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Influence of Geology, Hydrogeology, and Climate on Ground Source Heat Pump Distribution in Slovenia and Selected European Countries

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Abstract: Shallow geothermal energy (SGE) is a renewable energy that could contribute to the decarbonatization of the heating and cooling sector. SGE is predominantly harnessed through ground source heat pump (GSHP) systems. The choice of which type of GSHP system depends on various factors. Understanding these factors is crucial for optimizing the efficiency of GSHP systems and fostering their implementation. In this paper, we have analysed the spatial distribution of GSHPs in Slovenia. We identified 1073 groundwater and 1122 ground-coupled heat pump systems with a total heat pump capacity of almost 30 MW. We quantitatively assessed the influence of geological, hydrogeological, and climate conditions on their spatial distribution. Using the χ^2 test and information value method, we identified hydrogeological conditions as the most influential factor for the GSHP systems' spatial distribution. We also performed the spatial analysis of geological and hydrogeological data in 22 European countries, including Slovenia. We collected the reported numbers of installed GSHP units in 2020 and were able to distinguish the shares of groundwater and ground-coupled heat pump systems for 12 of these countries. The analysis showed that ground-coupled heat pumps predominate in most countries, even if the natural conditions are favourable for groundwater heat pumps.

Keywords: shallow geothermal energy; renewable heating and cooling; ground-source heat pump; spatial distribution; natural condition

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1. Introduction

The promotion of the positive aspects of geothermal energy and accurate assessment of the natural conditions are the key factors that could help to foster geothermal energy use and accelerate the transition to low-carbon energy sources. Shallow geothermal energy (SGE) is a renewable energy source [1,2], defined as "energy stored in the form of heat under the surface of solid earth" [3]. It will play an important role in future energy solutions, as it can be used for space heating and cooling, as well as for thermal energy storage, through the use of various ground-source heat pump (GSHP) technologies, including groundwater heat pump (GWHP) and ground-coupled heat pump (GCHP) systems [1,4–6]. In GWHP systems, the main heat carrier is groundwater extracted through wells, while, in GCHP systems, fluid circulates in closed pipes of various configurations [4,7–9].

In 2019, the EU set its 2030 climate and energy targets to reduce at least 55% of greenhouse gas emissions (GGE) compared to 1990 levels and achieve at least 32% of their energy from renewable energy sources (RES) as a share of gross final consumption [3]. But to achieve the EU's GGE reduction target, the share of renewable energy in the gross final consumption of energy should need to increase to 40% by 2030 [10]. This will enable the EU's transition to a carbon-neutral economy by 2050 [11]. The REPowerEU Communication outlined a plan to make the EU independent of fossil fuels before the end of this decade [12].

In this context, it was proposed to increase the EU's renewable energy target up to 45% of gross final consumption. The Slovenian National Energy and Climate Plan aims to achieve a share of at least 27% of gross final energy use by 2030 from RES, with a share of 41% in the heating and cooling sector and at least 2/3 of the energy consumption in buildings [13]. Slovenia has also set a target to reduce GGE by 2030 by at least 15% compared to 2005. The targets were assessed as unambitious by the European Commission, which recommends a 37% share of RES in gross final energy consumption and a 20% reduction of GGE by 2030 [14].

In 2020, GSHP systems accounted for 71.6% of installed capacity and 59.2% of geothermal energy use in the world [15]. The number of GSHP systems increased in 2022 by 17% compared to the year 2021 [16], with most units sold in Germany (31.000), Sweden (28.160), and the Netherlands (20.000) in 2022 [16]. A common factor fostering shallow geothermal use among the leading countries is the overall national strategy and financial incentives framework aimed at reducing the carbon footprint, air pollution, and energy poverty [2]. Based on Eurostat data [17] (Figure 1), Slovenia emitted 6 tonnes of GGE per capita, which is like the EU average of 6.4 tonnes of GGE per capita in 2021 (Figure 1a). EU financial incentives for the use of SGE could also help to reduce the problem of energy poverty. This refers to households or communities that do not have access to or cannot afford adequate energy for essentials, such as heating and cooling. In 2022, an average of 7.6% of the EU population lived in energy poverty, while in Slovenia this share was 1.7%. (Figure 1b) [18].

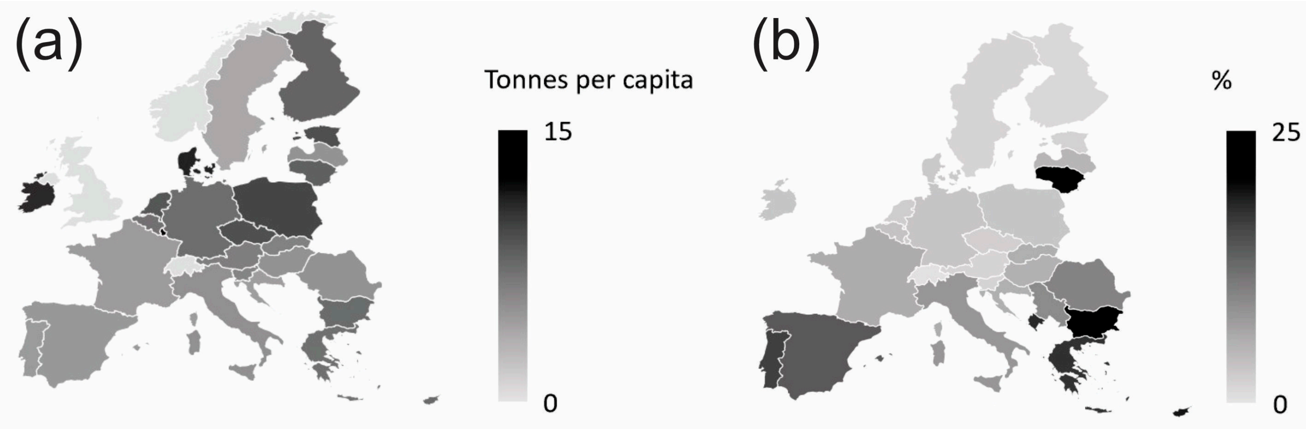

Figure 1. (**a**) Greenhouse gas emissions per capita in 2021, (**b**) Share of the population unable to keep their home adequately warm in 2022 [17,18].

