



# Article TDEM Soundings as a Tool to Determine Seasonal Variations of Groundwater Salinity (Villafáfila Lakes, Spain)

Pedro Huerta <sup>1,\*</sup>, Pedro Carrasco-García <sup>2</sup>, Ildefonso Armenteros <sup>3</sup>, Clemente Recio <sup>3</sup>, Javier Carrasco-García <sup>4</sup> and Esther Rodríguez-Jiménez <sup>3,5</sup>

- <sup>1</sup> Dpto. Geología, Escuela Politécnica Superior de Ávila, Universidad de Salamanca, Av. Hornos Caleros, n° 50, 05003 Ávila, Spain
- <sup>2</sup> Dpto. Ingeniería Cartográfica y del Terreno, Escuela Politécnica Superior de Ávila, Universidad de Salamanca, Av. Hornos Caleros, n° 50, 05003 Ávila, Spain
- <sup>3</sup> Dpto. Geología, Facultad de Ciencias, Universidad de Salamanca, Pza. de la Merced S/N, 37008 Salamanca, Spain
- <sup>4</sup> Técnicas Geofíscas, S.L. Paseo de San Roque 21, 3°1, 05003 Ávila, Spain
- <sup>5</sup> Confederación Hidrográfica del Duero, Avda. de Italia, 1, 37007 Salamanca, Spain
- \* Correspondence: phuerta@usal.es

Abstract: Interaction between groundwaters with different salinities and lakes show seasonal variations driven by changes in precipitation and evapotranspiration. In the vicinity of Villafáfila lakes, local fresh and brackish regional groundwaters feeds the lakes, forming a brine in the lake sediments aquitard. Two TDEM surveys (summer 2019 and winter 2020) were carried out. Five TDEM soundings were acquired at the same location for each survey, forming a profile from the hills to the lake-shore. Simultaneously to the TDEM surveys, electric conductivity of lake water and groundwater was measured. The resistivity boundary between the local fresh (10–35 Ohm/m) and regional brackish groundwater (2–5 Ohm/m) is well marked at 600 m above sea level (masl) below the hills, and at 650 masl below the lowlands surrounding the lakes. During the summer, fresh-brackish groundwater interphase rises due to evaporative pumping occurring in the lowlands. This increases groundwater salinity close to the terrain surface favoring precipitation of halite efflorescences. Annual record of EC in a piezometer confirms the summer ascendant of the brine contained in the lake aquitard. TDEM sounding is fast and simple technique to monitor seasonal variations in fresh-brackish groundwater interphase and to detect possible salinization of consumption wells and environmental changes.

Keywords: electromagnetism; electric conductivity; duero; groundwater; wetland; saline

# 1. Introduction

Many lakes show interactions between their waters and groundwaters which sometimes have different salinities, densities, and compositions [1–4]. Time domain electromagnetism (TDEM) is a geophysical technique that is able to determine the lateral and vertical (depth) variations in electric resistivity ( $\rho$ ) of the subsoil. Since the beginning of its application, TDEM has proven useful in research fields such as hydrogeology [5,6], mining [7], underground environmental pollution [8], and archaeology [9]. TDEM technique is useful to identify the interface of groundwaters with different salinities due to its high capacity to discriminate between units with high electric conductivity (EC) [10–13]. The dynamics of groundwaters and the lake-groundwater interaction can show seasonal and multi-annual changes due to the variations in evapotranspiration and precipitation along the year. Such variability can result in lateral and vertical changes in ground- and lake-water salinity and circulation [14]. Villafáfila lakes in Zamora province (Spain) are brackish to saline lakes located in a saline grassland. These lakes are protected by several environmental protections such as Natural Park, area of special protection for birds, and a Site of Community Interest (SCI) of the European Union, and are included in the intergovernmental RAMSAR treaty



Citation: Huerta, P.; Carrasco-García, P.; Armenteros, I.; Recio, C.; Carrasco-García, J.; Rodríguez-Jiménez, E. TDEM Soundings as a Tool to Determine Seasonal Variations of Groundwater Salinity (Villafáfila Lakes, Spain). *Water* 2022, *14*, 2402. https:// doi.org/10.3390/w14152402

Academic Editor: Ryan Bailey

Received: 6 July 2022 Accepted: 29 July 2022 Published: 2 August 2022

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**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/). for protection of wetlands. These lakes are wintering place for migrant birds such as ducks and geese, and host one of world's largest populations of Great Bustard (*Otis tarda*) [15,16]. The aim of this study is to characterize, by means of TDEM surveys, the margins of the Salina Grande lake in Villafáfila, during both the dry and wet seasons and to compare simultaneously the  $\rho$  data with the EC of lake and groundwaters. This characterization is of interest for correlating the variations in soil and water salinity with faunal and plant changes. The location of the saline-freshwater interface will serve to the local and regional stakeholders to identify the areas and maximum depths to pump fresh groundwaters for human consumption.

## 2. Study Area

Villafáfila lakes are located in the northwestern part of the Duero river hydrological basin in northern Spain (Figure 1A), on Cenozoic sedimentary rocks that constitute a great aquifer system, with groundwaters flowing from the periphery of the basin toward the Duero river that flows westwards, to the Atlantic Ocean, along the central axis of the basin [17,18].



