Sustainability of Groundwater Resources of Weathered and Fractured Schists in the Rural Areas of Galicia (Spain)

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Research Article

Keywords: Sustainability, rural water supply, groundwater resources, schists, climate change, groundwater pollution

Posted Date: April 21st, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-438348/v1>

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Version of Record: A version of this preprint was published at Environmental Earth Sciences on February 18th, 2022. See the published version at <https://doi.org/10.1007/s12665-022-10264-5>.

Abstract

Water supply deficits in droughts, groundwater pollution and climate change are the main challenges for the sustainability of groundwater resources from hard rock aquifers in the rural areas of Galicia (Spain). Here we address the sustainability of groundwater resources of weathered and fractured schists in the rural areas of Abegondo municipality. The conceptualization of the hydrogeology of the study area includes: 1) The regolith, 2) The fractured rock layer; and 3) The underlying fresh bedrock. Groundwater flows mostly through the regolith and the fractured rock. Rainfall infiltration is the source of aquifer recharge. Groundwater discharges in seepage areas, springs and along creeks and valleys. The water table is generally shallow and shows seasonal oscillations of up to 4 m. The equivalent transmissivity ranges from 15 to 35 m²/d. Electrical resistivity tomography identifies a shallow water table and attests that the contact of the fractured rock and the fresh bedrock is highly heterogeneous. Groundwater resources were quantified with a hydrological water balance model. The mean annual recharge is approximately equal to 185 mm. Groundwater recharge at the end of the 21st century could decrease from 6% to 10% due to climate change. The decline in groundwater table could aggravate the shortages during droughts. Groundwater quality data show bacteriological and nitrate contamination due to a poor management of the manure in the fields and occasional discharges of slurry from pig and mink farms. Groundwater management and protection actions are proposed to prevent groundwater pollution and achieve a sustainable groundwater supply in the study area.

1. Introduction

The European regulations concerning the water protection and management (Directive 2000/60/EC) and the quality of water for human consumption (Directive 98/83/EC) pose a great challenge for water supply in dispersed rural communities such as those of Galicia in the northwestern corner of the Iberian Peninsula (Fig. 1) (Naves et al. 2019; 2021). The technical and economic feasibility of centralized infrastructures in these regions is severely limited by the distance to highly populated areas and the large required investments to undertake them. Local people have developed spontaneously autonomous water supply systems based on spring catchments, shallow dug wells and deep drilled wells. More than 650,000 people rely on groundwater supply from hard-rock aquifers through this kind of solutions in the rural areas of Galicia.

Improving the knowledge of the hydrogeology of hard-rock aquifers in the area is essential for the proper groundwater protection and management. Hard rocks generally show a large spatial heterogeneity in both vertical and horizontal directions, which causes large differences in the values of hydrogeologic parameters. Hard rock aquifers usually present: 1) A shallow regolith layer with clay-rich material derived from the in situ weathering of the bedrock; 2) A fractured rock layer, which often presents a dense horizontal network of fractures in the first few meters and a depth-decreasing density of subhorizontal and subvertical fractures (Taylor and Howard 2000); and 3) The fresh rock basement which is permeable only when tectonic fracture zones are present (Krasny 2002; Lubczynski and Gurwin 2005; Dewandel et al. 2006). The proposed conceptualizations of groundwater flow in hard rocks include (Selroos et al. 2002): double porosity models (Barenblatt et al. 1960), discrete fracture models (Lee and Farmer 1993; Long et al. 1982; Molinero and Samper, 2004; Molinero et al., 2004; Dong et al. 2019), parallel plate models (Bear 1993; Lee and Farmer 1993) and equivalent porous media models (Lubczynski and Gurwin 2005; Dewandel et al. 2006).

The main challenges for the sustainable groundwater supply in the rural area of Galicia include: (1) Low guarantee of water supply in dry periods, (2) Groundwater quality deterioration and (3) Deficiencies in the governance of groundwater use and waste treatment and disposal (Naves et al., 2019; Life Rural Supplies, 2020).

Previous hydrological research and water resource assessment have been performed in a small pilot watershed in Abegondo, the Abelar watershed (Fig. 1). The basin has an area of approximately 10.7 ha. It was equipped in 1997 with two meteorological stations, two piezometers and a streamflow gauging station to monitor the effects of eucalyptus plantations on surface water and groundwater resources (Soto et al. 2005; Rodríguez-Suárez et al. 2011; 2014). The results reported by Rodríguez-Suárez et al. (2011; 2014) show that fast-growing trees may reduce the availability of the water resources in dry periods, leading to a decline of the water table and the drying up of springs and small creeks.