GSHP efficiency is highly dependent on local geological and hydrogeological conditions, so identifying the natural conditions is crucial for their proper design and operation [19,20]. The GWHP system uses the pumped groundwater directly in the heat exchanger [8]. A typical configuration consists of a well-doublet in a shallow aquifer, taking care to ensure that the distance between the extraction and injection wells is large enough to prevent hydraulic short-circuiting or thermal breakthroughs [21]. The basic advantage of this system, compared to a GCHP system, is that it is more efficient. However, this is only true if the site is located on a highly permeable aquifer that provides sufficient yield and has suitable chemical conditions so that maintenance problems related to scaling, clogging, and corrosion are avoided [1,22]. In a GCHP system, a pipe is installed horizontally or vertically underground to act as a heat exchanger [1]. A heat carrier fluid circulates through the pipes to absorb heat from the ground in winter and inject heat into the ground in summer. Such systems are based on single or multiple boreholes, depending on the heat demand that needs to be supplied. The main advantage of this system, compared to the GWHP system, is that there is no need for an aquifer and the fluid circulates in closed pipes, so the whole system requires little maintenance [22].

Alcaraz et al. [23] proposed a method to establish a market of shallow geothermal energy use rights based on the GIS framework, consisting of a geodatabase that stores the main information needed for the management of the GSHP, such as groundwater flow velocity, thermal conductivity or thermal heat capacity of rocks. Ramos-Escudero et al. [24] performed a spatial assessment of geological, climatic, and environmental indicators to determine the performance of shallow geothermal energy systems on a continental scale in Europe. The establishment of a national database of already-installed systems could help reduce the cost of future systems. In order to make data available, Macenić et al. [25] collected available data on GCHP systems in the Republic of Croatia, as there is no agency or government department responsible for collecting and publishing this data. They created a map of known GCHPs and made a first assessment of the shallow geothermal potential in Croatia. Majuri et al. [26] analysed the permitting documents for groundwater areas in Finland and found out that SGE issues were not considered in the preparation of the legislation, thus they do not provide support for permitting decisions. They emphasised the need for professional technical and scientific instructions to support geologically sound arguments in permitting decisions.

In Slovenia, no uniform national database on installed GSHP systems exists, and data on shallow geothermal installations are scattered in multiple data sources [27–29]. In this paper, we gathered the publicly available data on GWHP and GCHP system locations and statistically assessed the influence of geological, hydrogeological, and climate conditions on the spatial density of GSHP systems with the objectively derived indexes. Furthermore, we analysed the spatial distribution of GSHP systems in operation in 2020 in relation to geological and hydrogeological conditions, based on the available data.

2. Materials and Methods

The collection of material for this study consisted of gathering spatial data on natural conditions in Slovenia (Figure 2) and selected European countries. We then collected different databases on GSHP systems in Slovenia and selected a database containing the geographical locations of installed GSHP systems for further statistical analysis (Figure 2a). To our knowledge, the chosen statistical methods (χ^2 test and information value method) were used for the first time to assess the influence of natural conditions on GSHP distribution. However, they have already been used to assess the influence of natural factors on the spatial distribution of observed phenomena, e.g., in landslide hazard analysis and disease mapping [30–33].