**Figure 1.** Location of the Duero hydrological basin and the Villafáfila basin. (**A**) Digital elevation model of the Duero hydrological basin and reference piezometry obtained from wells deeper than 200 m (purple lines). (**B**) Geological map and schematic stratigraphic section of the Villafáfila lakes basin. Location of the TDEM profiles represented in Figure 3 is marked with an orange line, and the different sounding sites with red squares. Note that Culebra Fm. crops out in the southwestern part of the map.

#### 2.1. Climate

Villafáfila has a semi-arid, Continental Mediterranean climate, characterized by cold and wet winters (November–February) and hot and dry summers (June–September). During the winter, average monthly temperatures are about 4 °C, but minimum temperatures are commonly below zero. During the summer, average monthly temperatures are about 22 °C [19]. Mean annual evaporation is 720 mm and real evapotranspiration is 237 mm. Mean annual precipitation is 330 mm, largely concentrated from October to May. During this wetter period, when precipitation exceeds evapotranspiration, soil surplus occurs; the aquifer is recharged and the lakes fill up. On the other hand, during the summer, when evapotranspiration exceeds precipitation, the soils suffer water deficit and the lakes dry out [20].

## 2.2. Hydrogeology

Villafáfila lakes are brackish to saline lakes that occur in the Salado river valley, a tributary of the Valderaduey river, which discharges downstream into the Duero river. Villafáfila lakes occur in a flat area at 677 m above sea level (masl) surrounded by gently sloping hills that reach up to 730 masl [21]. The Miocene rocks outcropping in the area (Facies Tierra de Campos and Facies Aspariegos Units; mainly siliceous/litharenite sand-stones and siltstones) constitute the main local aquifer, that belongs to the large Duero basin aquifer system. The clayey-sandy Quaternary lake deposits behaves as an aquitard at the bottom of the lakes (Figure 1B).

The water of the lakes comes mainly from the rain, but the ions dissolved are provided by shallow fresh groundwaters coming from the hills and regional deep brackish groundwaters. In Villafáfila, the regional component of the groundwater flow comes from the northeast (Figure 1A) and shows an increase in salinity southwestwardly [17]. Deep brackish groundwaters raise toward the lakes bottom and the lowland areas due to the presence of a near surface Paleozoic metamorphic basement elevation. This elevation is perpendicular to the general flow and locates in the southern zone of the Salina Grande Lake (Figure 1B) [20]. The basement is constituted by the Culebra Fm. and the Salamanca sandstone Fm. which does not crop out in the Villafáfila basin.

Groundwaters below the hills are of the calcium-bicarbonate type, with low salinities (TDS = 250 mg/L). Deep groundwaters, however, are sodium-chlorine waters with high salinities all year round (TDS = 3200-5000 mg/L). Lake waters have sodium-chlorine composition and show salinity variations along the year, with values ranging from 800-6200 mg/L. The brine contained in the Quaternary lake aquitard has salinities of 12,000-27,000 mg/L TDS [20].

#### 3. Methodology

Two TDEM surveys were carried out, one during the winter (February 2020) and the other during the summer (July 2019) at the same five sounding sites. Soundings were placed aligned in a NNW-SSE trend, from higher in the hills to the lowlands around Salina Grande lake, close to the Villafáfila village (Figure 1B). The position of the different soundings was chosen to evaluate the distribution of salinities from the upper part of the hills (700 masl), where local groundwaters recharge, to the lowland areas (677 m), where the regional groundwaters discharge and mixing processes occur [20,22]. The soundings were placed 200–600 m apart from each other, at the same positions for the summer and winter surveys, to evaluate the  $\rho$  variations along the year. The surveys were carried out by the company Técnicas Geofísicas S.L. with a TerraTEM (MONEX GeoScope

Co., Ltd., Melbourne, Australia) transient electromagnetic survey system. Time domain electromagnetic sounding (TDEM) consists on injecting a constant electric current into a cable loop (transmitter coil). The transmitter loop generates an electromagnetic wave that propagates into the subsoil through the subsurface when the electric current is suddenly interrupted [23–25]. As the electromagnetic energy finds different materials underground, it induces eddy currents that generate secondary electromagnetic fields. These secondary electromagnetic fields are measured on the surface by a receiver loop or magnetic antenna and recorded as the induced energy diffuses into the earth. The resistivity of the subsurface materials depends on the rate of diffusion. The array consisted on  $50 \times 50$  m square loops in the mode of coincident loops. Several 10 ms measurements were performed in every site, varying the number of stacks (up to 3000 stacks) to minimize electromagnetic noise. Similar arrangements have been performed for hydrogeological research [20,26,27]. Management of the obtained data and its conversion from apparent to real resistivities were made with IX1D V3 (INTERPEX Co., Ltd., Golden, CO, USA). A smooth model was generated for every TDEM site measured. Occam's inversion [28] was used to obtain the 30-40 layers smooth model (Figure 2). The obtained resistivities were used to construct the NNW-SSE profiles (Figure 3). Alongside TDEM survey acquisition, hydrogeological field measurements (groundwater level, temperature, and electric conductivity) were made in the Salina Grande lake, springs, boreholes and dug wells located closest to the TDEM sites (see next sections for more details). EC and temperature were measured with a Hanna HI 9835 m and probe. SGR-3 piezometer was monitored at 8 m depth with a conductivity, temperature, depth data logger (CTD) (OTT Hydromet Inc., Loveland, CO, USA). Local piezometry was measured during the summer of 2018 in dug wells screened at depths lower than 40 m. The data were interpolated with a convergent interpolation method and later manually redrawn to avoid inconsistencies due to the lack of data in certain areas. The piezometer SGR-3 is screened below the aquitard, and overflows at 0.4 m above lake bottom.