Climate change could aggravate the current problems of water supply guarantee in the region during drought periods. Raposo et al. (2013) evaluated the impacts of climate change on groundwater resources in Galicia by using a hydrological model and the meteorological series of the PRUDENCE climate project (Christensen et al. 2007). Raposo et al. (2013) reported that groundwater recharge could concentrate in the winter and decrease dramatically in the summer and the autumn.

There is a concern about the chemical and microbiological quality of groundwater supply in rural areas due to the lack of proper control of the water quality by well owners. Agricultural contamination is often a pressure on the groundwater chemical status where nitrate is the main concern for groundwater quality (EC, 2010). Other risks for groundwater contamination are the poor management of the manure in the fields, the discharge of slurry from farms and the inadequate planning of land use, which does not account for groundwater protection.

Here we address the sustainability of groundwater resources of weathered and fractured schists in the rural areas of Abegondo (Galicia, Spain). The available topographic, meteorological, geological, electric resistivity tomography (ERT), piezometric, streamflow and hydrochemical data are integrated into a conceptual hydrogeological model of the study area. The impact of climate change on groundwater resources is quantified with a hydrological water balance model. The study includes also the assessment of groundwater chemistry and pollution and the recommendations for groundwater management and protection to prevent groundwater pollution and achieve a sustainable groundwater supply.

2. Description Of The Study Area

The study area is located in the in the highest part of the Abegondo municipality (Fig. 1). It covers a surface area of 29 km² with altitudes ranging from 250 to 409 m a.s.l.

The climate in the region is wet oceanic with relatively abundant rainfall. It is classified as Csb, temperate with dry or temperate summer, according to Köppen Climate Classification system (AEMET and IM, 2011). The autumn and the winter are the rainiest seasons. The complete weather station at the Agricultural Research Center of Mabegondo is located 4 km at the north of the study area at an elevation of 94 m, which is significantly lower than that of the study area (Fig. 1). The average annual temperature and precipitation in this station are equal to 12.3 °C and 1133 mm, respectively. The Olas weather station is located 6 km at the south

boundary of the study area at an elevation of 401 m (Fig. 1), which is similar to the altitude of the elevated zones of the study area. The average annual precipitation in this station is 1539 mm. Most of the study area drains to the north to the Mero and the Barcés river basins (Fig. 1). However, a small area drains to the south and tributaries to the Tambre river. The drainage network is very dense.

The study area is mostly framed in metapsamites and metapelites of the Betanzos-Arzúa Unit (Fig. 2), which is part of the Complex of Ordes, a polymetamorphic unit with intercalations of amphibolites and ultrabasic intrusions (Anthonioz and Ferragne 1978; Galán et al. 1978; Raposo et al. 2012). Narrow insertions of phyllites can be found in the south of the study area which are less than 4 km long. Quaternary colluvial and alluvial deposits are found in the lowest areas and in the flood plains of the main watercourses. Rock outcrops are hardly available for direct observation due to the covering by soil and abundant vegetation.

The study area is a rural area with dispersed and low-density population (~ 66 inhabitants per km^2). The main land uses include pastures, thickets, forests and crops. The economy depends on agriculture, livestock and forestry with a few derived industries. The population in the study area does not have a public water supply system. Instead, the inhabitants rely on autonomous domestic groundwater supply systems based on spring catchments and dug and drilling wells.

3. Materials And Methods

3.1. Geophysics

Geophysical techniques provide a tool to improve the knowledge about spatial heterogeneity in hard rocks. The electrical resistivity tomography (ERT) is a rapid method for determining the spatial distribution of the electrical resistivity in the subsurface, which can be linked to variations in the clay content, rock porosity, water saturation and the concentration of dissolved electrolytes (Loke et al. 2003; Cassidy et al. 2014). The multi electrode dipole-dipole array allows for a large spacing between the survey lines while still containing significant 3-D information (Loke 2016). The dipole-dipole array is very sensitive to the horizontal changes in resistivity, but relatively insensitive to the vertical changes in the resistivity. Thus, it is well suited for mapping vertical structures (Loke 2016). According to Samouëlian et al. (2005), this array allows obtaining a depth of investigation larger than that of the Wenner and Schlumberger arrays. However, it has the disadvantage of a lower signal strength.