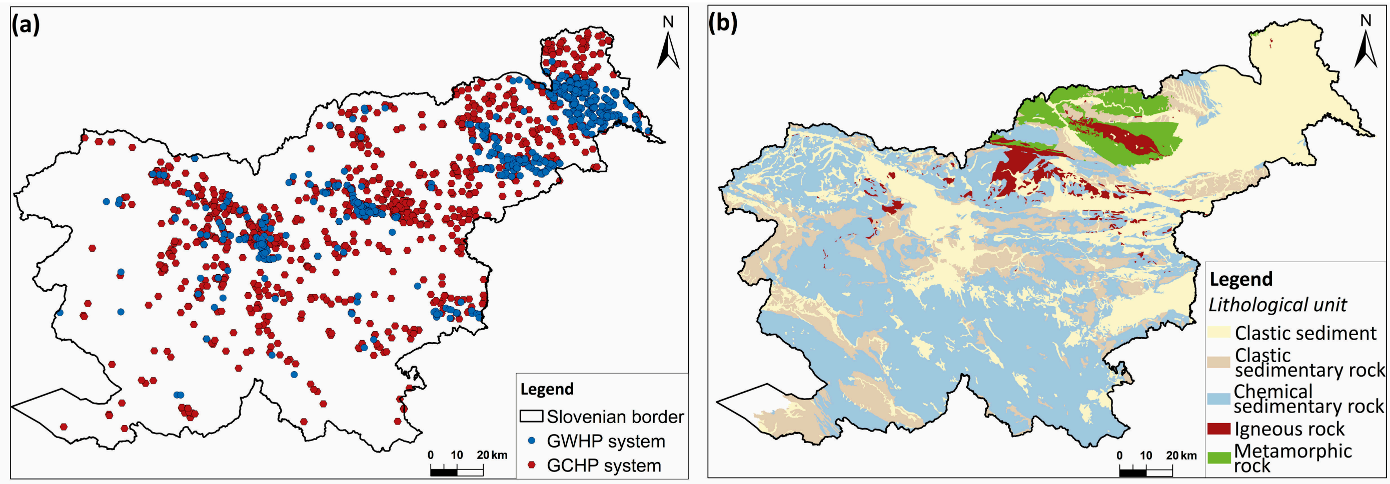

Figure 2. *Cont.*

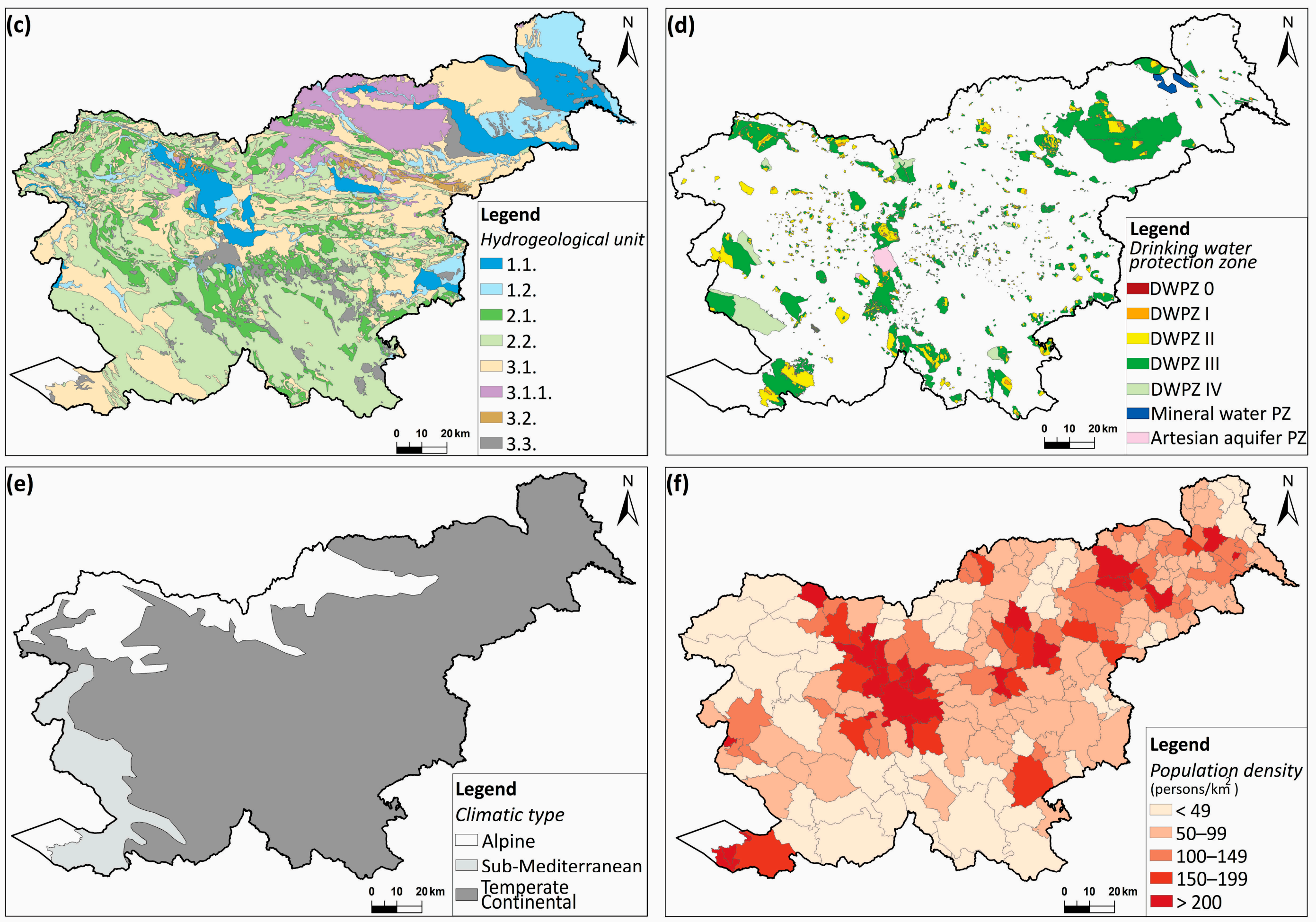

Figure 2. (**a**) Locations of GSHP systems [27,28], (**b**) Geological map (after [34]), (**c**) Hydrogeological map (after [35]), (**d**) Drinking water protection zones [36], (**e**) Climate types (after [37]), and (**f**) Population density in municipalities in Slovenia [38].

We were unable to obtain a GSHP database with geographical locations for the European countries. Therefore, we only made a descriptive comparison between the shares of GWHP and GCHP systems and the geological and hydrogeological classes representative for the selected country.

2.1. Study Area

Shallow subsurface of Slovenia is dominated by sediments and sedimentary rocks, which account for about 93% of the surface area (Figure 2b) [34]. Half of the territory (49.5%) is covered with sediments and clastic sedimentary rocks. Sediments (gravel, sand, silt, and clay) fill riverbeds and young sedimentary basins. Clastic sedimentary rocks predominate in central, southwestern, and northeastern parts of Slovenia. Carbonate rocks cover 39.3% of the territory. Limestone and dolomite form the massifs in southern Slovenia and in the Alpine region in the northwestern and northern part of Slovenia. Metamorphic rocks account for 3.9% of the area, while igneous rocks cover 3.3% of the area [34].

Groundwater is the main source of drinking water in Slovenia and 18% of its territory is protected by drinking water protection zones (DWPZ) (Figure 2d) [36]. Based on the travelling time of groundwater toward the abstraction well, the zones are divided into abstraction (DWPZ 0), inner (DWPZ I), middle (DWPZ II), and outer (DWPZ III, DWPZ IV) protection zones [36]. The occurrence of groundwater is related to the porosity and other geological characteristics of sediments and rocks (Figure 2c). Groundwater temperature is typically between 10 and 15 °C, and the groundwater table is, on average, between 2 and

25 m below the surface in intergranular aquifers [39]. In some parts of Slovenia (e.g., Ljubljana moor), where aquifers are confined, low concentrations of oxygen in groundwater are observed, which can lead to specific hydrochemical conditions where iron and manganese become mobile. In parts with unconfined aquifers, the risk of calcification or corrosion could also be a problem for GWHP systems if groundwater temperature changes exceed 5 °C [40].

Three climate types are found in the territory of Slovenia: Temperate Continental, sub-Mediterranean, and Alpine (Figure 2e) [37,41]. The sub-Mediterranean area is the warmest in Slovenia, with an average annual air temperature of 13 °C, while in most of Slovenia, the average annual temperature is between 8 °C and 11 °C, and in the highest parts with an Alpine climate, it is only around 0 °C [42].

2.2. Sales Figures of GSHP Systems in Slovenia

Development of the shallow geothermal energy market in Slovenia has been followed on a regular basis from 1994 onwards, with country update reports presented at the World and European Geothermal Congresses [29,43,44]. It was the first Slovenian database that comprised data on GSHP units with power higher than 20 kW, sold by domestic manufacturers and sales agents [29]. From 1994 to 1999, the number of geothermal systems grew by 4%, from 1999 to 2004 by 9%, and from 2004 to 2009 by 14%. Since 2010, the number of installed geothermal heat pumps has grown steadily by around 7% per year [45]. In 2020, there were, in total, 13,654 installed GSHPs, of which 48.1% were GWHP units, 36.4% were horizontal GCHP units, and 15.5% were vertical GCHP units (Table 1). In total, 72% were small (<20 kW) and 28% were large GSHP units (>20 kW).

Table 1. Shares of installed GSHP units till 2020 in Slovenia, divided into small (<20 kW) and large (>20 kW) units [45].