**Figure 2.** Example of TDEM soundings. (**A**) SEDT 6, (summer survey). Apparent resistivity curve versus time (**left**), Smooth inversion model (**right**). (**B**) SEDT 6BIS, (winter survey). Apparent resistivity curve versus time (**left**), Smooth inversion model (**right**).



**Figure 3.** TDEM profiles measured from the hills to the lowlands and Salina Grande lake shore. Location in Figure 1. EC values measured in lake waters, dug wells and springs close to the profile path have been projected (Table 1). (**A**) TDEM profile acquired during the winter survey (13/02/2020), (**B**) TDEM profile acquired during the summer survey (27/07/2019). Note that red colors indicates low resistivity while blue colors means high resistivity values.

## 4. Results

4.1. Time Domain Electromagnetic Results

4.1.1. Winter Geoelectric Profile

Resistivities vary from 1 to 35 Ohm/m. The lowest values have been registered in the lowlands surrounding the lakes while the highest values have been measured in the upper part of the hills (SEDT-6BIS and 7BIS) (Figure 3A). 2D profiles show a decrease in  $\rho$  with depth in the soundings located in the upper parts of the hills (SEDT-6BIS and 7BIS) showing four geoelectric units that have been named from top to bottom as U-1, U-2, U-3,

and U-4, in order to facilitate the description. U-1 appears in the upper part of the hills (700–680 masl), has  $\rho$  values ranging from 25 to 35 Ohm/m, and extends toward the toe of the hills. U-2 appears in the lowlands surrounding Salina Grande and in the lake shore and shows low resistivity values ( $\rho < 5$  Ohm/m) in the upper part of the terrain. U-3 locates generally at an intermediate position between U-1 and U-4, below the upper parts of the hills (SEDT-6BIS and 7BIS), and between U-2 and U-4 in the lake shore. For the winter survey U-3 locates very close to the terrain surface (SEDT-3BIS and 4BIS). U-3 has  $\rho$  ranging from 10 to 25 Ohm/m and appears at 680–600 masl, below the hills and at 685–640 masl at the lowlands. U-4 appears at the lower part of the profile and is present at all sites; below the hills it is between 600–500 masl (SEDT-7BIS) and below the lake shore between 640–500 masl (SEDT-4BIS,) and has  $\rho$  lower than 5 Ohm/m (Figure 3A). The boundary between the U-3 and U-4 is almost horizontal between SEDT-6BIS and 7BIS (600 masl) and has a gentle slope between SEDT-6BIS and 3BIS. Below SEDT-3BIS and SEDT-4BIS is horizontal again.

#### 4.1.2. Summer Geoelectric Profile

Resistivities measured during the summer survey have similar values (2-35 Ohm/m) to those recorded during the winter. The lowest  $\rho$  is registered in the lowlands surrounding Salina Grande and at the lake shore (SEDT-5, 4, 3) and the highest is recorded in the upper parts of the hills (SEDT-6 and 7), in the upper zone (Figure 3B). As in winter, in the upper parts of the hills there is a decrease in  $\rho$  from the upper parts of the terrain where geoelectric U-1 occurs toward the lower parts where U-4 appears. The boundary between U-1 and U-3 deepens slightly from the upper parts of the hills (SEDT-7) toward their toe (SEDT-6), but the boundary between U-3 and U-4 deepens 20 m from SEDT-7 (600 masl) to SEDT-6 (580 masl). The slope of this boundary is one of the main differences with the winter geoelectric profile, which is horizontal. In the lowland areas (SEDT-5, 4, 3) the upper part of the terrain (U-2) shows low  $\rho$  values (lower than 5 Ohm/m) and in comparison with the  $\rho$  data of the winter survey, U-2 extends from the lake shore (SEDT-4) to SEDT-5. U-3 has a similar thickness in SEDT-3, 4, and 5 and the  $\rho$  values are slightly lower (18 Ohm/m) towards the lake shore (SEDT-4). The interface between U-3 and U-4 in the lowland areas locates 20 m shallower in SEDT-5 (640 masl) relative to the winter survey, when it was located at 620 masl (SEDT-5BIS) (Figure 3). The geometry of the interface between U-3 and U-4 in the 2D profile shows a steeper slope between SEDT-6 and SEDT-5, in the summer (Figure 3B) than in the winter profile (Figure 3A).

#### 4.2. Hydrogeological Data

#### 4.2.1. Piezometry

Piezometry in the Duero hydrological basin indicates that regional groundwater flow in the northern half of the basin has a southwestward component, from recharge areas located in the Cantabrian Mountains and the northern edge of the Duero basin to the valley of the Duero river (Figure 1A) [17,18]. Local deep and brackish groundwater discharge occurs in Villafáfila due to the existence of an elevation of the Paleozoic impermeable basement [20].

