



Article Groundwater Resources in a Complex Karst Environment Involved by Wind Power Farm Construction

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Abstract: The need to produce energy from clean energy sources has caused public administrations and private companies to look for suitable places. The windiness detected in the eastern area of the Matese karst massif (southern Italy) has favored the construction of wind farms to produce electricity from clean energy sources. During the installation of the first wind turbines, some alterations in the supply of drinking water, fed by the springs of this area, were attributed by the population to this installation. Therefore, in order to assess whether there has been an impact produced by the wind farms on the quality of groundwater, a detailed hydrogeological study was developed. Karst hydrogeological features of the area were mapped, focusing on endorheic areas, sinkholes and karst springs. Artificial tracer tests were then carried out to investigate groundwater flow circulation and connection between surface karst landforms and springs. Chemical and physical characteristics of the groundwater were monitored during the construction of the wind farms and, for the following months, by infield measurements and laboratory analysis of spring water samples. This study highlights that wind farms mainly develop along the boundary of endorheic areas, which are important recharge zones for groundwater resources, and are directly connected to the major karst springs through sinkholes and a dense network of karst conduits. The results of the monitoring did not reveal any anomalies in the quality of the water and, therefore, any alterations cannot be attributed to the wind farms. Our investigation appears useful for a better understanding of the possible actual and future effects of the wind farms on both groundwater circulation and spring water quality in this karst area.

Keywords: wind power; karst landscape; environmental impact assessment; groundwater; Matese Mountains; southern Italy

1. Introduction

Countries around the world today are increasingly striving to adopt energy that harnesses renewable resources from wind and sunlight, rather than fossil-based energy. This would allow us to achieve zero carbon emissions by 2050 [1], making our lives more sustainable. The improvement in technology and the reduction in costs of these plants make them competitive on the market; furthermore, they are less harmful to the environment [2–5]. Considerable effort has been made in recent years to increase the distribution of renewable energy rather than fossil fuels and nuclear power, but it is still insufficient.

Among renewable energies, especially for technological evolution and innovation, the one that uses the wind to produce electricity, or that uses the kinetic energy created by the moving air, has reached a certain consistency both in terms of diffusion and production [6–8]. According to data from the International Renewable Energy Agency (IRENA) report [9], wind energy is currently the second most popular type of renewable energy for production in the world, and is constantly growing: wind power supplies about 5% of the world's electricity production, a figure that has almost doubled over the past 10 years. Italy has achieved fifth place in Europe regarding its plants. In fact, Italian wind production



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). represents 9% of the national electricity production. About 90% of the wind farms are concentrated in the south and on the islands, due to the greater availability of suitable windy sites in these regions [10].

Each wind power generation plant, alternatively called a wind farm, consists of a group of wind generators with sizes ranging from 600 kW up to 5 MW, arranged throughout the area in order to make the most of the site's wind resource. Unlike what one might imagine, a wind farm occupies a very small portion of land in proportion to the renewable energy it is capable of producing. Despite this, it will be increasingly necessary to search for significant surfaces to be used for such plants [11,12]. This research involves citizens and authorities, who do not always accept such use of their respective territory [13–15]. In consideration of current situations, local communities should have greater awareness in terms of the location choice of the plant, and receive adequate information regarding dates, contents and local compensation measures. A shared choice could be to select areas unsuitable for other uses.

Generally, wind installations have marginal impact when compared to conventional power plants [16–18]. However, the greatest concerns of the communities are for the visual modification of the landscape [19,20], which would become less attractive to tourists; the noise of the turbine blades [21], which would disturb grazing animals and wild fauna. Furthermore, birds and bats [22,23] could be killed by the blades of rotating turbines. To these impacts, which can be more easily observed, are added those detectable only by specific activities, such as electromagnetic disturbances on air traffic control radars [24,25].

There are different mitigation strategies to the various environmental problems deriving from wind farms [26–28], allowing for agriculture or pastoralism. These strategies involve technological development, such as the installation of bladeless wind turbines and the correct location of the respective wind farms.

Even if most of the impacts described above refer to the activity of the wind turbines, there are others related to the construction phase of the wind farm. During this phase, activities involve not only the installation of wind turbines, but also the building of the infrastructures and logistics network for the transmission of the generated energy [29–31], which often requires the excavation of huge amounts of rock and soil, and the storage of waste materials.

The severity of the produced impact strongly depends on the characteristics of the environment. Therefore, specific analyses are needed when investigating the possible effects of wind farms on the natural conditions of an area.

