

1 **The oldest managed aquifer recharge system in Europe: new insights from the Espino**  
2 **recharge channel (Sierra Nevada, southern Spain)**

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27 **Abstract**

28 In Sierra Nevada (southern Spain), the highest mountain range in southern Europe, the  
29 application of an ancestral Integrated Water Resources Management system (IWRM), based  
30 on the conjunctive use of groundwater and surface water, provides water resources for  
31 irrigation and supply in the driest months of the year at this semiarid mountain. Meltwater is  
32 derived from the headwaters of the mountain streams and rivers through a set of uncoated  
33 channels excavated in the ground (locally known as *acequias de careo*) to infiltrate at the  
34 upper part of the valleys. Water infiltrated along the *acequias de careo* slowly flows down the  
35 hillsides, through the weathered zone of the hard rock aquifer and the glacial and periglacial  
36 sediments. The recharge accomplished through this Managed Aquifer Recharge technique  
37 (MAR) activates numerous springs located halfway up the hillside and increase the base flow of  
38 the rivers. In this study, focused on a *careo* channel located on the southern slope of Sierra  
39 Nevada and called *Acequia de El Espino*, we have applied different archaeological,  
40 sedimentological, geophysical and hydrogeological techniques in order to determine the age,  
41 the resilience and the effectivity of this ancestral example of MAR and IWRM system. Results  
42 suggest that the *acequias de careo* may represent the oldest MAR system in Europe and that  
43 this MAR technique could be applied in other high mountain alpine watersheds to mitigate the  
44 effects of climate change.

45 **Keywords:** Water Resources Management; Managed Aquifer Recharge; Alpine watershed;

46 Hard Rocks

47

48 **1. Introduction**

49 Sierra Nevada, the highest mountain range of the Iberian Peninsula (reaching 3479 m a.s.l.), is  
50 located less than 35 km far from the Mediterranean Sea, the boundary between Africa and  
51 Europe (Fig. 1). The substantial climate contrast between its high-mountain conditions and the

52 surrounding Mediterranean semiarid climate favours the development of a complex and  
53 singular system from different perspectives: weather, hydrogeology, ecology, culture and  
54 ethnology. In fact, Sierra Nevada is the area with greater diversity and endemism of the  
55 Iberian Peninsula (Blanca et al., 1998; Brewer et al., 2002; Granados and Cano, 2015), and has  
56 been recognized as Biosphere Reserve by UNESCO (1986) and as National Park (1999). Due to  
57 its altitude and orographic effects, rainfall is higher than the average in the area and often  
58 occurs in the form of snow. For these reasons, runoff is essential for supplying agriculture and  
59 tourism, beside the environmental value of the associated ecosystems.

60 The Sierra Nevada foothills and the adjacent depressions have been colonized since the  
61 Palaeolithic and Neolithic times by subsequent civilizations, attracted by the abundance of  
62 water coming from the snow accumulated at its summits (Gómez-Ortiz et al., 2013). Close to  
63 Sierra Nevada, there are several sites where irrigated agriculture has been suggested to be  
64 practiced in the framework of the El Argar and Los Millares cultures, more than 4000 years ago  
65 (Giráldez et al., 1988; Gilman and Thornes, 2014). However, irrigation techniques flourished in  
66 the Middle Age during the Spanish Islamic period (Glick, 1988; Glick and Kirchner, 2000;  
67 Barceló, 1989; Trillo, 2004; Watson, 2008; Roldán and Moreno, 2010). Since the 8<sup>th</sup> century up  
68 to the conquest of Granada by the Christians in the 15<sup>th</sup> century, the Arab culture left an  
69 outstanding imprint on the water management of the whole Al-Ándalus, as it is known the vast  
70 territory of the Iberian Peninsula conquered by the Arabs in that period (Glick and Kirchner,  
71 2000; Vivas et al., 2009; Martín Civantos, 2011). Water supply to large cities such as Córdoba,  
72 the most populous city of that time with more than one million inhabitants, contributed to  
73 recover and even exceed the splendour of the Roman Empire (Roldán and Moreno, 2010).  
74 However, the main advances introduced by the Arabs were focused on irrigation.