Local piezometry also indicates a southwestern component of groundwater flow in the watershed of the Salado river, parallel to the river flow. The hills that surround the lakes have a local component flowing from the upper part of the hills toward the lowlands around the lakes (Figure 4). In the upper part of the hills the groundwater table locates about 700 masl, with depths between 5 and 10 m. In the lowlands around the lakes the groundwater table is at 680 masl, 10–30 cm below the surface. The hydraulic gradient in the upper part of the hills is about 0.1 and in the lowlands is about 0.001. The vertical component of the groundwater flow is downwards in the upper part of the hills, but it is upwards at its toe and in the lowlands (Figure 4). This is evidenced by the differences in hydraulic head between boreholes screened at more than 40 m depth and wells and dug wells screened at depths shallower than 15 m. In the upper part of the hills hydraulic head is lower in boreholes (screened > 40 m) than in dug wells (screened < 15 m). On the contrary, at the toe of the hills and in the lowlands hydraulic head in wells, some of which are flowing wells, is higher than in dug wells [20]. The occurrence of springs around Salina Grande lake shore is an additional evidence for the ascendant component of groundwater flow. Seasonal variations produce minor changes in groundwater level (about 10 cm) in the upper part of the hills. At the toe of the hills many springs dry out during the summer, and groundwater and Salina Grande lake level decrease by about 30–40 cm (Figure 4). Salina Grande lake is normally dry during the summer (from  $\approx$  mid-July till October), although some years stays dry till December, when soils have surplus water and evapotranspiration is low. Lake level reaches maximum depth of 35 to 40 cm during the spring (April–May) (Figure 5). In SGR-3 piezometer, located in the lake shore (Figure 4), hydraulic head overflows with a minimum discharge at 0.4 m above lake floor. Some springs and flowing boreholes, all of them with brackish Na-Cl regional waters, maintain a constant discharge and temperature all year round.



**Figure 4.** Water table map (blue lines) obtained from wells screened at depths below 40 m. Location of the TDEM profiles (orange line) the sounding sites, EC measurement sites and vertical components of groundwater flow are also indicated (see legend). Red lines indicate the altimetry. Black lines indicate the location of profile 1 and 2 in Figure 7.



**Figure 5.** (A) Precipitation, minimum, and maximum temperatures measured in Villafáfila meteorological station along the 2020–2021 hydrologic year. (B) Record of the EC and temperature at 8 m depth in piezometer SGR-3. Hydraulic head in SGR-3 is constant and overflows to 0.4 m above lake bottom. Lake level in Salina Grande lake is marked by yellow points.

## 4.2.2. Electric Conductivity

Electric conductivity (EC) of shallow groundwaters in the Villafáfila area show an increasing trend from the lowest values measured in the upper parts of the hills, toward the lowlands surrounding the lakes and to the lake itself (Figure 6), where a brine occurs within the lake sediment's aquitard [20]. EC data, measured in the summer of 2018, were used to construct with a convergent interpolation method the EC map (Figure 6), that shows the lateral changes in this parameter. EC was also measured in lake waters, springs and dug wells in locations closest to the TDEM soundings at the time of the summer and winter surveys (in July 2019 and in February 2020) (Table 1). EC in the shallow groundwaters occurring below the upper part of the hills are between  $300-600 \,\mu$ S/cm, with no significant

variations along the year (Table 1). Towards the toe of the hills and lowlands around the lakes, EC of shallow groundwaters increases to 1000–6000  $\mu$ S/cm (Figure 6). The brine within the lake sediment 's aquitard has values reaching 42,000  $\mu$ S/cm during the summer, when the lake is dry. Lake waters in Salina Grande vary along the year from about 1000 to 20,000  $\mu$ S/cm (Figure 6). Low EC values in lake waters are registered from February to May. On the other hand, high EC values in lake waters occur at the end of June or along July when the lake is concentrated by evaporation (Table 1). During December and January, there is an increase in lake salinity, reaching values of 10,000  $\mu$ S/cm. Groundwaters sampled from boreholes screened below 40 m has EC values ranging from 3000–6000  $\mu$ S/cm, and show minor variations along the year [20].



**Figure 6.** EC map of the surroundings of the Villafáfila lakes. Location of TDEM profile and soundings are marked with an orange line and red squares respectively.

**Table 1.** Electric conductivity (EC) values measured during the TDEM surveys in the lake, dug wells, and springs close to the different soundings. See location in Figure 4.

Name	Category	Location	Date	EC (µS/cm)
Salina Grande	Lake	Lake	27 July 2019	36,200
Salina Grande	Lake	Lake	13 February 2020	7222
12-F-002	Spring	Low lands	27 July 2019	4550
12-F-002	Spring	Low lands	13 February 2020	3641
F-003	Spring	Toe hills	27 July 2019	Dry
F-003	Spring	Toe hills	13 February 2020	1719
30-P-006	Dug well	Upper part hills	27 July 2019	350
30-P-006	Dug well	Upper part hills	13 February 2020	537

The electric conductivity record of SGR-3 piezometer along 2020–2021 has been measured at 8 m depth, below the aquitard (Figure 5). It shows values that vary between 8760  $\mu$ S/cm and 9030  $\mu$ S/cm (Figure 5). The lowest values occur during October while the highest ones are recorded in May and June (Figure 5). During the summer there is a trend toward decreasing EC, till the end of September–October. From October to June there is an increasing trend in EC. Groundwater temperature in SGR-3 has little variations along the year, from 13.5 °C to 14.7 °C. The highest temperatures occur during December and January, when the lowest air temperatures occur. On the other hand, the lowest groundwater temperatures in SGR-3 occur during May and June (Figure 5).