When wind farms are built in karst areas, the major interest for researchers, communities and economies is to evaluate the impacts on the quantity and the quality of groundwater. This is because karst areas are of fundamental importance to people since they hold huge groundwater reservoirs, which feed springs and represent the main source of fresh water in many areas of the world [32].

The recharge of the groundwater resources is produced by the infiltration of the surface water into the underground, which occurs in a concentrated or diffuse manner [33]. Concentrated infiltration occurs at points, such as sinkholes/shafts and swallow holes, and allows for the fast transfer of water from the surface to the underground. On the other hand, diffuse infiltration occurs via the soil mantle or fractures in the outcropping karst rocks, and generates percolation, which can take a significant amount of time before water reaches the water table [34].

In karst areas, infiltration is strongly controlled by the features of the topographic surface, which is generally characterized by peculiar landforms called endorheic areas. These are closed depressions where the internal runoff [35] is completely absorbed by one or more sinkholes or swallow holes. Endorheic areas represent important recharge areas for groundwater, and are often connected to one or more springs.

In such an environment, wind farms can affect groundwater resources in several different ways. Water quantity and quality may change due to alterations in the natural surface and subsurface flow paths and the interactions between the groundwater and sur-

face water [36]. Water can be diverted by road systems or systems for collecting rainwater, avoiding the supply to endorheic areas and sinking streams. The excavation and extraction of geological material can also alter the surface and groundwater flow, draining water and moving it away from the springs. Water quality can be affected by activities that aggravate soil erosion and alter the surface conditions, such as heavy equipment traffic, rock and soil extraction/accumulation for the construction of access roads to work sites, as well as the excavation of deep foundations.

These works on site are often perceived in a negative way by communities, due to both the possible consequences and the loss of quality that they imagine the works before and the wind farm after will inflict on their territory [37–39]. In this sense, conflicts are generated based on the need for the plants and on the management of the works, to which a solution can only be found by establishing direct communication with the community [40,41]. To this end, it is important that we deepen our knowledge of the characteristics of the soil and water components of the area subjected to the intervention, to provide concrete and effective answers with respect to a series of advantages, such as the production of low-cost, zero-emission energy [42,43].

This research illustrates a case study of a typical karst area where the construction of wind farms has worried the local communities due to the possible impact on the groundwater resources. This area is located in the south of Italy, and supplies several local aqueducts by karst spring water, which have been monitored, also including specific chemical analyses. Some typical karst surface features (endorheic areas and sinkholes) have been mapped in detail due to their importance in the recharge processes; tracer tests have been carried out to reconstruct groundwater circulation.

2. Study Area

The area falls in the eastern part of the Matese massif, inside the province of Benevento (Campania, southern Italy), and involves several municipalities: Morcone, Pontelandolfo, Cerreto Sannita, Pietraroja, Casalduni, San Lupo and Campolattaro (Figure 1).

The delimitation criterion of the study area is essentially based on an orographic basis, where the limits are generally constituted by watercourses or watersheds, in order to incorporate all the aquifer systems of the apical sector of the Morcone and Pontelandolfo municipalities, where the main wind power farms are located. According to this criterion, the study area is delimited mainly by rivers and in particular by the Sassinoro stream to the north, Tammaro river to the east, Lente stream to the south and Titerno river to the west (Figure 1). It has an extension of approximately 150 km². The topographical altitudes are very variable: from about 1200 m a.s.l. in the northwestern sector it passes at about 400 m a.s.l. along the southern border. Within these limits, the landscape is characterized by numerous mountain ridges, which are contrasted against more or less engraved river furrows eroded by runoff waters.

From a geological point of view, the Matese massif belongs to the southern segment of the Apennines. It consists of the superposition of several tectonic nappes deriving from the deformation of Meso–Cenozoic sedimentary successions originating in various environments, from the deep-sea basin to the shallow sea [44]. The main tectonic nappes are limited by low-angle Cenozoic thrusts sealed by Mio–Pliocene discordant deposits. The latter are further deformed and segmented by normal or transcurrent quaternary faults that have produced numerous intramontane basins along the Apennine axis, and large coastal plains on the Tyrrhenian edge [45].



Figure 1. In the box at the top right, the location of the study area highlighted by red rectangle, inside the Campania region (southern Italy). DTM of the study area (border colored in red), with drainage lines and endorheic basins.