75 From a technological point of view, the Islamic civilization made an extensive compilation and  
76 improvement of the irrigation technical practices of the ancient world and, obviously, applied

77 them in Al-Ándalus (Roldán and Moreno, 2010). They knew, therefore, the techniques of water  
78 collection by construction of dykes and dams to derive water from rivers and ephemeral  
79 streams, the groundwater extraction techniques using *qanats* and wells (Kamash, 2012) and  
80 water harvesting techniques; the latter used for thousands of years in North Africa and the  
81 Arabian Peninsula (Prinz, 1996). Water harvesting comprises the collection of runoff and its  
82 use for the irrigation of crops, pastures, trees and for livestock consumption (Finkel and Finkel,  
83 1986). Indigenous systems were applied and still remain in use, such as those of: *jessour* and  
84 *meskat* in Tunisia, *tabia* in Libya, *cisterns* in north Egypt, *hafaer* in Jordan and Syria, and  
85 systems such as the hillsite conduit systems used in Israel and North Yemen (Evenary et al.,  
86 1971; Adato, 1987; Bruins, 1986; Brunner and Haefner, 1986; Bamatraf, 1994; Prinz, 1996;  
87 Oweis and Hachum, 2006). The surficial water and the groundwater collected were  
88 subsequently distributed to the growing areas through irrigations channels or *canals* (Kamash,  
89 2012; Roldán and Moreno, 2010).

90 In Sierra Nevada, water harvesting and groundwater use were combined and incorporated into  
91 an original and advanced Integrated Water Resources Management (IWRM) system, which is  
92 based on the conjunctive use of groundwater and surface water. Indeed, the Muslims, who  
93 were experts in irrigated crops (Barceló, 1989; Trillo, 2004; Watson, 2008; Martín Civantos  
94 2011), made an outsized effort to develop innumerable cultivation terraces (Fig. 2A) around  
95 the villages of Sierra Nevada (Guzmán and Navarro, 2010; Martín Civantos, 2007). These  
96 orchards were flooded by means of irrigation channels (*acequias*) that were built and  
97 maintained by the community (Fig. 2C). However, the rivers' and the springs' flow diminished  
98 in summer, when the water demand was greater. Then, the Muslims established a water  
99 management system that consisted of deriving the meltwater from the headwaters of the  
100 mountain streams and rivers (Figs. 2C and 2D) and to recharge it in the halfway up the hillside  
101 (Figs. 2E and 2F) through long uncoated channels excavated in the ground (Pulido and Sbih,  
102 1995). These channels are locally known as *acequias de careo*.

103 Water infiltrated along the *acequias de careo* slowly flows down the hillsides, through the  
104 weathered zone of the hard rock aquifer. During the dry season, it arises through the springs  
105 located halfway up the hillside and/or by the rivers from which it was derived during the thaw,  
106 increasing its base flow (Fig. 3). In summer, the *acequias de careo* are no longer used and  
107 another extensive network of irrigation channels, located at a lower altitude, begins to divert  
108 water from the rivers to the agricultural areas (Fig. 3).

109 In Sierra Nevada, there are more than 700 km of *acequias de careo* (Fig. 1C), most of them still  
110 working. We have already historically proved their existence at least since the 11<sup>th</sup> century  
111 (Martín Civantos, 2010) and it is known most of these channels (Fig. 4) were already operative  
112 when the Castellians conquered the territory by the end of the Middle Age (Delaigue, 1995).  
113 Our analysis is focused on a *careo* channel called *Acequia de El Espino*, which is located in the  
114 Bérchules river valley (Fig. 4), on the southern slope of Sierra Nevada. In this study, we have  
115 applied different archaeological, sedimentological, geophysical and hydrogeological  
116 techniques in order to determine the age, the resilience and the effectivity of this ancestral  
117 example of MAR and IWRM system.