#### 5. Discussion

#### 5.1. Aquifer System Characterization

TDEM resistivity data and electric conductivity (EC) values of lake waters and groundwaters show a consistent spatial distribution. Field geological mapping and well logs indicate that the upper part of the Cenozoic rock record is a sandstone aquifer [18,29,30]. Background resistivity values measured in the Miocene aquifer in the southern part of the Duero aquifer system are about 20 Ohm/m for similar lithologies [26]. Estimates of formation  $\rho$  using the measured groundwater EC (Table 1) and Archie's Law [31] for water saturated units with porosities of 0.35 for the Miocene unconsolidated sandstones and 0.2 for the Quaternary lake mudstones using Archie's standard parameters (a = 1.2; m = 1.3) are shown in Table 2. Estimated formation resistivity values are similar to those obtained in the TDEM surveys except for those measured in the proximities of dug well 30-P-006 (SEDT-7 and 7BIS), for which the calculated formation resistivity of 87.5 Ohm/m is notably higher than the  $\rho$  measured (25 Ohm/m) for U-1 in the SEDT-7 sounding. This is probably due to the existence of a 7 m thick non-saturated zone above the groundwater table, that if were considered in calculations (Sw-n = 0.3) would reduce the formation resistivity. U-1 is interpreted as the non-saturated part of the Miocene aquifer in the hills (Figure 7). Previous geophysical surveys have revealed the existence of an elevated threshold in the Paleozoic metamorphic basement that forces regional brackish groundwater flow to rise [20] (Figure 7). TDEM profiles perpendicular to the lake's axis (Figure 3) show the occurrence of brackish regional groundwaters (<8 Ohm/m) below 600–550 masl (U-4). The upper parts of the profiles with  $\rho$  ranging between 20 to 10 Ohm/m are interpreted as the local fresh groundwaters recharged on the hills (U-3). Piezometry indicates lateral groundwater flow from the hills to the lowlands and to the lake. TDEM profiles evidence the gradual decrease in  $\rho$  from the upper part of the hills towards the lowlands. This is consistent with the increase in EC of groundwaters and is interpreted as an increased contribution of the brackish regional groundwaters that mix with fresh groundwaters locally recharged in the hills.

Archie's formula that refers to tortuosity and cement respectively.								
EC (µS/cm)	Site	Sw-n	φ (Porosity)	а	m	ρf (Ohm/m)		
537	30-P-006	1	0.35	1.2	1.3	87.5		
1719	F-003	1	0.35	1.2	1.3	27.3		
3641	12-F-002	1	0.35	1.2	1.3	12.9		
7222	Salina Grande	1	0.35	1.2	1.3	6.5		
36,200	Salina Grande	1	0.2	1.2	1.3	2.7		

**Table 2.** Conversion of different EC values measured in waters into formation resistivities ( $\rho$ f) using Archie's law [31]. Sw-n is the water saturation,  $\varphi$  is the porosity, and "a" and "m" are the parameters of Archie's formula that refers to tortuosity and cement respectively.



**Figure 7.** Schematic cross sections of the Villafáfila geological structure and groundwater flow. Location of (**A**) Profile 1 and (**B**) Profile 2 are indicated in Figure 4. Geological reconstruction is based on the data of [20].

Underneath the lowlands and the Salina Grande lake bottom, the low  $\rho$  values in the upper part of the profile (U-2) are interpreted as a concentrated brine contained within the Quaternary lake sediment aquitard [20] and highly saline capillary waters and the halite efflorescences that form within the soils of the lake margins by evapotranspirative concentration (Figure 7).

## 5.2. Seasonal Changes in Groundwater

TDEM profiles show a similar  $\rho$  distribution pattern during summer and winter, but there are some differences that are related to the different hydrological processes occurring in Salina Grande lake and its surroundings. At the lake (SEDT-4BIS)  $\rho$  values in the upper part of the profile are low (r < 5 Ohm/m) during winter, due to the occurrence of brackish waters and the presence of the brine contained in the lake sediment aquitard (U-2 in Figure 3). During summer this low  $\rho$  zone (U-2) extends to the lowlands surrounding the lake. This is interpreted as an effect of groundwater concentration by evaporation in the upper part of the vadose-capillary zone in an area with mixing of local and regional groundwaters. This agrees with the occurrence of halite efflorescences on the surface of the lowland areas. The summer profile (Figure 3B) also shows a rise of the interphase between the local groundwaters coming from the hills (U-3) and the regional brackish groundwaters (U-4), in the lowland areas. The annual record of SGR-3 piezometer (at 8 m depth) shows the highest EC values in May-June decreasing during the summer until reaching the minimum in October (Figure 5). This decrease in EC (Figure 5) is interpreted as the rise of the interphase between the brine (U-2) and the waters coming from the hills, that in the lake shore are mixed with the regional brackish groundwaters (U-3). The rise of the interphase is favored by evaporation pumping and capillary rise in the lake aquitard. This is consistent with the summer rise of the U-3/U-4 interphase observed in the TDEM profiles (Figure 3). In contrast, at the beginning of winter the salinity increases not only in SGR-3 but in the lake waters as well due to the dissolution of halite efflorescences in the lowland areas and the aquifer recharge that favors the transport of the groundwaters and their dissolved salts to the lake area. This processes favor the lowering of the U-2/U-3 interphase in the lake area. Similar processes have been described in other saline lakes where the most soluble salts, mainly halite, can show precipitation-dissolution cycles [32,33]. Other less soluble mineralogical phases can remain, as it occur with the loose calcite cementation observed in the lacustrine mudstones.