A 3D electrical resistivity tomography was performed by using the ABEM Lund Imaging system and a multi electrode dipole-dipole array with 40 electrodes and 5 m inter-electrode spacing. Five parallel survey lines with a separation of 10 m were performed in the southwest part of the study area near a spring, wells 1 and 2 and a piezometer (Fig. 3). The actual subsurface resistivity was derived from the apparent resistivity values by solving the inverse problem with the RES3DINV software (Loke, 2016) and accounting for the ground topography. The results of the inversion of the ERT data file were post-processed with the Voxler 3D data visualization package software of Golden Software, Inc.

3.2. Piezometric data and hydraulic tests

An inventory of domestic dug and drilling wells, natural springs, and spring catchments for rural water supplies was performed throughout all the study area. The location of these 133 water points is shown in Fig. 4. Three piezometers were drilled in the study area to monitor hydraulic heads and groundwater quality (Fig. 1). The electrical pressure transducers installed in these piezometers provided the continuous monitoring of the water table depth over more than 2 years. Pumping tests were performed at two locations in the study area.

3.3. Hydrological water balance

The water resources of the study area were evaluated with a hydrological water balance, which was calibrated with available streamflow and piezometric data.

The hydrological model was performed with VISUAL-BALAN (Samper et al. 2015), a semi-distributed hydrological code that computes daily water balances in the soil, the unsaturated zone and the aquifer. Land use data were taken from the CORINE map (Bossard et al. 2000), the aerial photos and the field observations. The following land uses were considered in the hydrological model: (1) Transition forest, mixed forest and thickets and (2) Crops.

The first version of the hydrological model of the Abelar site was derived from the hydrological model of the Valiñas river basin, which is a nearby watershed extensively studied by Samper and Pisani (2013) and Samper et al. (2015). The model of the Abelar site was updated by considering the actual land uses, the dense vegetation, the soil parameters and geology. The water balance was calibrated with the available piezometric and streamflow data measured from 2007 to 2010. The parameters of the hydrological model at the Abelar site were used as initial estimates for the models of the other three zones. Soil, interception and evapotranspiration parameters of each zone were adjusted to account for the vegetation and slope conditions of each zone. The results of the water balance in the rest of the study area were obtained by extrapolating the results obtained in the 4 small zones.

3.4. Evaluation of the impact of climate change

Current global and regional climate models generally do not reproduce correctly the observed climate annual and monthly temperature and precipitation normals (three-decade averages) in the historic period. The bias of the simulations also affects the predictions for the future climate scenarios (Wilby et al. 2000). This limitation is usually overcome by running hydrological models with the meteorological data provided by climatic models for both the historic (control) and the prediction periods. The impacts of the climate change are evaluated from the differences between the results of the hydrological model in the control and the prediction periods (Akhtar et al. 2008). Although this method does not provide accurate predictions of the hydrological variables for the prediction period, it ensures that simulated climatic variables preserve the day-to-day variability (Hay et al. 2002; Wood et al. 2004).

The effects of climate change on the water resources at the end of the 21st century were evaluated for A2 (more pessimistic) and B2 (more optimistic) IPCC scenarios (Nakicenovic et al. 2000) with the precipitation and temperature predictions of the PROMES-HadAM3H climate model developed for the PRUDENCE European project (AEMET 2008; Christensen et al. 2007). The effects of climate change on the water resources for the period 2071–2100 were quantified by using the hydrometeorological conditions of the reference historic period 1961–1990 and by assuming that the land uses in the simulation period are the same as those in the historical

period. The meteorological series generated by the climate model for the historical and the simulation periods were used as inputs to the calibrated hydrological model of the study area. The results of the water balance in the historical period were compared to those of the simulation period. The relative changes of the water balance components were calculated in a manner similar to Espinha et al. (2010) and Pisani et al (2017) who evaluated the effects of climate change in the Serra da Estrela hard-rock area in Portugal.

3.5. Groundwater chemistry and pollution

Groundwater quality was evaluated based on the results of 202 physicochemical and microbiological analyses performed on samples in springs, domestic wells and piezometers within the study area from 2014 to 2016 (Aqua Plann, 2011). The following chemical and microbiological parameters were determined: pH, electric conductivity, the concentrations of major cations (Na, K, Ca, Mg), major anions (Cl^- , SO_4^{2-} and HCO_3^-), ammonium, nitrate, nitrite, sulfate, organic carbon, metals (Al, As, Cd, Cu, Cr, Hg, Ni, Pb, Se, Zn, Fe, Mn and Sr), total and faecal coliform, E. Coli and Faecal Streptococcus colonies.