In the eastern area of Matese massif, calcarenites and conglomerates essentially emerge, often recrystallized (crystalline limestones: Maastrichtian-Paleocene), which evolve into deposits produced by shale and limestone breccias (Scaglia Formation: Eocene-Aquitanian) (Figure 2). These lithologies also differ in their hydrogeological behavior, because if crystalline limestones can offer good circulation, even if due to secondary permeability, clays and limestone breccias can prevent it, and therefore, be considered an aquitard. These terms complete the carbonate succession of the Apennine platform, which forms the Matese massif extensively, and includes the basal Triassic dolomites and the Jurassic-Cretaceous limestones (pre-orogenic carbonates in Figure 2). This succession continues with the calcarenites and calcirudites (Cusano Formation: Burdigalian pp-Lower Tortonian), marls, marly limestones and calcarenites with macroforaminifera (Longano Formation: Serravallian-Lower Tortonian) and, finally, clayey marls and sandstone (Pietraroja Formation: Middle Tortonian), which shows a gradual deepening of the marine sedimentation environment. These latter deposits, spread essentially to the north and west of the study area, certainly represent an aquiclude, unlike the Miocene formations that complete the carbonate succession are well associated with the karst aquifer. This aquifer is certainly the most important in the study area both in terms of extension and thickness. The overall thickness of the Meso-Cenozoic succession exceeds 2500 m in outcrop, however, a well for oil exploration dug near the study area at the end of the 1980s allows a better understanding of the structural setting [45]. In fact, in the Morcone exploration well, the thickness of the succession appears limited to the upper portion in the underground, and therefore, tectonically superimposed onto conglomeratic and arenaceous deposits of the upper Miocene (Castelvetere Group: Upper Tortonian–Lower Messinian [46].

Lateral to the study area outcrop: clastic deposits of the neritic domain of the Baronia Formation (upper Zanclean) to the west, deposits similar to deep slope basin domains analogous to the Flysch Rosso (Upper Cretaceous–Burdigalian) to the northeast, and the arenaceous deposits of the San Giorgio Formation (Upper Serravallian–Middle and Upper Tortonian) to the southeast. In addition, there are some lentiform sandstone plaques from the Numidian Flysch (Langhian), covered with post-Numidian marl. With the exception of the Flysch Rosso, whose clayey and marly outcrop can constitute an aquitard, a heterogeneous porous aquifer can be associated for all the remaining deposits of the Middle Miocene–Lower Pliocene, which almost surround the karst aquifer. Finally, the deposits described are sealed by Quaternary deposits both as detrital talus and as pyroclasts attributed to Ignimbrite Campana (39,000 years a.p.) [47]. Such Quaternary deposits represent heterogenous porous aquifers, which are mostly diffuse in the northeastern portion of the study area (Figure 2).



Figure 2. Hydrogeological sketch of the study area (border colored in black).

This area corresponds to a sector of the Southern Apennines [48] experiencing an extensional regime after the orogenic phases. Thrust tectonic evidence, in fact, is strongly obscured by the post-orogenic tectonics. NW–SE normal fault systems and, subordinately, NE–SW, E–W and N–E are widely represented [49,50].

These structural features are legible from the morphologies observed in this area: straight slopes in the shape of triangular or trapezoidal facets, fault escarpments, alignment of sinkholes, river elbows and so on [51]. However, active tectonics still influence the morphodynamic processes, as confirmed by the effects of the strong historical earthquakes (for example, 1456, 1688, 1732, 1805, 1857 and 1980) [52] that hit this sector of the Apennine chain. This seismicity constrains the realization of the static nature of each building.

Carbonate rocks are widespread in the study area, which have been impacted by karst processes. Given the karst nature of the area, significant amounts of water flow towards the numerous sinkholes located in endorheic areas and directly infiltrate the underground [53]. Consequently, the surface water circulation is conditioned by these sinkholes, which determine the infiltration of water and the recharge of the local aquifer

system [54]. This peculiar characteristic constitutes an important aspect for understanding the mode of circulation of groundwater [55,56].

Numerous endorheic areas can be recognized in the study area based on the conformation of the topographic surface [57,58]. In practice, each endorheic area is bound by its own watershed, and is therefore hydrographically closed. Many endorheic areas are adjacent, constituting a large recharge area as a whole. An example is shown in Figure 3.



Figure 3. Drone view of the ridge bordering the main endorheic areas.

The wind farms occupy most of the tops of the ridges of the reliefs. Most of the towers of wind turbines are located along the boundaries of endorheic areas (Figures 1 and 3).

The towers with an attached nacelle containing the wind turbine and the three blades stand out clearly in the landscape profiles, despite having a rather light and pale coloration. They constitute at least three wind farms built over a short timescale (between 2018 and 2020) for a total of 56 towers in just over 140 square kilometers. The wind turbines that compose them are located between the altitudes of 500 m and 1100 m (Figure 1). Most wind turbines are considered to be of large size, that is, with powers up to 3 MW, with a three-blade rotor, with a maximum diameter of 112 m and a hub height not exceeding 100 m. The construction of these plants and, more specifically, the transport and assembly of the wind turbines involved access to the site by vehicles of exceptional size. For this reason, it was preferred in many cases to adapt the existing road system and to open new tracks only for some sections.