118

## 119 **2. Hydrogeological setting**

120 Two main kinds of aquifer formations, with a clearly differentiated hydrogeological behaviour,  
121 can be found in Sierra Nevada (Fig. 1B): (1) the shallowest part of the schists of the Nevado-  
122 Filábride Complex, which crop out in the core of Sierra Nevada where the range reaches the  
123 highest elevation. The weathered zone of these rocks together with the glacial and periglacial  
124 Quaternary formations of the highest areas of the mountain, constitute an extensive aquifer in  
125 hard rocks (1358 km<sup>2</sup>), and (2) the carbonated rocks of the Alpujarride Complex that partially  
126 surround the schists from the west and south of Sierra Nevada (Fig. 1B).

127 Metamorphic rocks of the Nevado-Filábride Complex, mainly fine grained feldspathic graphite  
128 schists with quartzite intercalations, crop out in nearly all the Bérchules river basin (Fig. 5B).  
129 They show a very penetrative foliation with a general dip towards the N-NE. The weathered  
130 zone of metamorphic rocks constitutes a surficial aquifer of reduced thickness (maximum  
131 depths of 30-50 m) but very extensive, since it practically covers the whole Sierra Nevada. It  
132 comprises an upper part formed by weathered and disintegrated schists (saprolite), and a  
133 lower fissured and fractured zone (saprock) that extends in depth until the unaltered rock. At  
134 elevations higher than 2500 m a.s.l., low temperatures determine the predominance of  
135 physical weathering by crioclastic processes with the development of a crioclastic layer that  
136 occupies the entire summit area with the exception of the most rugged zones. In highest  
137 zones, the surficial aquifer is formed by debris deposits. They are scree or talus deposits,  
138 located at the foot of the escarpments, and the glacial sediments accumulated at the top of  
139 the highest valleys. Below 2500 m a.s.l., the increase in temperature favours edaphization and  
140 chemical weathering processes, which may produce a subsequent decrease in permeability at  
141 the alteration zone, due to the presence of a greater clayey fraction.

142 The hydrogeological behaviour of this shallowest aquifer depends on the altitude (Martos-  
143 Rosillo et al., 2018). In the upper parts of the study zone almost all the runoff infiltrates in the  
144 aquifer. This is due to the high permeability of the existing talus deposits along with the low  
145 slope of the Sierra Nevada highlands. In these zones, infiltration is even enhanced by the high  
146 proportion of snowfall precipitation and its slow melting process. Moreover, as altitude  
147 decreases mean precipitation gets lower and mean temperature increases along with  
148 evapotranspiration as the glacial and periglacial sediments disappear. As a result, the aquifer is  
149 mainly constituted by the surface weathered zone of the schists. All these facts condition that  
150 the natural aquifer recharge noticeably decrease in the altitudinal range between 2000 and  
151 1600 m a.s.l. with respect to the highest areas of Sierra Nevada. However, below 1600 m a.s.l.,

152 which is the average altitude of the recharge channels (Ortiz-Moreno, 2010), recharge  
153 increases again (Martos Rosillo et al., 2017).

154 The limits of the studied aquifer coincide with those of the surface watershed of the Bérchules  
155 river basin (67.6 km<sup>2</sup>). The Bérchules River is a tributary of the Guadalfeo River, which flows  
156 into the Mediterranean Sea with an average altitude and slope of 2072 m a.s.l. and 37%,  
157 respectively. Its maximum height is Cerro del Gallo peak (2910 m a.s.l.), to the North, and the  
158 minimum corresponds to the Narila gauging station (979 m a.s.l.), to the South. In the  
159 Bérchules watershed there is an intricate network of irrigation channels and *acequias de careo*  
160 (Fig. 5) that is used to (1) transfer water between the neighbouring basins, (2) recharge the  
161 surface aquifer and (3) irrigate the crops. There are 19 main channels with a total length of  
162 57,45 km, where 21 km of them are specifically *acequias de careo*. The main recharge channels  
163 of the Bérchules Basin are the *Acequia de El Espino* (7 km) and the *Acequia de Trevélez* (11 km,  
164 until it enters the Bérchules basin). The latter *acequia* transfers water from the left bank of the  
165 Trevélez river to the Bérchules river basin, where it is recharged. On the other hand, the  
166 *Acequia de Mecina* captures water from the Grande River and carries it towards the Mecina  
167 river basin, located in the neighbouring eastward hydrological basin. The *Acequia de El Espino*  
168 is therefore one of the recharge channels or *acequia de careo* that are still active in Sierra  
169 Nevada. It is located in the Bérchules river basin, in the southern slope of the range (Figs 4 and  
170 5). For the period 1970-2013, at the Bérchules meteorological station (1319 m a.s.l.), the mean  
171 annual precipitation is 677 mm/yr and the mean annual temperature is 13.3 °C. For the same  
172 period, the average annual flowrate of the Berchules River at the Narila Gauging station (Fig. 4)  
173 is 12,23 hm<sup>3</sup>/year, showing a seasonal pluvio-nival fluvial behaviour (Jódar et al., 2017, 2018).