	Small Units (<20 kW)	Large Units (>20 kW)	Total
Number of units	12,853	801	13,654
GWHP (%)	46	79	48
Horizontal GCHP (%)	38	4	36
Vertical GCHP (%)	15	17	16

2.3. Data Compilation

2.3.1. Slovenia

The criterion for the input data used in the study was the availability of the geographical locations of the installed GSHP systems. Table 2 lists all databases that contain information on GSHP systems. Data from domestic manufacturers and sales agents do not contain the geographical locations of the GSHP systems and were therefore not included, although this database contains the largest number of installed GSHP systems (since 1994) [29]. The locations of 2601 GWHP systems were available from the joint databases of Water rights (since 2004) and Recorded special use of water (since 2018), which record locations based on the Water Act (Table 2) [27]. From the Eco Fund database, which contains installed subsidised systems from 2016, we obtained the locations of 1122 GCHP systems and 1073 GWHP systems [28], which we used for the statistical and spatial analysis of GSHP systems (bold values in Table 2, Figure 2a).

Table 2. Number of GSHP systems from different sources with the data collection time interval. Numbers in bold represent systems that were further used in statistical and spatial analysis.

Database	Data on Locations	Data Collection Interval (Year)	GWHP (Number)	GCHP (Number)	Total GSHP (Number)
Eco Fund [28]	yes	2016–2021	1073	1122	2195
Water rights and Recorded special use of water [27]	yes	2004–2021	2061	-	-
		2016–2021	1340	-	-
Sales figures [29]	no	1994–2021	6571	7083	13,654
		2004–2021	5851	6923	12,774
		2016–2021	2077	2222	4299

2.3.2. European Countries

Data on sold GSHP units for 22 European countries (i.e., Austria, Belgium, Bulgaria, Cyprus, Czech, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden) were obtained from the Heat Pump Barometer 2020 [46] and the geothermal country updates [47] (Figure 3). The shares of GWHP and GCHP systems were available for 12 countries (Figure 3). Prevailing shares of GCHP systems (more than 95%) are reported from Hungary, Denmark, Belgium, Czech Republic, and Sweden. The lowest shares of GCHP systems are observed in Romania (50%), Slovenia (52%), Slovakia (65%), France (70%), and Finland (70%).

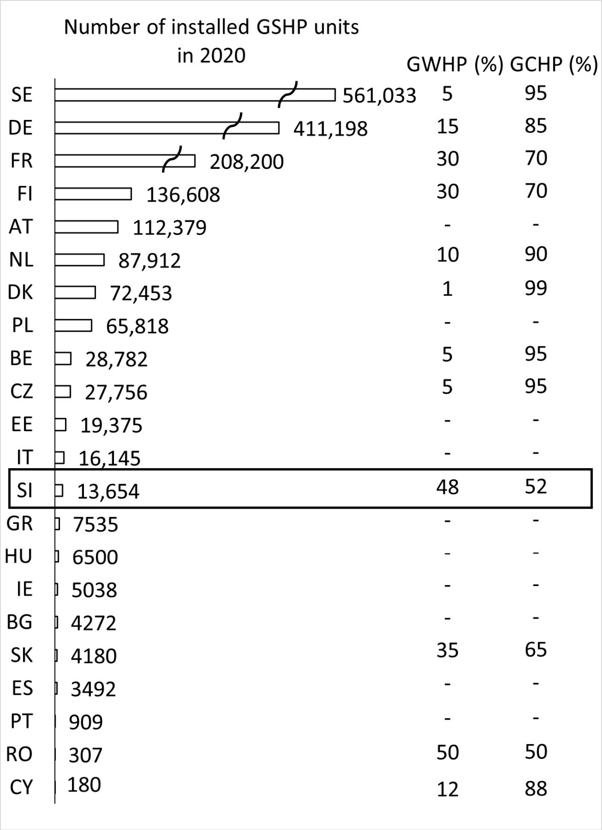

Figure 3. Number of installed GSHPs in selected EU countries in 2020, with shares of GWHP and GCHP systems [data from [15,46,47]].

2.4. Spatial Distribution

The spatial analysis of the natural factors was performed in a GIS environment [48] with the shapefiles of the geological [34], hydrogeological [35], and climatic [37] maps of

Slovenia. The area and population density shares of the individual classes within the factors were calculated. The units of the geological map (Figure 2b) were classified into 5 geological classes: clastic sediments, clastic sedimentary rocks, chemical sedimentary rocks, igneous rocks, and metamorphic rocks. The hydrogeological map (Figure 2c) is consistent with recommendations of International Association of Hydrogeologists (IAH) and is divided into 8 main groups based on the type of porosity and aquifer yield (Figure 2b): 1.1. Extensive and highly productive intergranular aquifers, 1.2. Local or intermittently productive aquifers or extensive but only moderately productive intergranular aquifers, 2.1. Extensive and highly productive fissured/compacted aquifers, 2.2. Local or intermittently productive aquifers or extensive but only moderately productive fissured/compacted aquifers, 3.1. Minor aquifers with local and limited groundwater resources, 3.1.1. Minor aquifers with local and limited groundwater resources (metamorphic, igneous), 3.2. Areas with essentially no groundwater resources, and 3.3. Aquitards overlaying aquifers of type 1. or 2. [49]. Three climate types are typical for the territory of Slovenia: Temperate Continental, sub-Mediterranean, and Alpine (Figure 2e) [37]. The average population density in Slovenia is 104 people/km^2. For the analysis, the distribution of the population at the municipality level was used (Figure 2f) [38].

To obtain the shares of geological and hydrogeological classes in the European countries, we used publicly available geological (Figure 4) [50] and hydrogeological data [51] at the European level, which we classified into the same classes as used on Slovenian maps.