Most of the tower foundations of the wind farms in the study area were built on a circular reinforced concrete plate, which was in turn founded on piles up to 30 m below ground level [59,60]. Where it was possible, both for the road system as well as for the assembly areas, rainwater control works were carried out. Many of these were of a provisional nature, and were therefore made definitive in the subsequent phase.

Unlike the interventions for transport and assembly, the construction of the cable duct generally entailed minimal impact both for the choice of the route, which was superimposed on the roads, and for the type of vehicle used. There are, however, situations in which the runoff has undergone evident deviations from the previous flow, indirectly affecting agricultural areas and soil conservation. The minimum quantity of excavated soil was in any case reused for the backfilling of the excavation after the laying of the cables, rather than being disposed of in landfills.

3. Materials and Methods

The present study aims to recognize the possible impacts of wind power farms on the physical–chemical characteristics of major springs and on groundwater circulation.

In consideration of the shapes and processes that act in the study area, detailed mapping of the endorheic areas and sinkholes was necessary, as these play an important role in the infiltration of surface waters, and therefore in the supply of springs.

Remote sensing data (Digital Elevation Model, DEM, and digital orthophotos) and topographic maps were used to perform the detailed mapping of the karst hydrological features of the area with the aid of geographic information systems (GIS). The location of the endorheic areas and sinkholes was determined by analyzing contour maps derived from a high-resolution DEM (5×5 m cell) and digital orthophotos with a resolution of 0.5 m. For the identification of both small and manmade sinkholes, a geological survey of the field was required, combined with the analysis of detailed topographic maps.

At the same time, the geological structure of the area was investigated both stratigraphically and structurally. This was made possible by the recent revision of the stratigraphic units, which also allowed the publication of new geological maps; in particular, the Geological Map of Campania on a scale of 1:250,000 [45] and, in part, the new sheet n.419 "S. Giorgio La Molara" of the Geological Map of Italy, 1:50,000 in scale, available on the web [48]. The detailed definition of the hydrogeological complexes and their spatial resolution was based on this new geological basis. In-depth knowledge of the relationships was also possible for the acquisition of various forms of stratigraphy relating to wells for oil exploration and responses from high-resolution geophysical surveys carried out on the Apennine chain.

Another fundamental aspect in this study was the characterization of the waters of the main springs of the area (Figure 2), since it could have provided useful information for the reconstruction of the local hydrogeological structure and the related underground water circulation [32]. This characterization was performed in the period from August 2018 to January 2020, when the last installation of the wind turbines located in the northwest was underway, and involved (i) infield systematic surveys of the physical-chemical characteristics, (ii) three chemical laboratory analysis campaigns of the water according to the current legislation, and (iii) a test with chemical tracers for the reconstruction of the underground water circulation.

The infield surveys of the spring waters were performed in the period from August 2018 to January 2020, when the last installation of the wind turbines located in the northwest was underway. Measurements were carried out monthly, using a multiparametric probe Horiba U50 to acquire information on the temperature (°C), pH, electrical conductivity (mS/cm), dissolved oxygen (mg/L), total dissolved solids (g/L), redox potential (mV) and turbidity (NTU). The measurements were compensated at 20 °C. In addition to these monthly surveys, for some areas, a measurement control unit was installed inside the collection water structure. The measurement control unit was used for the determination of the main chemical–physical parameters of the water (electrical conductivity, turbidity and temperature) and of the flow rate through "diver" sensors. For each of the monitored springs, a specific sheet was created in which the periodic monitoring data, the concentrations of the individual analytes examined by the laboratory chemical analyses and the related graphical elaborations, were reported.

Water sampling for laboratory analysis was also carried out both during the construction of the wind farms (in August–September 2018) and at the end of construction (February–March and September–October 2019), when the wind turbines were already working.

The water samples were analyzed in a certified laboratory (EATlab srls, Maccoliperrillo, Italy) in order to investigate the presence of any parametric anomalies of the water with respect to the legal limits imposed by the current legislation. The analysis methods comprised APAT CNR IRSA, UNI EN ISO. More specifically, the concentrations of the main cations (calcium Ca^{2+} , magnesium Mg^{2+} , sodium Na^+ , potassium K^+) and anions (sulfate SO_4^{2-} , bicarbonate HCO_3^- , carbonate CO_3^{2-} , chloride Cl^- , fluorides F^-) were detected. In addition to these, the complete series of metals, inorganic elements, aromatic organic compounds, aromatic polycyclics, carcinogenic and non-carcinogenic chlorinated aliphatics, nitrobenzenes, chlorobenzenes, aromatic amines, phenols and chlorophenols, dioxins and furans were determined. Finally, any microbiological components were analyzed.