174 The soil cover (Fig. 5A) is mainly represented by sparse scrub crops, conifers and grassland, as  
175 well as by irrigated horticulture crops, particularly in the lowlands, but also in a reduced area in  
176 the uplands (about 260 hectares; 4% of the total catchment surface area).

177 The limits of the aquifer generally coincide with those of the surface watershed of the  
178 Bérchules River (Fig. 5B). For the period 1970-2013 the average recharge of the aquifer is 6,3  
179 hm<sup>3</sup>/year, although 3,1 hm<sup>3</sup>/year are interflow discharged through numerous springs hanging  
180 on the river slopes (Martos-Rosillo et al., 2015). Therefore, the rain infiltrated under edaphic  
181 soil, and not drained through interflow, is recharged in the aquifer and discharged in the  
182 Bérchules River. Besides, there are 20 wells (Fig. 5B) with flows lower than 2 L/s which are  
183 used as support for irrigation and supply to livestock.

184 Hydrological models have allowed estimating the groundwater component of the total runoff  
185 at the Bérchules Basin between 76-95% (Martos-Rosillo et al., 2015; Jódar et al., 2017, 2018).  
186 This large contribution of groundwater to the total basin runoff underlines the important role  
187 of aquifer recharge in the basin. This result has been also confirmed by studies through  
188 environmental tracers (Barberá et al., 2018). Moreover, the high inertial functioning of this  
189 river is the consequence of the Managed Aquifer Recharge (MAR) carried out with the  
190 *acequias de careo* (Martos-Rosillo et al., 2017).

191

### 192 **3. The recharge channel of *Acequia de El Espino***

193 The *Acequia de El Espino* is a channel excavated in metamorphic rocks. It starts as a simple and  
194 small diversion dyke, locally known as *toma*, made of slabs of schists without mortar and  
195 arranged in the Chico de Bérchules river bed (Fig. 2c and d) at 1998 m a.s.l.. This dyke allows  
196 the diversion of water from the river towards the channel. The average height, slope and width  
197 of this channel are 1905 m a.s.l., 6,8% and 1,5 m, respectively. The management and control of  
198 the diversion dyke is conducted by two members of the Irrigation Community of Bérchules  
199 (Fig. 2C). They are in charge of repairing the basin channel system, and distributing the  
200 diverted water. This is done by following the same ancient technical procedures of their  
201 ancestors that has been transmitted from generation to generation.

202 *The Acequia de El Espino* ends in the *Sima de Bérchules* at 1820 m a.s.l., and it does not present  
203 any derivation for irrigation purposes along its entire path. However, four main recharge zones  
204 (Fig. 6) can be distinguished along the channel: (1) *Sima de Los Helechales* (average elevation  
205 and area of 1888 m a.s.l. and 4910 m<sup>2</sup>, respectively); (2) *Sima del Barranco de Montina* (1866  
206 m a.s.l. and 2117 m<sup>2</sup>); (3) *Sima de Márcula* (1821 m a.s.l. and 25901 m<sup>2</sup>) and finally (4) *Sima de*  
207 *Bérchules* (1820 m a.s.l. and 32328 m<sup>2</sup>) which is the most important recharge zone, and  
208 consists of a surface covered with grass, whose substrate is characterized by its high  
209 infiltration capacity (Figs 2E and 2F).