## 5.3. Implications for Groundwater Use

TDEM identifies the fresh groundwater domain and is an important tool to locate its contact with brackish or saline groundwaters. Many research papers have highlighted the importance of TDEM soundings to identify groundwater resources [34–36]. In Villafáfila, where regional brackish groundwaters occur in many boreholes that then have to be abandoned, it is important to identify the mentioned interphase, especially for the construction of new boreholes for human consumption. TDEM results reported in this paper indicate that the best places to drill boreholes for human consumption of groundwater are the upper part of the hills, and that the lowlands surrounding the lakes should be avoided. The maximum depth of boreholes should not reach below 600 masl on the hills, which is the depth of the fresh (U-3) and brackish groundwaters (U-4) interphase (Figure 3). Seasonal variations in groundwater dynamics do not affect severely the position of this boundary below the hills, but at the toe of the hills and in the lowlands this boundary can rise significantly during the summer. If intense groundwater pumping is planned in the area, monitoring the fresh-brackish groundwater boundary with TDEM is recommended. The collected data published in this paper and other previous hydrogeological, hydrochemical, and isotopic research in the area could be used to construct a hydrogeological model that will contribute to understand the role of groundwaters in the changes observed in this ecosystem.

## 6. Conclusions

TDEM profiles in the surroundings of Villafáfila lakes allowed identifying the lateral and vertical variations in terrain resistivity, which are mainly dominated by variations of groundwater salinity. The occurrence of high  $\rho$  zones below the hills (U-1 and U-3) show that these zones, dominated by fresh groundwaters, are the main recharge zones of the local aquifer. This is consistent with the piezometry which indicates that local groundwater flows go from the upper part of the hills toward the low lands and the lakes. The low  $\rho$ zones close to the surface toward the Salina Grande correspond to the brine contained in the Quaternary lake sediments aquitard (U-2). The deeper part of the terrain explored by the TDEM soundings shows low  $\rho$  that represent the regional brackish groundwater flows. The occurrence of a structural relief that elevates the metamorphic basement of the basin perpendicularly to regional groundwater flows forces the flow to increase, favoring the contribution of brackish groundwaters to the Villafáfila lakes [20,21].

Two TDEM surveys during summer (dry season) and winter (wet season), undertaken in the same location, from the hills toward the Salina Grande lake, have shown that there are some differences in  $\rho$  which are the response to the hydrological processes occurring in the lake vicinity. The summer expansion of the low  $\rho$  area (U-2) close to the surface in the lowland areas and in the lake is produced by the increase in salinity favored by the evapotranspiration of surficial groundwaters and from the capillarity zone. This evaporative groundwater pumping also produces the rise of the interphase between local fresh groundwaters and the regional brackish groundwaters. The continuous record of EC and temperature in the piezometer SGR-3 confirms the rise of the interphase between the saline brine in the aquitard and the local fresh groundwaters.

EC of groundwaters was measured alongside TDEM sounding acquisition. This has allowed correlating the  $\rho$  values of the terrain with those of water and groundwater salinity. The correlation between the measured EC of groundwaters and the  $\rho$ f values obtained from Archie's law formula is consistent with the  $\rho$  values obtained from TDEM soundings. This means that TDEM sounding is an excellent tool to monitor the seasonal changes of groundwater salinity. This can help to prevent aquifer salinization problems. EC map reveals that surficial groundwaters in the low lands has values between 6000 and 9000  $\mu$ S/cm and the brine below the Salina Grande Lake reaches 42,000  $\mu$ S/cm.

The best places in the area to obtain fresh groundwaters are the hills that surround the Villafáfila lakes. Below 600 masl in the hills, brackish regional groundwaters are present. In the low lands, the brackish regional groundwaters can be found below 640 masl.

Author Contributions: Conceptualization, P.H.; methodology, P.H., P.C.-G. and J.C.-G.; software, P.C.-G. and J.C.-G.; validation, P.H. and P.C.-G.; investigation, P.H., P.C.-G., I.A., C.R., J.C.-G. and E.R.-J.; resources, E.R.-J.; data curation, P.C.-G. and J.C.-G.; writing—original draft preparation, P.H. and P.C.-G.; writing—review and editing, P.H., P.C.-G., I.A. and C.R.; project administration, P.H.; funding acquisition, P.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** This paper is part of the Research Project I+D+i/ PGC2018-094566-B-C21, supported by the MCIN/ AEI/10.13039/501100011033/ and FEDER "Una manera de hacer Europa".