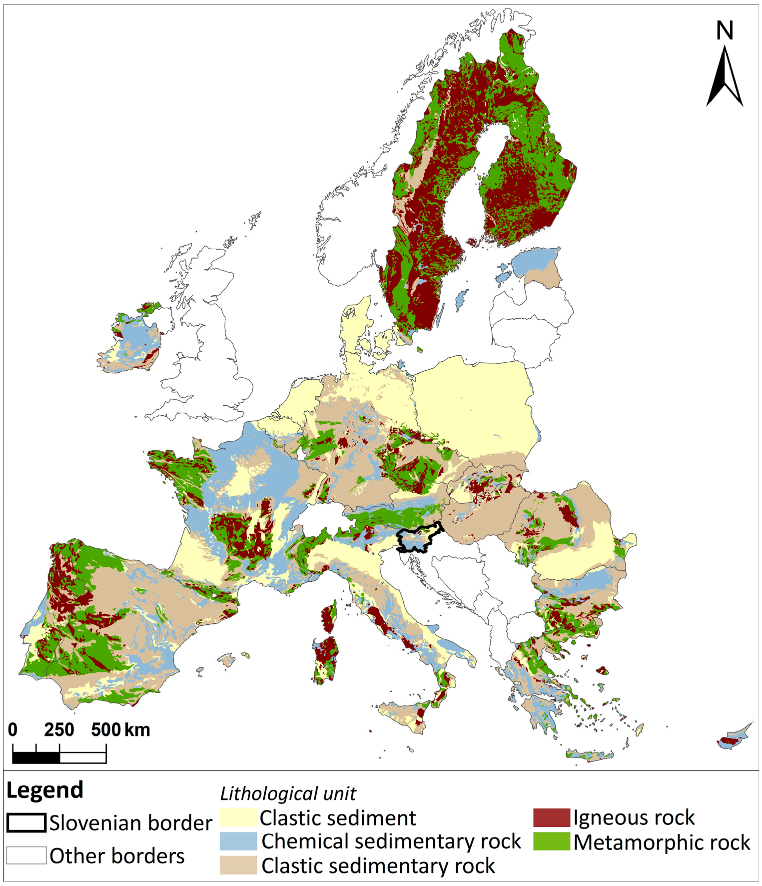

Figure 4. Generalised geological map of 22 countries, with the location of Slovenia (after [50]).

2.5. Statistical Analysis

We first analysed the influence of natural (geological, hydrogeological, and climate) factors on the spatial distribution of GWHP and GCHP systems in Slovenia using the non-parametric χ^2 test [52]. In the next step, we used the information value method [30] to objectively evaluate the influence of different factor classes on GSHP spatial distribution.

The latter method does not consider the overall influence of the factors on GSHP distribution, as χ^2 test does. Both methods are commonly used to assess the influence of natural factors on the spatial distribution of observed phenomenon [30–33]. The input data was determined as the ratio between the actual number of systems and the population density. The population density was calculated as the ratio between the population and the area of each factor class. In this way, the influence of population density on the number of GSHP systems was minimized.

Statistical comparisons for 22 European countries, including Slovenia, were made based on data on the area, population, and gross domestic product (GDP) of the countries [53–55].

2.5.1. χ^2 Test

A χ^2 test is a non-parametric statistical test for categorical data that compares the distribution of observed data (O) with the distribution of theoretically expected data (E) [52,56]:

$$\chi^2 = \sum_{i=1}^{n} \frac{(O-E)^2}{E} \tag{1}$$

The confidence interval of the test was set at 95% $(\alpha = 0.05)$. Statistical significance is confirmed when the probability (p) of the test is $p \le \alpha$. Further, a higher value of χ^2 means a higher probability that the observed natural factor influences the spatial distribution of the GSHP systems if the difference between O and E has a positive value. If the difference between O and E has a negative value, the probability that the observed natural factor influences the spatial distribution of the GSHP systems is lower, although the final χ^2 is positive.

2.5.2. Information Value Method

The information value method is based on a Bayesian conditional probability theorem through which information values for each factor class can be obtained [33]. The method considers the influence of natural factors on GSHPs' spatial density in each factor class, using the natural logarithm to control the large variations in the values (Equation (2)). The method is considered suitable for a large study area with limited data, due to its simplicity and insensitivity to dependent variables [57]. It is defined as

$$I = \ln\left(\frac{D_i}{D}\right) \tag{2}$$

where I is the information value for the analysed class; D_i is the number of GSHPs within the class; D is the total number of GSHPs within the whole area of Slovenia. Positive values of I_i indicate a stronger influence between the factor class and the GSHP spatial density, while negative values of I_i indicate a low influence of the factor class on the GSHP spatial density.

3. Results

First, we analysed the spatial distribution of the GWHP and GCHP systems within each geological, hydrogeological, and climate class based on the population density using a GIS environment [48] for further χ^2 test and information value method calculations.

3.1. χ^2 Test

The χ^2 test showed that the geological, hydrogeological, and climatic classes have a statistically significant influence on the GSHP systems' spatial distribution (Table 3, Figures 5–7). The highest probability that natural conditions influence GSHP spatial distribution was found for hydrogeological conditions (χ^2 = 296), followed by geological conditions (χ^2 = 160) and climatic conditions (χ^2 = 28) for GWHP systems. The same ranking of factors was obtained for GCHP systems. In this case, the χ^2 values are lower but still indicate a strong influence of natural factors: 110 for hydrogeological conditions, 108 for geological conditions, and 26 for climatic conditions. More detailed results for each factor class are presented in Table 3.

Table 3. Results of χ^2 tests for geological, hydrogeological, and climate classes. Light grey colour indicates low influence (negative *O*–*E*), and dark grey indicates strong influence (positive *O*–*E*) of natural factors on the GSHP spatial distribution. *O*—observed values,*E*—expected values.

Factor	**Area (km^2)**	**Population (Number)**	**GWHP System**			**GCHP System**		
			Number of Units	***O*–*E***	**χ^2**	**Number of Units**	***O*–*E***	**χ^2**
Geological class								
Clastic sediment	6382	1,209,150	540	152	59	424	−152	40
Clastic sedimentary rock	3245	290,258	8	−41	34	113	41	23
Chemical sedimentary rock	9193	494,672	59	−97	60	329	97	40
Igneous rock	602	33,629	9	−10	5	38	10	3
Metamorphic rock	851	81,268	6	−4	2	20	4	1
SUM	20,273	210,8977	622	0	160	924	0	108
Degrees of freedom					4			4
p-value (two-tailed)					<0.001			<0.001
Hydrogeological class								
1.1.	1484	677,895	194	124	219	65	−124	82
1.2.	1447	122,102	63	−18	4	233	18	1
2.1.	2064	169,056	12	−11	5	73	11	2
2.2.	7056	358,265	41	−24	9	199	24	3
3.1.	5612	472,414	36	−77	53	380	77	20
3.1.1.	1461	114,897	14	−4	1	51	4	0
3.2.	167	33,668	0	−2	1	7	2	0
3.3.	982	160,680	36	11	5	57	−11	2
SUM	20,273	210,8977	397	0	296	1066	0	110
Degrees of freedom					7			7
p-value (two-tailed)					<0.001			<0.001
Climate class								
Alpine	2976	267,137	10	−28	20	68	28	19
Temperate Continental	15,636	1,695,488	978	37	1	960	−37	1
Sub-Mediterranean	1661	146,352	5	−9	6	23	9	5
SUM	20,273	2,108,977	992	0	25	1051	0	26
Degrees of freedom					2			2
p-value (two-tailed)					<0.001			<0.001