An artificial tracer test with different chemical tracers (Tinopal and Fluorescein) was carried out in the period November–December 2020 to reconstruct the possible connection between the surface hydrological features of the recharge areas (endorheic areas) with the monitored springs. The injection points were selected based on the maps of the karst features constructed in this study. The test took place at the main sinkholes connected to wind power plants a few hours after heavy rainfall, therefore capturing an important recharging phase. This allowed the solutions to reach the saturated zone of the aquifer without suffering excessive washout.

4. Results

Main Features of Springs

Karst springs are widespread in the area, with a discharge rate that varies widely in time and space. Some springs are taped for drinking purposes by local municipalities [61–63], while other springs have modest flow rates, and are generally left as troughs for grazing animals.

The groundwater circulation connected to these springs is fragmentary in many cases due to the geological and hydrogeological nature of the area [64,65]. The water points surveyed on a cartographic basis, from data from previous studies and from field surveys, are shown in Figure 2. Some springs (e.g., Le Grotte, Acqua della Lepre) fall within endorheic areas, hence their waters infiltrate again and emerge at one or more springs downhill. The main springs of the area in terms of flow, such as S. Elmo and Le Grotte of Pontelandolfo, actually constitute karst springs.

An important aspect concerns the phenomenon of turbidity, which affects some springs after intense rainy periods; this is evident for Le Grotte spring of Pontelandolfo. This phenomenon is well documented historically [61], and its intensification with the construction of the wind farm cannot be ascertained.

The analysis of the chemical–physical parameters, aimed at identifying the hydrogeochemical facies of the aquifer, is a fundamental tool for the purpose of typological classification of the waters circulating within a system, and also allows one to obtain useful information to trace the genesis of these resources [66]. The springs subjected to monitoring are in Table 1. Those located in correspondence with the top areas of the reliefs have negligible flow rates, while most of those situated at lower altitudes have the greatest flow rates.

Item	Monitoring Springs	onitoring Springs Quote Discharge Temperature m a.s.l. L/s °C p		pН	EC ms/cm	TDS g/L	Turbidity NTU	
1	Acqua del Campo	774	15.0	11.5	7.1	0.365	0.237	0
2	Acqua della Lepre	1041	1.5	11.2	7.2	0.355	0.231	2.2
3	Ammeri	774	5.0	12.9	7.6	0.477	0.290	0
4	Coccimonti	809	2.5	11.2	7.1	0.436	0.284	0
5	Fontana Piedi	487	3.0	11.6	7.1	0.427	0.279	4.3
6	Fontana Sant'Elmo	750	50.0	10.6	7.0	0.369	0.240	4.8
7	Le Grotte	540	80.0	12.5	7.2	0.386	0.251	2.5
8	Macioccio	862	4.0	11.6	7.4	0.318	0.207	2.4
9	Sorgenza	505	50.0	12.8	7.2	0.418	0.272	4.2
10	Tofi	795	3.0	11.9	7.3	0.321	0.214	2.3
11	Tre Fontane	818	11.0	11.7	7.3	0.327	0.213	1.4
12	Tre Fontane I	1023	2.0	9.8	7.1	0.330	0.230	0.1
13	Tre Fontane II	1023	2.0	9.7	7.2	0.342	0.222	0

Table 1. Main physical characteristics of the spring water subjected to monitoring in the study area. Springs are shown in Figure 1 and are identified by item number.

The systematic surveys carried out in this study made it possible to observe the ionic composition, detected via chemical analysis, of the samples taken during the campaigns. In particular, the main cations and anions were detected. The processing of the values was performed first through the use of the Piper classification diagram, which allows the definition of the hydrogeochemical facies, and subsequently through the Schoeller–Berkaloff comparison diagram, which provides information on the actual mineralization of groundwater [66].