210 In dry periods, river water begins to be diverted in November-December. In years with rainfall  
211 equal or greater than the average and with a large amount of snow accumulated in the upper  
212 part of the basin, water is diverted later (February-March). During the melting season (April to  
213 June) the river flowrate increases and hence the water derivations through the channel. This  
214 flowrate increase in the channel allows the diverted water to reach the *Sima de Bérchules*  
215 recharge area. If the infiltration capacity of both the channel and the *Sima de Bérchules* is  
216 overflowed, then the other three recharge zones located upstream (i.e. *Sima de Márcula*, *Sima*  
217 *Barranco Montina* and *Sima de los Helechales*) are put into operation using a simple water  
218 bypass system.

## 219 **4. Methodology**

### 220 **4.1. Historical and archaeological analysis**

221 The methodology is based on the idea that landscapes are the result of the continued  
222 modification along the several historical landscapes that have been happening over time  
223 (Godelier, 1989). Landscape, understood as a synthesis of social and environmental relations  
224 and taking into account its formation process, can be decoded, as a set composed of stratified  
225 apprehensible and measurable elements, among which are given a series of stratigraphic and  
226 contextual relationships. This means that a given landscape can be known and understood

227 diachronically from an archaeological perspective (Martín Civantos, 2006, 2008). This is the  
228 basis of Hydraulic Archeology, which will be the starting point for the technical and spatial  
229 analysis of historical irrigation systems. This implies that the study of hydraulic systems cannot  
230 be limited to a summary delineation of the irrigated spaces or to the simple observation of a  
231 close relationship between residence areas and the irrigated perimeters. The analysis should  
232 go deeper, evaluating the transformations of the irrigation space throughout its history in  
233 relation to the social relationships and the environment (Barceló, 1989; Kirchner and Navarro,  
234 1994). In this sense interdisciplinary approaches as the current one are essential to reach an  
235 integrated knowledge about such complex socio-ecosystems.

236 In addition to the archaeological perspective, a deep knowledge of historical written sources  
237 and place names is fundamental. In Bérchules, specific references are almost absent until the  
238 Castillian conquest in 1492. The main available document to gather information is the *Libro de*  
239 *Apeo y Repartimiento* (LAR, 1573). LARs are surveyings and demarcations made in the 16<sup>th</sup>  
240 century by the Christian authorities to register the existing assets in each village after the  
241 expulsion of the Moorish population. They served the crown for the reorganization of space as  
242 well as for obtaining tax revenue and constitute an interesting source for geographic data,  
243 agricultural productions, place names, surnames, crops, number of houses, mills, etc.

#### 244 **4.2. Sedimentary infill analysis**

245 The recharge zones (*simas*) related to the *Acequia de El Espino* are surfaces covered with  
246 pasture and very sparse rocky outcrops. Consequently, subsurface techniques (shallow  
247 geophysical methods and coring) are the main tools to characterize the geometry and nature  
248 of the sedimentary infill.

##### 249 4.2.1. Geophysical methods

250 Electrical geophysical methods like electrical resistivity tomography (ERT) and induced  
251 polarization (IP), have been widely applied in many hydrogeological and environmental  
252 investigations. These methods allow determining the subsurface resistivity distribution (Loke  
253 et al., 2013). This parameter is related to various geological features such as the mineral and  
254 fluid content, water salinity or porosity (Worthington, 1976; Barker and Moore, 1998). ERT  
255 data acquisition is performed by means of the reiterative injection of an electrical current  
256 through a source electrode pair belonging to a lineal electrode array, and the subsequent  
257 recording of the potential difference between another electrode pair. The IP method measures  
258 how the electrical potential decays along a given time interval after the removal of an applied  
259 electrical current (Seigel, 1959). This method is able to detect very low concentrations of  
260 metallic and clay minerals in the subsurface given that these minerals accumulate electrical  
261 charge at their interfaces while applying the electrical field to the ground, and gradually  
262 discharge once the electrical field is removed. These minerals might otherwise be missed if  
263 only resistivity surveys are applied.