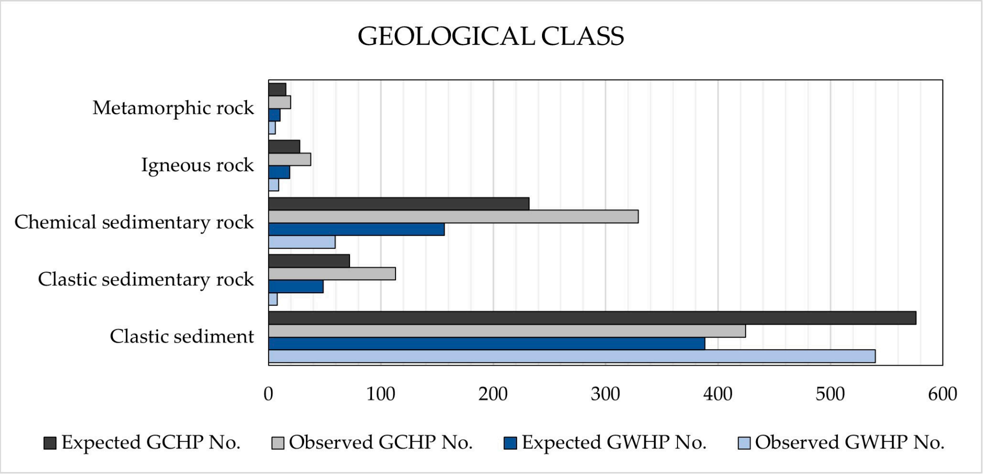

Figure 5. Number of observed and expected GWHP and GCHP units on geological classes.

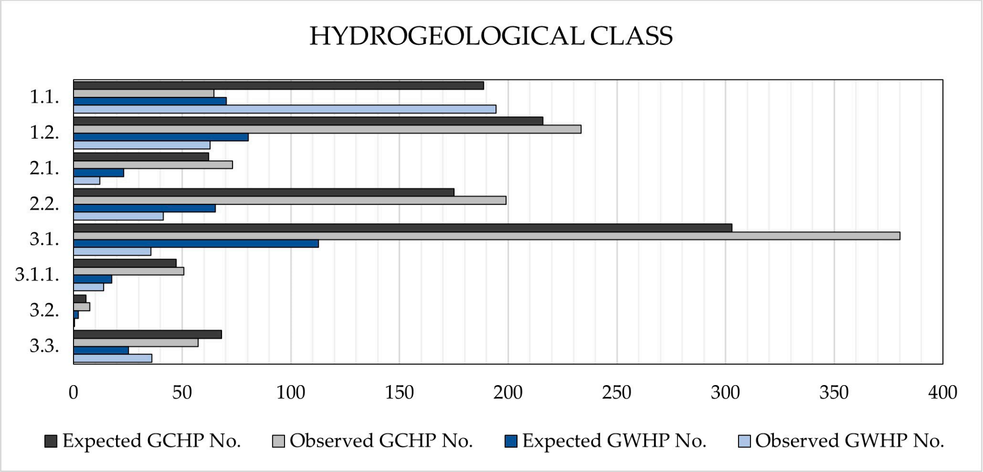

Figure 6. Number of observed and expected GWHP and GCHP units on hydrogeological classes.

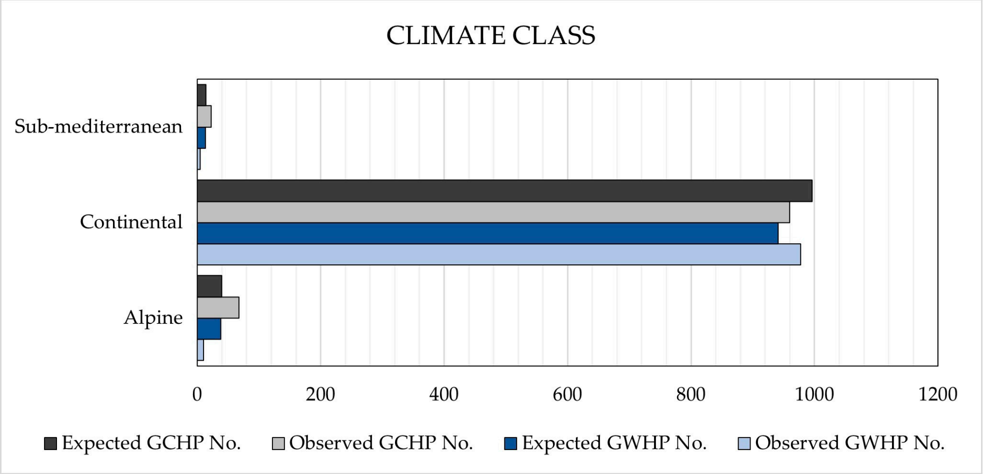

Figure 7. Number of observed and expected GWHP and GCHP units on climate classes.

3.2. Information Value Method

The highest information values (I) of the spatial distribution of GWHP systems within geological and hydrogeological classes have the clastic sediments and extensive and highly productive intergranular aquifers, respectively (Table 4). The highest I of the spatial distribution of the GCHP systems in these classes have clastic sediments and chemical sedimentary rocks, and minor aquifers with local and limited groundwater resources (3.1.), local or intermittently productive aquifers or extensive but only moderately productive intergranular aquifers (1.2.) and local or intermittently productive aquifers or extensive but only moderately productive fissured/compacted aquifers (2.2.). The *I* for the climate classes is highest for both types of geothermal systems in the continental class. For DWPZ, the *I* is low for both types of geothermal system in all protection zones.

Table 4. The information value of GSHP systems and analysed factors. The dark grey colour indicates a stronger influence of the factor class with the GSHP spatial density, while the light grey colour indicates a lower influence.

Factor	**GWHP Systems**		**GCHP Systems**	
	Number of Units	***I***	**Number of Units**	***I***
Geological class				
Clastic sediment	540	0.89	424	0.60
Clastic sedimentary rock	8	−3.34	113	−0.72
Chemical sedimentary rock	59	−1.32	329	0.35
Igneous rock	9	−3.21	38	−1.82
Metamorphic rock	6	−3.56	20	−2.46
Hydrogeological class				
1.1.	194	0.78	65	−0.37
1.2.	63	−0.35	233	0.92
2.1.	12	−1.99	73	−0.24
2.2.	41	−0.77	199	0.76
3.1.	36	−0.92	380	1.40
3.1.1.	14	−1.85	51	−0.61
3.2.	0	−5.19	7	−2.53
3.3.	36	−0.91	57	-0.49
Climate class				
Alpine	10	−3.62	68	−1.75
Continental	978	0.96	960	0.90
Sub-Mediterranean	5	−4.41	23	−2.85
Drinking water protection zone				
The capture zone	0	/	0	/
DWPZ I	0	/	5	−5.94
DWPZ II	10	−4.86	24	−3.97
DWPZ III + DWPZ IV	130	−0.82	111	−0.97
Artesian aquifer protection zone	0	/	1	−9.12
Mineral water protection zone	8	−5.52	5	−5.98