The pristine chemical properties of the shallow groundwater in the study area were previously established within the framework of the LIFE Aqua Plann Project (Aqua Plann 2011; Naves et al. 2019). Measured concentrations were compared with the reference concentrations and the admissible (parametric) concentrations established in drinking water regulations (Directive 98/83/EC).

4. Results And Discussion

4.1. Geophysics

The resistivity values obtained from inversion of the ERT data range from 60 to about 3000 $\Omega\cdot\text{m}$, with large horizontal and vertical heterogeneities (Fig. 3). The resistivity is large ($> 1500 \Omega\cdot\text{m}$) in a shallow layer corresponding approximately with the unsaturated regolith. The resistivity decreases sharply to less than 500 $\Omega\cdot\text{m}$, showing a sharp transition at depths ranging from 5 m to 10 m, which corresponds to the location of the water table which is located at 3 m depth in Well 1 and 6 m in Well 2. The thickness of the shallow high-resistivity zone reduces at the north-eastern corner near the spring. High resistivities (up to 3000 $\Omega\cdot\text{m}$) are observed at the bottom of the 3D block between Wells 1 and 2. These large resistivities correspond to the fresh bedrock while the zone of lower resistivities located below the water table and above the bedrock corresponds to the saturated regolith and fractured bedrock. The resistivity within the fractured rock shows spatial variability in both the longitudinal and the transversal directions. Anomalous resistivities were recorded at the southern edge of the 3D block due to the disturbances caused by a country road. The observed heterogeneities in the resistivities are consistent with the measured depths to the water table and the water-producing layers in Wells 1 and 2.

4.2. Piezometric data and hydraulic tests

The water table is generally shallow. Its depth is less than 10 m in most of the study area. The largest depths ($> 20 \text{ m}$) are found in the most elevated areas (Fig. 5). The measured hydrographs in the three piezometers show that the water table rises in response to rainfall events. The seasonal oscillations of the hydraulic heads are smaller than 4 m (Fig. 5).

The estimated equivalent transmissivity ranges from 15 to 35 m²/d. This range of transmissivities are consistent with those reported by Carvalho et al. (2003) for the fractured schists in northern Portugal. These transmissivities are also consistent with those adopted by Naves et al. (2019) for modelling spring protection zones in Abegondo.

4.3. Groundwater flow conceptual model

Groundwater flow in the metamorphic rocks of the study area can be assumed to follow the equivalent porous media model. The conceptualization of the hydrogeology of the study area includes: 1) The regolith, 2) The fractured rock layer; and 3) The underlying fresh bedrock (Fig. 6). The ERT results do not allow distinguishing the regolith and the fractured rock layers. However, the information provided by well logs and the geological surveys conducted for the construction of a highway, which crosses the study area, show that: 1) The thickness of the schist regolith is spatially heterogeneous and ranges from 1 to 15 m; and 2) The depth of the of the unfractured rock ranges from 15 m to more than 50 m.

Most of the groundwater flows through the regolith and the fractured rock. Field evidences from borehole drilling have shown that groundwater flows into the drilled wells at the contact zone between the regolith layer and the fractured bedrock. The hydrogeological role of the fresh bedrock can be generally neglected. The available data do not allow distinguishing the properties of the regolith and the fractured rock layers. Therefore, these two layers are lumped into a single unconfined aquifer with an equivalent transmissivity ranging from 15 to 35 m²/day.

The aquifer recharge occurs due to infiltration of rainwater. Irrigation is restricted to small plots. According to piezometric data, the natural discharge of the groundwater occurs in seepage areas, springs, and the lower parts of the creeks and valleys. Springs are not found to be related to geological contacts, quartz dikes, tectonic fracture zones or other rock singularities.

4.4. Hydrological water balance

The hydrological model of Abelar pilot basin using historical meteorological data was calibrated with measured stream flows at the watershed discharge point (Fig. 7a) and available piezometric data from October 2007 to September 2010. The mean annual values of the components of the water balance for the period 2006–2015 are listed in Table 1. The average annual precipitation, P, is equal to 1499 mm (Table 1). Interception and actual evapotranspiration (AET) amount to 506 mm (34% of P). The remaining 66% of P is the annual streamflow, Q. Interflow is the major component of Q (78%), groundwater recharge is 19% of Q and surface runoff is approximately equal to 3% of Q (Table 1). The mean annual interflow is equal to 771 mm while the annual aquifer recharge is equal to 185 mm which is consistent with the recharge estimated by Raposo et al. (2012) with the chloride mass balance method in the Complex of Ordes.