264 Geoelectrical imaging was carried out with a multi-electrode high-resolution 4-channel  
265 resistivity meter ABEM SAS 4000, which allows the determination of resistivity and  
266 chargeability underground. In this survey, 81 steel electrodes were arranged in a straight line  
267 with constant spacing using a 4-channel multiple gradient electrode array (Dahlin and Zhou,  
268 2006). The gradient protocol uses a Wenner-Schlumberger electrode array configuration and it  
269 was developed for multi-channel resistivity meter systems. The data inversion was performed  
270 using Res2Dinv v.3.59 software (Loke, 2016) selecting a mesh made up of model cells  
271 increasing 25% in size with depth, trapezoidal finite-elements, 4 nodes per unit electrode  
272 spacing and 0,3 initial damping factor.

273 Data were collected along 7 profiles (Fig. 6) located at 3 preferential infiltration areas (*Sima de*  
274 *Bérchules, Sima de los Helechales and Sima de Márcula*) with electrode spacing ranging from 1

275 to 3 m. The normalized depth of investigation (DOI) index method (Oldenburg and Li, 1999;  
276 Marescot et al., 2003) provides information about the sectors of the profile where the  
277 inversion values are trusted. It was obtained carrying out two inversions with a background  
278 resistivity of the second reference model that was 100 times the first one. A restrictive 0,1 cut-  
279 off value was selected (Marescot et al., 2003).

#### 280 4.2.2. Sedimentological methods

281 Sedimentological profiling of the deposits of *Sima de Bérchules* is aimed to their genetic  
282 interpretation and architectural organization in order to characterize bounding surfaces,  
283 identifiable in the geophysical profiles. Vibracores (Fig. 2G) have been recovered at four drilling  
284 sites (Fig. 7) with twin cores, some decimetres away, at each point. The recovery has been  
285 continuous in PVC pipes of 5 cm in diameter and the retrieved lengths are: 4,7 m (SB1), 2 m  
286 (SB2), 1 m (SB3) and 2 m (SB4).

287 Geophysical profiling (density, porosity and magnetic susceptibility) with a 1 cm spacing has  
288 been done for cores SB1, SB3 and SB4 with a Multisensor Core Logger (®Geotek). In addition,  
289 from core SB1, four samples have been analysed for grain size (sieving and sedigraph) and four  
290 samples have been used for semiquantitative mineralogical analysis (total rock and clay  
291 fraction) by DRX in an XPERT PRO MPD (®PANalytical) following the procedure of Schultz  
292 (1964) and Barahona (1974). Original depths of the cores (mechanically compressed) were  
293 corrected to obtain the real depths of the deposits and bounding surfaces so they can be used  
294 in the interpretation of the geophysical profiles. The sedimentological studies have been  
295 completed by outcrop observations in two gullies of 1 m in height.

#### 296 4.2.3. Chronological methods

297 Chronological record has been established using optically stimulated luminescence dating  
298 (OSL). Luminescence signals of quartz grains provide a powerful means for examining daylight

299 exposure at the soil surface on a decadal to millennial time scale (Heimsath et al., 2002; Duller,  
300 2008; Preusser et al., 2009). Measurements including luminescence to estimate the  
301 accumulated dose and gamma spectroscopy to determine the concentration of radionuclides  
302 have been carried out at the University of Seville (Radioisotopes Unit, RDI). OSL dating has  
303 been applied on a total of six samples: two samples collected from the wall of two gullies (BER-  
304 1 and BER-2), located in the *sima*, two samples from core SB1 and one sample from each of the  
305 cores SB2 and SB4. Samples have been sieved to fraction 180-250  $\mu\text{m}$  and treated with HCl and  
306  $\text{H}_2\text{O}_2$  to dissolve carbonates and organic matter respectively. Density separation has been used  
307 to isolate the quartz rich fraction. This has then been treated with HF 40% to dissolve the  
308 remaining feldspar and remove the outer layer of quartz grains, affected by alpha irradiation.  
309 Initial measurements using infrared stimulation (IR) indicate the presence of feldspar in the  
310 quartz fraction, even after the chemical treatment. In order to deplete the contribution of  
311 feldspar in the OSL signal used to calculate the equivalent dose of each sample, post-IR OSL  
312 (Roberts and Wintle, 2003) has been used. 24 to 48 small multi-grain aliquots (~30 grains per  
313 aliquot) of each sample were measured. Burial doses have been estimated using the Central  
314 Age Model (CAM; Galbraith et al., 1999) unless otherwise stated.