3.3. Analysis of Installed GSHP in Selected EU Countries

The analysis of installed GSHPs considering the number of populations in 2020 (Figure 8) showed that Sweden is the leading country, with 54,053 GSHP systems per million people. It is followed by Finland with half as many systems (24,686 GSHPs/1′M people), Estonia (14,567 GSHPs/1 M people), and Austria (12,581 GSHPs/1 M people) (Figure 8a). The spatial density of GSHP systems was, in 2020, the highest in the Netherlands (2.12 GSHPs/km^2), followed by Denmark (1.68 GSHPs/km^2) and Austria (1.34 GSHPs/km^2) (Figure 8b). The ratio between the number of GSHP systems and GDP was the highest in Sweden (1270 GSHPs/1 B €), followed by France (970 GSHPs/1 B €), Austria (685 GSHPs/1 B €), and Slovenia (355 GSHPs/1 B €) (Figure 8c).

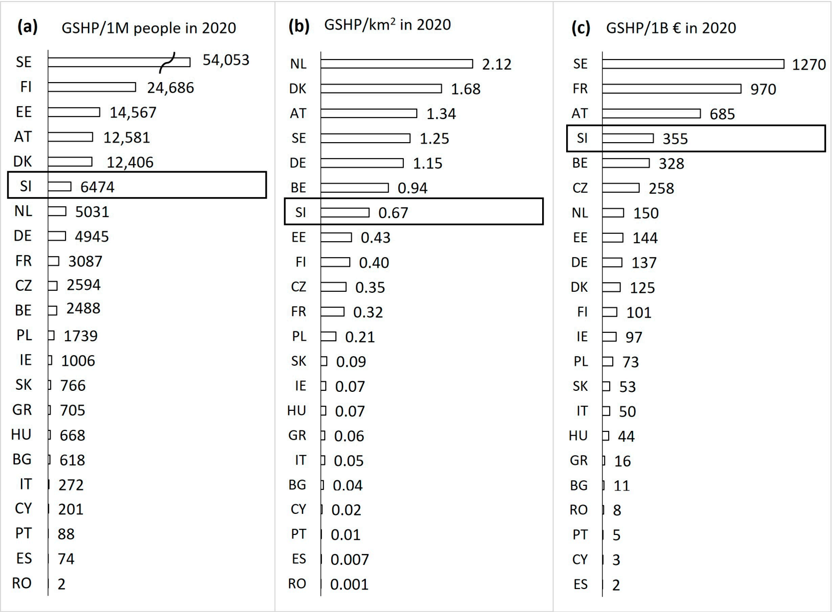

Figure 8. (**a**) Number of operating GSHP systems per million people in 22 European countries, (**b**) per square kilometre, and (**c**) per GDP in 2020 [46,47,53–55].

The generalised geological map of Europe (Figures 4 and 7a) [50] shows that clastic sediments predominate in Belgium, Denmark, the Netherlands, and Poland. More than 50% of clastic sedimentary rocks prevail only in Hungary (Figure 9a). This geological class also covers the highest share of the territory in Germany, Romania, Slovakia, Spain, and Estonia (Figure 9a). Chemical sedimentary rocks cover a relatively large portion of the territory in Cyprus (58%), Estonia (60%), Ireland (48%), and Slovenia (45%). Igneous rocks prevail in Sweden (56%) and Finland (45%), while metamorphic rocks account for 40% in Austria, 55% in Finland, 32% in Portugal, and 34% in Sweden.

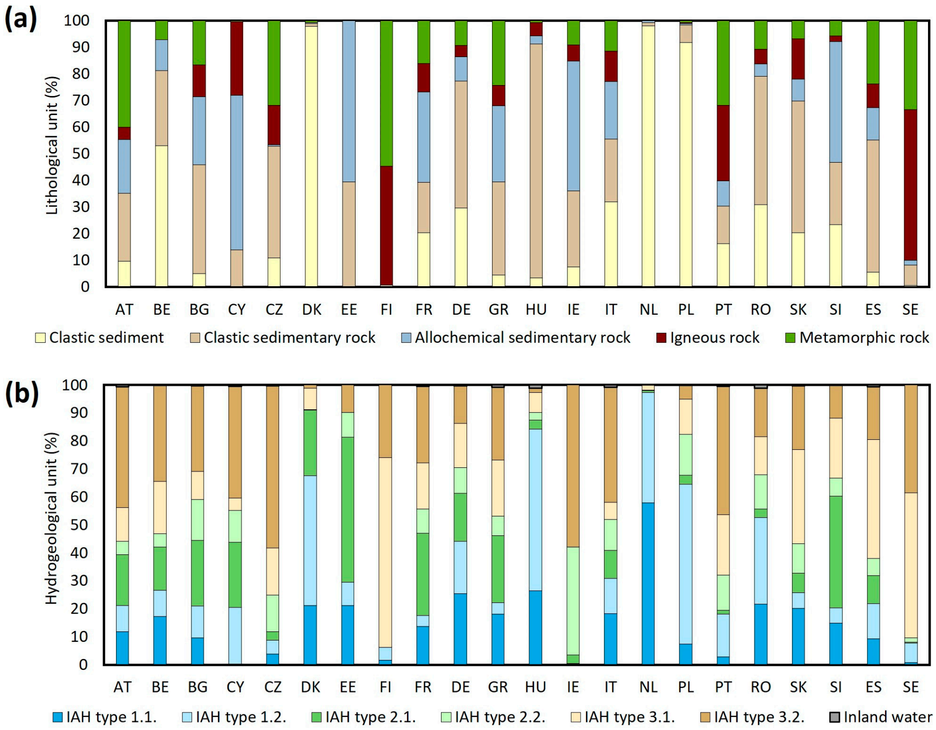

Figure 9. (**a**) Share of geological classes and (**b**) hydrogeological classes in selected EU countries.

The International Hydrogeological map of Europe [51] shows the highest shares of highly productive fissured aquifers (type 2.1.) in Estonia (52%), Slovenia (40%), and France (30%) (Figure 9b). A higher share of highly productive intergranular aquifers (type 1.1.) is in Germany and the Netherlands (Figure 9b). On the other hand, it is typical for Austria, Cyprus, Czech Republic, Ireland, Italy, and Portugal that 40% of country's area have essentially no groundwater resources (type 3.2.).