Within the Piper diagram, therefore, the concentrations of the detected analytes have been plotted, expressed in absolute terms in meq/l (Figure 4). Observing the resulting distribution, it is noted that, both in the descriptive triangle of the concentrations of anions and in that of cations, the spring waters are all concentrated in the lower left corner; this distribution indicates a prevalence of bicarbonate anions and calcium cations. The same distribution is found in the apical quadrilateral, with points concentrated in the left corner, that is, the one related to water circulating in carbonate rocks [66]. From this analysis, it follows that the main hydrogeochemical facies of the waters circulating in the examined area can be classified as alkaline earthy bicarbonate facies. The abundance of ionic concentrations of calcium bicarbonate can be attributed to the dissolution of calcium carbonate, which generates an abundance of this compound among the remaining electrolytes. The distributional homogeneity of these waters within the Piper diagram, concentrated in a single cluster, is an indication of the absence of the mixing of facies; therefore, it affirms the purity of the facies identified. Moreover, such a result confirms the genesis of these waters, which is mainly in the nature of reservoir rocks of calcareous origin.



meq/l

Figure 4. Piper classification diagram of the monitored springs.

In the semilogarithmic diagram of Schoeller–Berkaloff, the chemical characters of each of the monitored springs are compared (Figure 5a,b), based on two different spring water sampling events. This comparison does not show notable differences, and the broken lines

do not indicate variations in the main characteristic relationships of the spring waters. The only ratio that tends to reverse in some springs is the Na + K/Mg ratio, and its inversion could be related to a change in the lithology of the aquifer. In particular, the Sorgenza spring, which stands out more than the others (Figure 5a), is located in the eastern side of the study area, in correspondence with the contact between the scaglia and the crystalline limestone; this contact could affect the results. The Fontana Piedi spring, located at the foot of the village of Morcone, behaves similarly (Figure 5b).

These results exclude the effects of water contamination attributed directly or indirectly to the wind farms that have been built in the area. However, the analysis was extended using available data derived from the monthly monitoring performed to determine the chemical–physical characteristics of the waters from August 2018 to January 2020 of all the springs investigated. As already specified, the investigation was carried out using a multiparametric probe, which made it possible to produce an important database comprising the following parameters: temperature (°C), pH, electrical conductivity (mS/cm), total dissolved solids (g/L) and turbidity (NTU) (Table 1).



Figure 5. Schoeller–Berkaloff diagrams relating to two distinct spring water sampling events: (a) February–March 2019; (b) September–October 2019.

In particular, the analysis of the temperature detected at the springs provided information on underground circuits and any mixing of water. The temperature data show values that oscillate between 9 °C and 17 °C, in relation to the period considered. The lowest average temperatures were recorded during the surveys carried out in the winter period (December and January 2019), while the temperatures tended to be higher in the summer period (August and September 2018). Where the greatest variations were found (e.g., the springs of Acqua della Lepre, Tofi and Macioccio), there could have been runoff of water in the heterothermic zone of the reservoir rock [67]. This zone corresponds to the zone of the aquifer where the aquifer temperature is still affected by the external temperature, and this could mean that the waters have a shallow and/or rapid outflow. Conversely, where the temperature variations are more contained, it could mean that the waters have a deeper outflow, and that it occurs almost exclusively in the homothermal zone of the reservoir rock [68].

The pH, a parameter strongly influenced by the temperature of the solution, in the middle latitudes and in the prevailing climate, generally varied between 7 and 7.5 for the groundwater. The highest values were found in the waters circulating in limestone, while those circulating in siliceous lithotypes were poor in calcium carbonate and reached values

close to 6. The pH of the spring water examined remained, on average, slightly higher than 7, indicating a neutral or basic pH, in accordance with waters flowing in carbonatic aquifers.

The electrical conductivity values are indicative of the concentration of dissolved salts in groundwater. In general, waters that have slower and deeper outflows tend to have higher electrical conductivity than those that circulate with more superficial outflows, with the same feeder aquifer. By analyzing the electrical conductivity data, it was possible to observe values ranging from 0.250 mS/cm to about 0.540 mS/cm, with an annual average value close to about 0.350 mS/cm. Such a value, compared to others recorded for other springs fed by karst aquifers, is slightly low. These slight differences could be associated, as already observed for thermal fluctuations, with the existence of generally rapid and/or superficial outflows in the carbonate aquifer. The increase in electrical conductivity values recorded for some springs (Ammeri, Coccimonti, Piedi, Sorgenza) are probably associated with slower and deeper outflows.

The elevation–water temperature diagram (Figure 6) shows a clear trend of temperature increase as the altitude decreases; this can be explained by a close correlation of the water temperature with the environmental temperature, thus confirming the presence of surface/rapid water circuits. The relationship between altitude and pH (Figure 6) shows, on the other hand, the presence of four clusters characterized by groups of springs close to each other in terms of location which, also due to the meteorological and climatic characteristics related to their position, have similar pH values.