315 Dose rates have been calculated from the activity concentration of radionuclides in the  
316 surrounding sediment derived from high resolution gamma spectroscopy on approximately  
317 100 g of ground bulk material. Contribution from cosmic radiation has been calculated  
318 according to the sample depth assuming a linear accumulation of deposits. Water content of  
319  $17\pm 5\%$  has been assumed representative of the burial period; attenuation of the dose rate was  
320 calculated accordingly. Geographical position and sediment overburden were taken into  
321 account in the calculation. Total dose rates to an infinite matrix have been calculated using  
322 DRAC v1.2 (Durcan et al., 2015).

#### 323 **4.3. Infiltration capacity efficiency of *Acequia de El Espino***

324 During the 2014-15 hydrological year, flow infiltrated in *Acequia de El Espino* was determined  
325 through two automatic capacitance water level loggers. They were installed in order to  
326 measure the inlet flow in *Acequia de El Espino* and *Sima de Bérchules* (i.e. points 2 and 13,  
327 respectively, in Fig. 6A) and set to log the height of the water level in the channel every hour.  
328 The first one was installed 110 m from the beginning of the channel (point 2 in Fig. 6A), and  
329 the second was located upstream of *Sima de Bérchules* (point 13 in Fig. 6A). In these two  
330 points, the velocity of water flowing through the acequia was measured with a fortnightly  
331 frequency. To this end a C2 10.150 OTT flowmeter was used. The water flow rate at each point  
332 has been obtained by multiplying the obtained velocity by the corresponding channel section.  
333 The propellers and the body of the flowmeter have been regularly calibrated following the ISO  
334 3455 standard. In addition, 13 flow measurements were accomplished (04/28/2015)  
335 throughout of *Acequia del Espino* channel in order to identify the stretches in which the  
336 infiltration was concentrated (Fig. 6A).

## 337 **5. Results**

### 338 **5.1. Historical and archaeological analysis**

339 Little is known about the specific history and the origins of Bérchules village. Its own name  
340 meaning is even unknown. It appears for the first time in the 10<sup>th</sup> century as a district (*yuz*)  
341 called Buryil (Sánchez-Martínez, 1975; Trillo-San José 1994). The arrival of the new Arab and  
342 Berber conquerors in the 8<sup>th</sup> century provoked an important change in settlement patterns  
343 and landscapes with the creation of *alquerías* (villages) and the construction of new productive  
344 systems linked to water. New population coming from the Middle East (Yemen, Arabia, Syria,  
345 Jordan) and North Africa settled. There are not many data in this case and despite they are  
346 late, they are significant: there were neighbours named as Humeya, Quinda and Hanena that  
347 might have been part originally of the important eastern tribes of Umayya, Kinda and Canena.  
348 There is a neighbourhood and a small mosque referred as Beni Helil (a tribe name and a region

349 in current Morocco) and another called Beni Yahi (tribe and region in Algeria) (LAR, 1573). It  
350 was that population, organized by kinship relationships, which was responsible for the creation  
351 of irrigation and aquifer recharge systems from the 8<sup>th</sup> century onwards (Glick, 1988; Glick and  
352 Kirchner, 2000; Barceló, 1989; Trillo, 2004; Watson, 2008; Martín-Civantos, 2007, 2011;  
353 Barceló 1989). The *careos* system has been specifically documented in the Lugros Valley  
354 (Northern side of Sierra Nevada) during the 11<sup>th</sup> century, thanks to a lawsuit between two  
355 different villages fighting for water rights (Martín Civantos, 2010).