4. Discussion

The analysis of the spatial distribution of GSHP systems in Slovenia included the locations of 1073 GWHP systems and 1122 GCHP systems installed from 2016 till 2021 and registered in the Eco Fund database [28]. The time interval of data collection in this database is limited, but it is the only database that contains all data needed for the conducted analysis.

The results of a χ^2 test showed that all three factors (geological, hydrogeological, and climatic) have a statistically significant influence on the spatial distribution of the GSHP systems. Hydrogeological conditions (GWHP $- \chi^2 = 296$, GCHP $- \chi^2 = 110$) have the highest influence on the spatial distribution of GSHP, followed by geological conditions (GWHP $- \chi^2 = 160$, GCHP $- \chi^2 = 108$) and climate conditions (GWHP $- \chi^2 = 28$, GCHP $- \chi^2 = 26$) (Table 3). The strong influence of the hydrogeological factor is related to the fact that a highly productive aquifer is the main required condition for the operation of GWHP systems. Such aquifers are most often found in unconsolidated clastic sediments. GCHP systems do not require groundwater but could be more efficient in their presence. The climate conditions showed the lowest influence on GSHP spatial distribution compared to hydrogeological and geological conditions.

The results of the information value (I) showed within the geological classes the strongest influence on the spatial density of GWHP systems for the clastic sediment class (0.89). The other geological classes showed less influence (negative values of I). A similarly strong influence (0.78) within the hydrogeological classes was observed for highly productive intergranular aquifers in clastic sediments, which are a common environment for the installation of GWHP systems. The I of the climate classes showed a positive value in the continental class (0.96), indicating that the spatial density of GWHP systems is the highest there.

The I for the geological classes showed the strongest influence on the spatial density of GCHP systems for the clastic sediment class (0.6) and the chemical sedimentary class (0.35). Other classes had less influence on spatial density, although we know that the classes can be used for the installation of GCHP systems. Among the hydrogeological classes, the strongest influence was obtained for class 3.1. (1.4), which represents minor aquifers with local and limited groundwater resources. Classes 1.2. and 2.2., with local or intermittently productive aquifers or extensive but only moderately productive intergranular/fissured aquifers (Table 4), also had a stronger influence (0.92 and 0.76), probably related to the fact that the installation of GCHP systems does not require groundwater. The I for climate classes is positive only for the Continental class (0.9), indicating that the spatial density of GCHP systems is highest there.

The obtained values of I, when considering the spatial distribution of GSHP systems and DWPZ, are negative (Table 4). This indicates that the spatial density of GSHP systems is lower within DWPZs than outside these areas. This is related to Slovenian regulations, as research permits for boreholes cannot be issued in the protection zones DWPZ 0 and DWPZ I. In the protection zones DWPZ II, DWPZ III, and DWPZ IV, the acquisition of water rights depends on the specifics of the water source and corresponding risk analysis [41].

The analysis of installed GSHP units in 22 European countries, considering the country's population, area, and GDP, showed small differences in the leading countries. Sweden, Germany, France, and Finland are the leading countries in terms of installed units per population (Figure 8a). Due to the high market diffusion and moderate annual growth rates of units sold, all these countries have developed markets, as already discussed by

Götzl et al. [58]. The leading country in terms of GSHP spatial density is the Netherlands, followed by Denmark, Austria, and Sweden (Figure 8b). Comparing the GSHP units per the country's GDP, the leading country is still Sweden, followed by Estonia and Finland (Figure 8c).

The analysis of the influence of the geological and hydrogeological conditions in the selected European countries (Figure 9a,b) showed that despite the different conditions in these countries, the GCHP systems strongly predominate (Figure 8a). Even in countries with a high share of clastic sediments (NL, PL, DK) and highly productive aquifers, GCHP systems prevail. This is mainly related to the strict regulations for the installation of GWHP systems [59]. In European countries, except in Slovenia and Romania, the share of GCHP systems is higher than 65% (on average 86.5%). For example, in Denmark, clastic sediments with extensive intergranular aquifers predominate, but the share of GCHP systems is 98%. Legal requirements for the installation of GWHP systems in Denmark require investigations and documentation on the geology and hydrogeology of the aquifers as well as on the hydraulic and hydrothermal properties with chemical and microbiological conditions, which increase the cost of installation of GWHP systems [59]. Highly productive intergranular aquifers are present in almost 60% of the territory of the Netherlands (Figure 9b). However, the investment and operating costs for GWHP systems are higher than for GCHP systems, so systems smaller than <100 kW with GCHP technology are more economically effective [60]. In Finland, the dominance of GCHP systems is related to the fact that the country's subsurface mainly consists of igneous and metamorphic rocks, where essentially no groundwater resources or minor aquifers with limited groundwater resources are typical (Figure 9a,b). Therefore, GCHPs are installed without backfilling the borehole, as groundwater fills them naturally [26]. This makes drilling cheaper and GCHP systems more competitive with other renewable energy sources [26,61].

5. Conclusions

Knowledge of the spatial distribution of existing GSHP systems is important for future planning of new shallow geothermal systems to avoid interactions between systems and undesirable impacts on underground environmental conditions. The main conclusions from this study are as follows:

1. In Slovenia, there is a database of GWHP systems, while GCHP systems are not systematically collected. In the future, an increase in the spatial density of GSHP systems is expected due to the transition to renewable energy sources; thus, more systematic collection, better maintenance, and easier access to information on GCHP systems will be needed.
2. To our knowledge, the two quantitative statistical methods used in the study, the χ^2 test and the information value method (I), were applied to the GSHP system data for the first time.
3. The statistical results showed the predominant influence of hydrogeological conditions on the spatial distribution of GSHP systems in Slovenia.
4. The shares of GCHP (51%) and GWHP (49%) systems installed in Slovenia in the time interval 2016–2021, registered in the Eco Fund database, are comparable. The share of GWHP systems is among the highest in European countries.
5. The share of GCHP systems in the analysed European countries strongly prevails (on average, 86.5%), even though natural conditions are favourable for ground heat pumps. This is typical also for countries where the geological and hydrogeological conditions are similar to those in Slovenia (e.g., DK, FR, DE). The high share of GCHP systems is related to the stricter regulations for the installation of GWHP systems and natural conditions in these countries. In Slovenia, the high share of installed GWHP systems is related to the favourable hydrogeological conditions that allow the drilling of shallow wells, which makes the investment cheaper, although the regulations for these systems are stricter.

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