Figure 6. Medium values of temperature (**a**), electrical conductivity (**b**) and pH (**c**) in relation to spring water elevation. Items identify springs: Acqua del Campo (1), Acqua della Lepre (2), Ammeri (3), Coccimonti (4), Fontana Piedi (5) Fontana S. Elmo (6), Le Grotte (7), Macioccio (8), Sorgenza (9), Tofi (10), Tre Fontane (11), Tre Fontane I (12), Tre Fontane II (13).

The elevation–conductivity diagram (Figure 6) clearly shows what has already been said about the variations in electrical conductivity in the water in relation to the underground water flow. The electrical conductivity, in fact, tends to decrease with the altitude. This is indicative of the existence, at higher altitudes, of a faster flow and more directly correlated with the meteoric precipitation waters. On the other hand, as the emergency altitudes decrease, the flow occurs in deeper areas of the aquifer and in longer water-rock-reservoir interaction times [68].

5. Model of Groundwater Circulation

Geological data, karst features mapping and results of artificial tracer tests were used to reconstruct the model of the groundwater circulation in the study area.

Karst features mapping (Figures 1 and 7) results in the delineation of 67 endorheic areas (Figure 1), occupying an area of about 9.4 km² and having an average extension of 0.138 km². They concentrate in the central sector of the study area, where the largest endorheic areas are also located.

Table 2 summarizes the major karst features: Lagospino, Piano Moia and Lepre Basins, with extensions of 2.21, 1.50 and 0.6 km², respectively (Figures 1 and 3). These areas represent the most important recharge zones of the area, and occupy the highly elevated sectors. Wind farms are also located at high altitude and towers of wind turbines generally develop just along the boundary of endorheic areas.

Table 2. Morphometric characteristics of the main endorheic areas. ID: identification number in Figure 1; L: perimeter; A: surface in km^2 and in percentage respect to the entire surface covered by endorheic areas (9.34 km²); H_{min}: height of the lowest point; H_{max} altitude of the highest point.

ID	L (m)	A (km²)	A (%)	H _{min} (m a.s.l.)	H _{max} (m a.s.l.)	H _{max} -H _{min} (m)	Name of the Areas
1	4902.3	0.6	6.6	964.9	1116.1	151.2	Lepre Spring Basin
2	6354.4	1.5	16.2	967.4	1116.7	149.3	Piano Moia Basin
3	7233.8	2.2	23.8	872.2	1057.3	185.1	Lagospino Basin
4	2804	0.3	3.7	734.1	842.6	108.5	Lago Ciancione Basin
5	809	0.5	5.0	821.9	1012.1	190.2	Toppo Mangialardo Basin
6	487	0.4	4.0	895.7	1017.6	121.9	Monte Calvello Basin

The definition of the connections between the recharge areas of Lepre and Lagospino Basins with the monitored springs (S. Elmo, Le Grotte, Sorgenza, Ammeri, Acqua del Campo, Macioccio, etc.) was evaluated through the tracer test carried out in the period November–December 2020.

In particular, Tinopal tracer was injected into Lagospino sinkhole, on 12:00 of 22 November 2020; Fluoresceine tracer was injected into Lepre sinkhole 90 min later. In particular, the first arrive of tracers were recorded after several hours from the injection time (15 h for S. Elmo spring, 28 h for Le Grotte spring).

The connection between sinkholes and springs are shown in Figure 7, which allows to recognize a general groundwater flow through east.



Figure 7. Tinopal and Fluoresceine tracers were injected into Lagospino and Lepre sinkholes, respectively, on 22 November 2020.

Based on geological data, and karst features (endorheic areas, sinkholes and karst springs) spatial distributions, the main aquifer in the area is constitute by the formation of "crystalline limestone". This formation is widespread in the area and has complex geological contacts (both laterally and vertically) with poorly permeable terrains, such as Scaglia Formation, which act as an aquitard [69] (Figure 2).

Other hydrogeological complexes emerge on the perimeter of the aforementioned main ones and generally constitute very low permeable systems that limit water circulation both towards the Tammaro River to the E, and towards the Calore and Titerno rivers, respectively, to the S and to W [70] (Figure 2).

The soluble rocks for karst phenomena gave rise to a typically karst landscape, as already described, which occupies the morphologically highest part of the study area. Locally, the solubility of the rocks has given rise to the formation of numerous voids in the subsoil and consequent development of sinkholes on the surface. In this context, it is not possible to identify a single groundwater table, but a system of water tables placed at different heights, probably also overlapping and separated by the intercalations of less permeable rocks. In this context, as in other karst areas characterized by high permeability, it is possible to identify a water table upstream of each source, characterized by a low slope of the water table. These characteristics can certainly be defined for the most powerful springs in terms of average flow rate (e.g., S. Elmo and Le Grotte).

