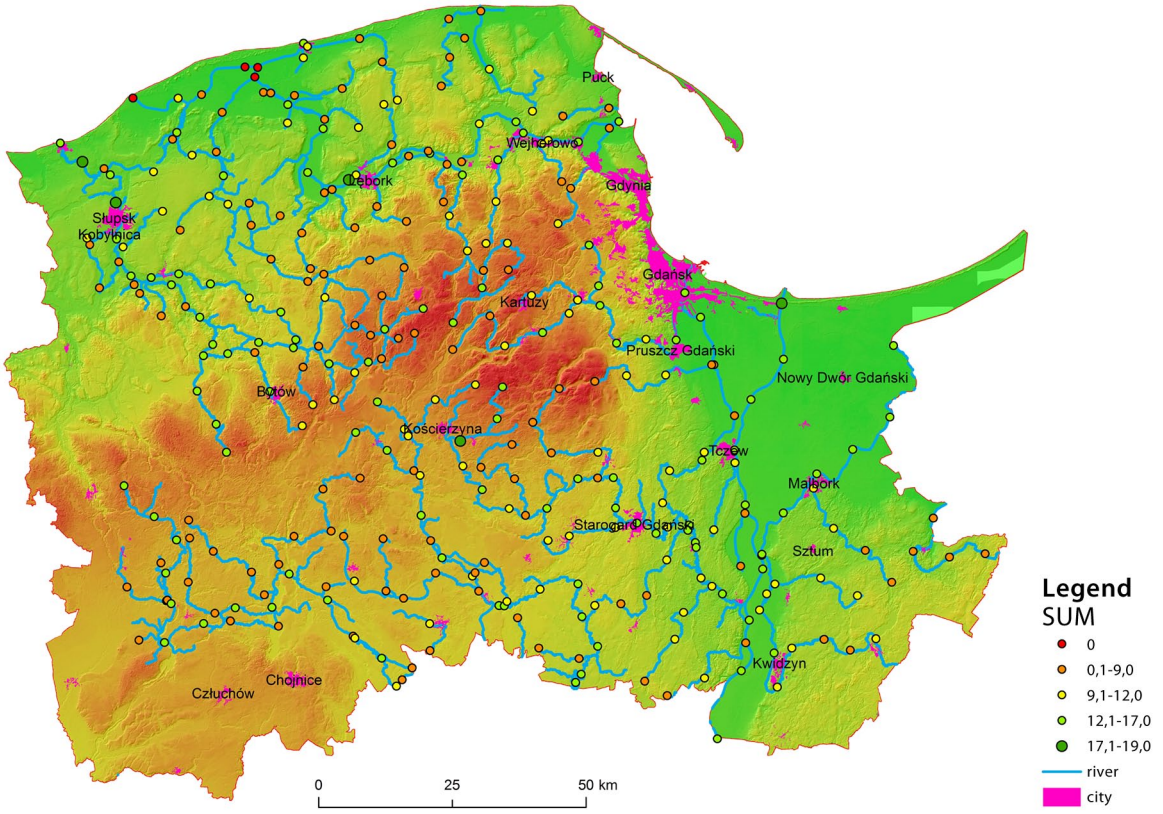

Fig. 6. Sum of weights for potential locations for hydroelectric power plants

area is located within Żuławy Gdańskie and is characterized by low urban density of population. Locations of higher suitability are scattered around the voivodship. These include: Bolszewska river, terrains near Kościerzyna, Sztum and Starogard Gdański.

92 sites have been identified, with a high utility to locate hydroelectric power plants. Those areas are mostly around the biggest rivers and large cities. Five of them are situated near Wejcherowo on Bolszewka River and Reda. Very good conditions are located on the Motława and Radunia rivers. Those locations are already being used. In the south of the voivodship the best conditions are found on Brda, Nogat and Wda rivers. In the eastern part, hydroelectric potential is concentrated around Vistula, Nogat and Liwa rivers and also around Kwidzyn. A large part of hydroelectric potential is located on Łeba, Słupia and Skotawa rivers. The best location conditions for hydroelectric power stations are found mainly in the vicinity of larger urban centers. Many such places are around Słupsk and Kobylnica—as many as 4. Single points are located close to Łeba, Gdańsk, Malbork, Kościerzyna, Lębork and Tczew. In the south of the voivodship, two points are located on Wda river. Then first of them is close to Czarna Woda town and the second west of Lubiechowo. Areas with favorable conditions are located in the Vistula delta and between Lębork and Łeba (fig. 7). Those are locations which should be used first in the selection of investment sites for hydroelectric power plants.

In Pomorskie Voivodship, hydroelectric power plants are important in overall production of electricity. Based on RZGW Gdańsk, the combined capacity of hydroelectric power plants operating within the voivodship is over 26 MW. It is worth highlighting that the power of 30 power plants are not known. Furthermore, having regard to the lack of data concerning power plants in the