Data Availability Statement: Not applicable.

**Acknowledgments:** The research acknowledges the Consejería de Fomento y Medio Ambiente, Junta de Castilla y León, and the Casa del Parque (Villafáfila) for permission to do fieldwork in the Villafáfila Natural Reserve. Authors acknowledge the anonymous reviewers and the editor of water for the improvement of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

## References

- Kohfahl, C.; Rodriguez, M.; Fenk, C.; Menz, C.; Benavente, J.; Hubberten, H.; Meyer, H.; Paul, L.; Knappe, A.; López-Geta, J.A.; et al. Characterising flow regime and interrelation between surface-water and ground-water in the Fuente de Piedra salt lake basin by means of stable isotopes, hydrogeochemical and hydraulic data. J. Hydrol. 2008, 351, 170–187. [CrossRef]
- Cartwright, I.; Hall, S.; Tweed, S.; Leblanc, M. Geochemical and isotopic constraints on the interaction between saline lakes and groundwater in southeast Australia. *Hydrogeol. J.* 2009, 17, 1991. [CrossRef]
- Marazuela, M.A.; Vázquez-Suñé, E.; Custodio, E.; Palma, T.; García-Gil, A.; Ayora, C. 3D mapping, hydrodynamics and modelling of the freshwater-brine mixing zone in salt flats similar to the Salar de Atacama (Chile). J. Hydrol. 2018, 561, 223–235. [CrossRef]
- Sanz, D.; Valiente, N.; Dountcheva, I.; Muñoz-Martín, A.; Cassiraga, E.; Gómez-Alday, J. Geometry of the modelled freshwater/salt-water interface under variable-density-driven flow (Pétrola Lake, SE Spain). *Hydrogeol. J.* 2022, 30, 975–988. [CrossRef]
- Rhoades, J.; Raats, P.; Prather, R. Effects of liquid-phase electrical conductivity, water content, and surface conductivity on bulk soil electrical conductivity. Soil Sci. Soc. Am. J. 1976, 40, 651–655. [CrossRef]
- Danielsen, J.E.; Auken, E.; Jørgensen, F.; Søndergaard, V.; Sørensen, K.I. The application of the transient electromagnetic method in hydrogeophysical surveys. J. Appl. Geophys. 2003, 53, 181–198. [CrossRef]
- Jang, H.; Kim, H.J. Mapping deep-sea hydrothermal deposits with an in-loop transient electromagnetic method: Insights from 1D forward and inverse modeling. J. Appl. Geophys. 2015, 123, 170–176. [CrossRef]
- Metwaly, M.; Elawadi, E.; Moustafa, S.S.R.; Al Arifi, N.; El Alfy, M.; Al Zaharani, E. Groundwater contamination assessment in Al-Quwy'yia area of central Saudi Arabia using transient electromagnetic and 2D electrical resistivity tomography. *Environ. Earth Sci.* 2014, *71*, 827–835. [CrossRef]
- Tabbagh, A.; Dabas, M. Absolute magnetic viscosity determination using time-domain electromagnetic devices. *Archaeol. Prospect.* 1996, 3, 199–208. [CrossRef]
- 10. Goldman, M.; Gvirtzman, H.; Hurwitz, S. Mapping saline groundwater beneath the Sea Galilee and its vicinity using time domain electromagnetic (TDEM) geophysical technique. *Isr. J. Earth Sci.* 2004, *53*, 187–197. [CrossRef]