However, the presence of springs located at different altitudes, even of several hundreds of meters, poses a certain difficulty in connecting all the recharging areas and the springs. The presence of vast endorheic basins and active swallow holes indicates that the groundwater circulation, at least in correspondence with the karst complex of Crystalline limestone, affects much deep layers; in practice, there is an unsaturated zone with a thickness of tens of meters, where percolation processes occur, and a saturated zone below the phreatic surface, where water flows mainly with horizontal motions. Following important rainy events, the area of the Lagospino plain and in a more limited way that of Piano Moia becomes the temporary site of a lake, rapidly drained by the system of swallow holes. The temporary flooding of these endorheic basins does not indicate the raising of the piezometric surface up to the ground level, but rather the drainage difficulty of the sinkhole system to drain the excess internal runoff of the basin. This phenomenon and the consequences it entails have been placed with greater attention, since the two endorheic plains subject to flooding are surrounded by a quarter of the wind turbines in the area concerned. From what has been verified, these wind turbines seem did not have any direct effect on the hydrogeological behavior of these endorheic areas and on the quality of the groundwater.

In other hydrogeological complexes, such as the Scaglia Formation, groundwater circulation is very limited; these terrains act as an aquiclude and constitute an obstacle to the more abundant and rapid water circulation that occurs in the karstified crystalline limestone. In the latter, the network of conduits is partly well developed and determines a typically karst behavior, with peaks of flow rate in the such as for the Sant'Elmo, Ammeri and Le Grotte springs. In other springs, the network of conduits is less interconnected, and the spring hydrographs appear smoothed respect to the inputs of precipitation; in this case their behavior is more similar to that of a porous medium. In the areas close to these springs, the number of wind turbines is decidedly less frequent and this could have a negligible impact on groundwaters.

The presence of a deep groundwater circulation in the karst terrains is attested by the experience of an oil drilling in the sixties, near the Ammeri spring (in the municipality of Morcone); during the drilling of the well a confined saturated karst aquifer was reached, causing a permanent rising of water due to artesian condition of the groundwater. The oil perforation stopped, the well was tapped and joined to the local aqueduct system, namely Coccimonti spring. It is evident that this experience attests the presence of a deep groundwater circulation, sometimes even under pressure due to the presence of the Scaglia Formation.

The hydrogeological cross-section in Figure 8 shows the model of groundwater circulation derived for the study area from geological data and results of tracer test. The main recharge area of the karst aquifer, corresponding to the main endorheic basins (Lagospino, Piano Moia and Lepre Basins), feeds all the springs located radially both towards the SE towards the Lente river (Acqua del Campo spring), and towards the NE in direction of the Tammaro river (Ammeri Spring), as well as towards the main addresses of the springs located towards the E (S. Elmo and Le Grotte di Pontelandolfo). A rapid groundwater circulation process in the area, characterized by a network of conduit connecting sinkholes and karst springs. The presence of faults and aquitard cause a progressive lowering of water table to the east.



Figure 8. Hydrogeological section (trace in Figure 2) showing the groundwater circulation between the recharge area (upstream endorheic basins) and the main springs. Some faults or heterogeneity of the aquifer determine the progressive lowering towards the E of the water table. The system of underground ducts hypothesized in the karst complex schematizes the connection between the main sinkholes and the springs.

6. Conclusions

The hydrogeological investigations conducted in this area of the eastern Matese made it possible to define the main characteristics of the groundwater circulation. The area is characterized by a series of summit endorheic basins that feed through a network of karst conduits numerous springs with a modest flow, many of which are used as water supplies for drinking purpose. In this area, a large number of wind turbines have been located during recent years, and raised worries on possible degradation of the groundwater quality. The monitoring processes on groundwater attempts to highlight the anomalies of water flow and quality following the installation of the wind farms; however, specific groundwater quality analyses are not systematically available before the wind farm construction. The chemical and physical groundwater analyses carried out during and after the wind farm construction do not provide any anomalous value beyond the range of the current legislation. In addition, the phenomenon of turbidity of some spring waters, indicated by the municipalities supplied by the spring waters, as a possible impact of the wind farms, is connected with the karst and silico-clastic nature of the terrains in the study area and it was already known historically.

The preliminary results have provided further knowledge about the groundwater circulation in a complex karst system and allows to improve awareness of the safety and impact of the wind farms in this area. This knowledge could improve the positive perception of these wind farms by the communities, especially if there is more participation of the local community in these important investment in the territory, trying to obtain higher benefit both from energy produced.

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