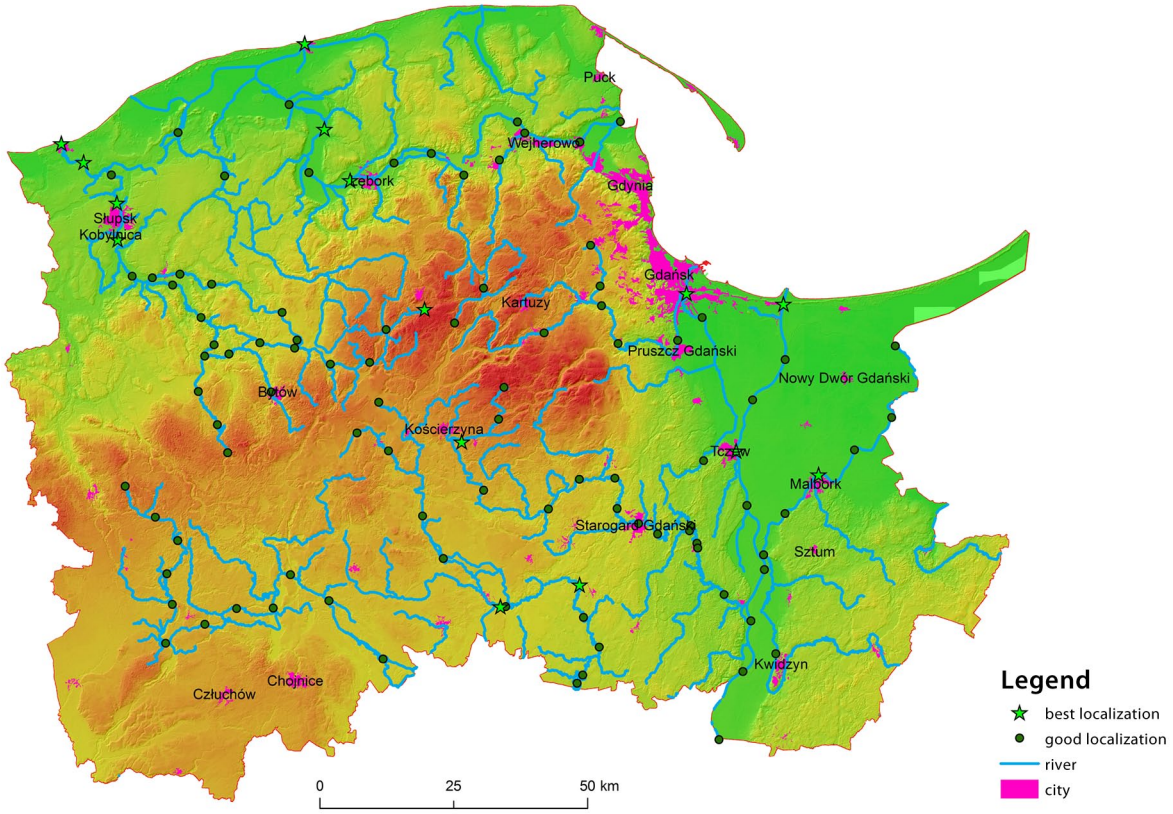

Fig. 7. Best potential locations for hydroelectric power plants (based on fig. 6)

Tab. 8. Flow and power of hydroelectric potential of the best locations

Number	River	Flow (m^3/s)	Reachable potential (kW)	Maximum potential (kW)
1	Radunia	6,00	300,00	540,00
2	Wisła	1 046,00	52 300,00	94 140,00
3	Wisła	1045,07	52 253,40	94 056,00
4	Wierzyca	7,25	362,56	653,00
5	Wda	11,67	583,50	1 050,00
6	Wda	10,79	539,51	971,00
7	Słupia	17,55	877,50	1 579,00
8	Słupia	17,40	870,00	1 566,00
9	Słupia	16,30	814,92	1 467,00
10	Słupia	15,40	769,91	1 386,00
11	Słupia	11,68	583,82	1 051,00
12	Nogat	28,05	1 402,71	2 525,00
13	Łeba	11,70	585,00	1 053,00
14	Łeba	11,33	566,62	1 020,00
15	Łeba	10,64	532,11	958,00
	Total		113 341,56	204 015,00

extreme western part of the voivodship, it can be estimated that the power of all hydroelectric power plants exceeds 30 MW. The missing data usually refers to power plants not belonging to the State Treasury. Private power plants are usually characterized by low power, which does not exceed 100 kW. Reachable potential of the best locations (fig. 7) is 113 MW, what allows us to obtain 81 GWh per month. While the maximum potential exceeded 204 MW. Table 8 shows that the greatest potential, apart from the Vistula river, is concentrated on the Słupia and Łeba rivers.

The utilization of all good locations would allow us to reach the power of 413 MW. At maximum utilization, the power would be 743,6 MW. The total energy produced by these power plants would amount to almost 540 GWh. It is almost 8% of the overall energy demand of Pomorskie Voivodship.

Conclusions

Taking into account all the locations analyzed in the work, it can be estimated that the overall hydroelectric potential of the voivodship is almost 700 GWh. The Pomorskie Voivodship is supplied with 60% of its energy from external sources. Full utilization of hydroelectric potential would reduce this value by 10%. In addition, it will increase the degree of diversification of energy sources and energy security. The choice of optimal location for a hydroelectric power plant is very difficult. It requires the analysis of many factors. In addition to those presented in this paper, a field study should be carried out, along with analysis of the strategic documents of individual municipalities, ground surveys and environmental impact analysis. Often, people do not have sufficient knowledge for this type of investments. Another aspect is social. The energy produced by a hydroelectric power plant is more expensive than that produced from coal. In Poland, people do not want to pay more for "green energy," as is the case in Norway, which is a pioneer in the field of hydro power. Up until now, most renewable energy sources have meant wind farms. In recent years, most of the areas with strong winds have been used. At present, wind farms are beginning to stir up controversy, and more and more attention is paid to water and hydroelectric power plants. Changing policies and finding new solutions will surely have a positive impact on the development of hydropower. So far, the programs have exploited the potential to a very small extent — just 4% of the potential for example is used in the Pomorskie Voivodship.

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