Table 1

Mean annual values of the components of the water balance calculated with the hydrological model for the historic period in the study zone and in the Abelar pilot basin using historical meteorological data and predicted results and changes (Δ) in the mean annual values of the components of the water balance at the Abelar basin for the prediction period 2071–2100.

	Hydrological model of the Abelar basin by using historical meteorological data	Hydrological model of the study area by using historical meteorological data	Hydrological model of the study area using meteorological data generated by climate model simulations				
	Historic period: 2007–2010	Historic period: 2006–2015	Control period 1961–1990	Scenario A2 2071–2100	Scenario B2 2071–2100		
	(mm)	(mm)	(mm)	(mm)	Δ (%)	(mm)	Δ (%)
Precipitation	1597	1499	1272	1112	-12.6%	1158	-9.0%
Interception	108	69	86	77	-10.5%	79	-8.1%
Potential recharge	806	956	557	498	-10.6%	524	-5.9%
Potential evapotranspiration (PET)	705	962	699	832	19.0%	787	12.6%
Actual evapotranspiration (AET)	668	437	606	525	-13.4%	530	-12.5%
Surface runoff	15	37	23	13	-43.5%	24	4.3%
Interflow	632	771	437	391	-10.5%	411	-5.9%
Groundwater recharge	174	185	120	108	-10.0%	113	-5.8%
Streamflow	821	993	580	511	-11.9%	548	-5.5%

4.5. Effects of climate change on water resources and groundwater recharge

The annual average temperature in the period 2071–2100 could increase 2.4°C in scenario B2 and 3.4° C in scenario A2. Table 1 shows the mean annual values of the components of the water balance in the whole study area in the control period (1961–1990) and the projected changes for the period 2071–2100 caused by the climate change. Groundwater recharge could decrease from 6–10%. This reduction should not affect the availability of groundwater resources because groundwater use in the study area is much smaller than the average resources. A slight decline of groundwater levels and spring and fountain flows is expected. Recharge could increase in the winter and decrease in the rest of the year. The periods without recharge could become more frequent and last longer. Climate change could aggravate the problems of guarantee of water supply from spring catchments in droughts. Moreover, the effects of climate change could aggravate the decline of groundwater levels and the reduction of groundwater resources caused by the water consumption of eucalyptus

plantations. For the most part, our predictions of climate change effects on water resources are consistent with those reported by Raposo et al. (2013).

4.6. Groundwater quality and pollution

The measured pH ranges from 5.7 to 6.5. These slightly acidic values are similar to the pH of natural groundwater. The measured electrical conductivities are low and slightly larger than the reference values for this aquifer (from 40 to 110 $\mu\text{S}/\text{cm}$). The measured pH, electrical conductivity and chloride concentration do not show significant spatial variability.

The natural concentration of dissolved nitrate ranges from 1 to 10.4 mg/L (Aqua Plann 2011). The measured nitrate concentrations attest a contamination in the southern part of the study area (Fig. 8). Groundwater pollution is caused by the poor management of the manure in the fields and occasional discharges in pastures of large volumes of pig and mink slurries from local farms. Figure 8 clearly shows that most of the wells and springs affected by nitrate contamination are located near the areas with a large density of rural estates authorized for slurry discharge.

The measured total concentrations of some metals such as Al, Mn, Fe, As and Pb exceed the parametric values for drinking water in some water points, when water samples are not properly filtered in situ. This pollution is associated in most of cases with suspended matter. Dissolved metal concentrations are below their parametric values. Therefore, metal pollution is prevented by groundwater filtration. Other metals such as aluminum, arsenic, copper, cadmium, nickel, mercury, lead and zinc are found in very low concentrations.

4.6. Recommendations for groundwater management and protection

The extensive bacteriological contamination of groundwater in the study area could be overcome simply by appropriate filtering and chlorination. Filtering should also prevent groundwater metal pollution. Nitrate contamination, however, cannot be eliminated with a reasonable cost treatment. Alternative groundwater water supply catchments for communities affected by strong nitrate pollution could be found in areas where appropriate land use planning measures are implemented to preserve groundwater quality.

Land use planning and groundwater protection regulations should be established from a common consensus among by all the involved stakeholders such as local administration, environmental, water and agriculture regional authorities, pig breeders, farmers and water users. Regional environmental authorities should take into groundwater resources to plan and authorize the discharge of slurry by farmers in rural states.