- Tchouta, K.D.; Marie, B.; Emmanuel, M.V.Y.; Guillaume, F.; Benjamin, N.N.; Nicaise, Y.; Baba, G.I.; Anatoly, L. Contribution of time domain electromagnetic and magnetic resonance soundings to groundwater assessment at the margin of lake chad basin, cameroon. J. Appl. Geophys. 2019, 170, 103840. [CrossRef]
- 12. Levi, E.; Goldman, M.; Hadad, A.; Gvirtzman, H. Spatial delineation of groundwater salinity using deep time domain electromagnetic geophysical measurements: A feasibility study. *Water Resour. Res.* 2008, 44, W12404. [CrossRef]
- Flores Avilés, G.P.; Descloitres, M.; Duwig, C.; Rossier, Y.; Spadini, L.; Legchenko, A.; Soruco, Á.; Argollo, J.; Pérez, M.; Medinaceli, W. Insight into the Katari-Lago Menor Basin aquifer, Lake Titicaca-Bolivia, inferred from geophysical (TDEM), hydrogeological and geochemical data. J. S. Am. Earth. Sci. 2020, 99, 102479. [CrossRef]
- Yihdego, Y.; Webb, J. Modelling of seasonal and long-term trends in lake salinity in southwestern Victoria, Australia. J. Environ. Manag. 2012, 112, 149–159. [CrossRef] [PubMed]
- 15. Martinez, C. Daily activity patterns of Great Bustards Otis tarda. Ardeola 2000, 47, 57–68.
- 16. Nilsson, L.; Kampe-Persson, H. Changes in migration and wintering patterns of greylag geese Anser anser from southernmost Sweden during three decades. *Ornis Svec.* **2018**, *28*, 19–38. [CrossRef]
- 17. IGM. Investigación Hidrogeológica de la Cuenca del Duero: Sistemas nº 8 y 12; IGME: Madrid, Spain, 1980; p. 75.
- IGME-DGA. Apoyo a la Caracterización Adicional de las Masas de Agua Subterránea en Riesgo de no Cumplir los Objetivos Medioambientales en 2015. Demarcación Hidrográfica del Duero. Masa de agua Subterránea 31 Villafáfila; IGME: Madrid, Spain, 2009; p. 84.
- AEMET. AEMET Open Data. Benavente. Available online: http://www.aemet.es/es/datos\_abiertos/AEMET\_OpenData (accessed on 1 July 2020).
- Huerta, P.; Armenteros, I.; Recio, C.; Carrasco-García, P.; Rueda-Gualdrón, C.; Cidón-Trigo, A. The origin of the saline waters in the Villafáfila lakes (NW Spain). A hydrogeological, hydrochemical, and geophysical approach. *Sci. Total Environ.* 2021, 789, 147909. [CrossRef]
- Armenteros, I.; Huerta, P.; Cidón-Trigo, A.; Rueda-Gualdrón, M.C.; Recio, C.; Martínez-Grana, A. Hydrogeology of the lagunas de villafáfila area (Zamora). *Geogaceta* 2019, 66, 51–54.
- 22. Fernández Pérez, L.; Cabrera Lagunilla, M.P. Estudio Hidrogeológico de las lagunas de Villafáfila (Zamora). In *Geología Ambiental y Ordenación del Territorio. III Reunión Nacional*; Universitat de Valencia: Valencia, Spain, 1987; Volume 1, pp. 441–459.
- 23. Fitterman, D.V.; Stewart, M.T. Transient electromagnetic sounding for groundwater. Geophysics 1986, 51, 995–1005. [CrossRef]
- 24. Spies, B.R. Depth of investigation in electromagnetic sounding methods. *Geophysics* **1989**, *54*, 872–888. [CrossRef]
- 25. Nabighian, M.N. *Electromagnetic Methods in Applied Geophysics: Volume 1, Theory;* Society of Exploration Geophysicists: Houston, TX, USA, 1988.
- 26. Nieto, I.M.; Carrasco García, P.; Sáez Blázquez, C.; Farfán Martín, A.; González-Aguilera, D.; Carrasco García, J. Geophysical Prospecting for Geothermal Resources in the South of the Duero Basin (Spain). *Energies* **2020**, *13*, 5397. [CrossRef]
- Hoekstra, P.; Blohm, M.W. Case histories of time-domain electromagnetic soundings in environmental geophysics. In *Geotechnical an Environmental Geophysics: Volume II: Environmental and Groundwater*; Society of Exploration Geophysicists: Houston, TX, USA, 1990; pp. 1–16.
- Constable, S.C.; Parker, R.L.; Constable, C.G. Occam's inversion: A practical algorithm for generating smooth models from electromagnetic sounding data. *Geophysics* 1987, 52, 289–300. [CrossRef]
- 29. Martín Serrano, A.; Piles Mateo, E. Villafáfila (308). In Mapa Geológico de España y Memoria, Escala 1:15.000; IGME: Madrid, Spain, 1982.
- Martín Serrano, A.; Barba Martín, A. Manganeses de la Lampreana 340. In Mapa Geológico de España y Memoria. Escala 1:50.000; IGME: Madrid, Spain, 1979.
- 31. Archie, G.E. The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics. *Trans. AIME* **1942**, *146*, 54–62. [CrossRef]
- Yadav, D.; Sarin, M.; Krishnaswami, S. Hydrogeochemistry of Sambhar Salt Lake, Rajasthan: Implication to recycling of salt and annual salt budget. J.-Geol. Soc. India 2007, 69, 139–152.
- 33. Drever, J.I.; Smith, C.L. Cyclic wetting and drying of the soil zone as an influence on the chemistry of ground water in arid terrains. *Am. J. Sci.* **1978**, *278*, 1448–1454. [CrossRef]
- Descloitres, M.; Chalikakis, K.; Legchenko, A.; Moussa, A.M.; Genthon, P.; Favreau, G.; Le Coz, M.; Boucher, M.; Oï, M. Investigation of groundwater resources in the Komadugu Yobe Valley (Lake Chad Basin, Niger) using MRS and TDEM methods. J. Afr. Earth Sci. 2013, 87, 71–85. [CrossRef]
- 35. Amato, F.; Pace, F.; Vergnano, A.; Comina, C. TDEM prospections for inland groundwater exploration in semiarid climate, Island of Fogo, Cape Verde. J. Appl. Geophys. 2021, 184, 104242. [CrossRef]
- Martínez-Moreno, F.J.; Monteiro-Santos, F.A.; Madeira, J.; Bernardo, I.; Soares, A.; Esteves, M.; Adão, F. Water prospection in volcanic islands by Time Domain Electromagnetic (TDEM) surveying: The case study of the islands of Fogo and Santo Antão in Cape Verde. J. Appl. Geophys. 2016, 134, 226–234. [CrossRef]