Conclusions

The study of the sustainability of groundwater supply in the rural areas of Abegondo municipality (Galicia, Spain) has been presented. The conceptualization of the hydrogeology of the study area includes: 1) The regolith, 2) The fractured rock layer; and 3) The underlying fresh bedrock. Most of the groundwater flows through the two shallowest layers. The equivalent transmissivity of the regolith and the fractured rock layer ranges from 15 to 35 m^2/d . Infiltration of rainwater is the source of groundwater recharge. Creeks and the lowest valleys are discharge zones.

A hydrological water balance model has been constructed to evaluate the water resources in historical conditions. It has been calibrated by using measured streamflow and piezometric data. The average groundwater recharge in the study area in the historical the period 2006–2015 is 185 mm/year, which constitutes 12% of the average precipitation. The hydrological model was used to evaluate the effects of climate change at the end of the 21st century for the A2 (more pessimistic) and B2 (more optimistic) IPCC emission scenarios. Groundwater resources could decrease from 6 to 10% by the end of the 21st century. The reduction in groundwater resources could lead to a decline of groundwater levels and spring flows, especially in droughts. The expected decline in groundwater resources at the end of the 21st century due to climate change should not affect the availability of groundwater resources because current groundwater use in the study area is much smaller than the average resources. However, the water supply shortages in droughts could get worse. Shortages could be overcome by deepening the water catchments or drilling deep wells.

Groundwater in the study area is slightly acidic and has low electrical conductivity. Some wells and springs show bacteriological and nitrate contamination caused by inadequate management of the manure in the fields and occasional discharges of slurry from local pig and mink farms. Measured total concentrations of some metals, related to suspended matter, exceed their parametric values in some locations.

Filtering and chlorination should avoid groundwater bacteriological and metal pollution. Furthermore, appropriate management plans and groundwater protection actions are strongly recommended to prevent groundwater pollution and achieve a sustainable groundwater supply in the study area.

Declarations

Acknowledgments

This work has been performed within the framework of the project "Sustainable solutions for small networks of supply" of the LIFE program of the European Commission, its partners being: The Galician Water Authority ("Augas de Galicia"), the Regional Health Department and the Municipality of Abegondo. We acknowledge the support provided by Carlos Ameijenda, Raquel Piñeiro, Mónica Velo and Roberto Arias, Elvira Íñiguez and SAI-UDC Services. The work has been funded also by a project of the Spanish Ministry of Science and Innovation (PID2019-109544RB-I00), and the Galician Regional Government (Grant number ED431C 2017/67 from "Consolidación e estruturación de unidades de investigación competitivas", Grupos de referencia competitiva).

Declarations

No conflicts of interests. No additional data or material.

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Figures

Figure 1

Location of the study area in the Abegondo municipality (Galicia, Spain). The map includes the Digital Terrain Model and the drainage network, dividing the area which drains to the north to the Mero and Barcés rivers (black line) and the area which drains to the south and tributaries to the Tambre river (blue line). The location of the meteorological stations, the pilot experimental basin of El Abelar and the three piezometers (PZ1, PZ2 and PZ3) of the piezometric monitoring network are also indicated. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of

Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Geological map and boundary of the study area (white line). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Map of the study area with the location of the resistivity profiles, Wells 1 and 2 and the piezometer (A). 3D Electric Resistivity Tomography: Inverted subsurface resistivity (Ω) for the 3D block (B) and inverted resistivity (Ω) in a cross section along the second dashed line (C). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

Map of water points in the study area and the PZ1, PZ2 and PZ3 piezometers of the monitoring network. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 5

Scatterplot of average measured piezometric heads and ground elevations (z) in the recorded wells (top). Hydrograph of the water table elevation in PZ1 and daily precipitation from February 2015 to March 2017 (bottom).

Figure 6

Hydrogeological block diagram of the weathered and fractured schists of Abegondo (modified from Naves et al. 2019). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 7

Measured (symbols) and computed (lines) stream flows at the discharge Abelar site in 2007-2010 (a) and measured (symbols) and computed (lines) piezometric heads at the PZ2 piezometer in 2014-2015 (b).

Figure 8

Map of nitrate pollution classes in the study area, which indicates the points without evidence of pollution (green dots), with mild nitrate pollution (yellow dots) and exceeding the admissible limit (red dots). The rural estates authorized for slurry discharge by the regional environmental authority (white areas) are also shown. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.