356 They settled in separated neighbourhoods still mentioned in the 16<sup>th</sup> century documents (LAR,  
357 1573). In Bérchules there were three: Purchena, Cuchurrio and Alcútar. In addition, there were  
358 nine watermills and several farms spread in the territory. Bérchules was, indeed, the whole  
359 *alquería* (village) intended as the settlement, the territory and the community that lived in and  
360 managed it.

361 According with 16<sup>th</sup> century documentation (LAR, 1573), Bérchules neighbours had the right to  
362 use water from Berchules River (Fig. 5) throughout five channels (*acequias*): from the Grande  
363 River the highest channel was *Acequia de las Hoyas*, that irrigates the eastern slope of the  
364 valley. From the Chico River three channels were caught above the two rivers joining point and  
365 another one just below. The highest is the *Acequia de El Espino*. The second channel is called  
366 the *Acequia Real* which is located downstream with the beginning just where the intensive  
367 irrigated zone of the basin starts. Finally, the *Acequia Nueva* catches water after the two rivers  
368 joining, and it also irrigates until the Cairo ravine.

369 The Castilian conquest took place in 1492, when the kingdom of Granada surrender. But the  
370 population was allowed to stay, previous a forced conversion to Christianity, until they  
371 rebelled against the Castilian and were defeated between 1568-1571. After that, the Moriscos  
372 were forced to leave their land, and a population process occurred with people coming from  
373 different parts of the Iberian Peninsula. The *careo*-based water management system has

374 survived until now, being still in use despite the marginalization of traditional agriculture. The  
375 first specific reference to the aquifer recharge, including its description, was made in 1805 by  
376 the naturalist Simón de Rojas Clemente. Rojas visited the valley of Mecina Bombarón, close to  
377 Bérchules, and described the *careos* and *simas* and their management (Guzmán Álvarez, 2010).

378

## 379 **5.2. Sedimentary infill analysis and dating**

### 380 5.2.1 Geophysics

381 Seven geoelectrical profiles (Fig. 6) were conducted between October 2014 (*Sima de*  
382 *Bérchules*) and April 2016 (*Sima de Márcula* and *Sima de los Helechales*). Acquisition in the  
383 former location was performed after the infiltration period, meanwhile the geophysical  
384 profiles in *Sima de Márcula* and *Sima de los Helechales* took place after an anomalous dry  
385 winter, affecting the resistivity values. The effective penetration depths are around 13 and 50  
386 m, depending on the electrode spacing selected (ranging from 1 to 3 m). Total length of the  
387 profiles was comprised between 80 and 240 metres.

388 The resistivity models obtained from 2D inversion of data acquired in *Sima de Bérchules* (Fig. 7)  
389 show a relatively low resistive layer ( $<2000 \Omega\cdot\text{m}$ ) at surface, corresponding to the siliciclastic  
390 deposits. Below it, the non-altered rocks are represented by a resistive zone ( $>2500 \Omega\cdot\text{m}$ ) that  
391 extends downwards from the surface and/or from the lower boundary of the conductive  
392 altered area. This lower resistive body is laterally and abruptly distorted by sub-vertical lower  
393 resistivity bodies with high chargeability values around  $600 \Omega\cdot\text{m}$  (see supplementary data) that  
394 are interpreted as sub-vertical fractures with metallic mineralizations (high chargeability  
395 values). Core SB1 (Fig. 8) reveals a minimum thickness of 4,4 m for the sedimentary infill. The  
396 intersection of the core with the bedrock coincides with the  $\sim 2000 \Omega\cdot\text{m}$  resistivity contour line.

397 This boundary has been chosen to mark the base of the sedimentary infill by the black dashed  
398 lines, showing a maximum thickness of 10 m to the south of the SB1 borehole.

399 In the case of *Sima de Márcula* and *Sima de los Helechales* the resistivity values obtained  
400 through the 2D inversion models (Figs. S2 and S3, supplementary data) differ from those of  
401 *Sima de los Bérchules*, probably due to the amount of water contained in the subsurface.  
402 During the field survey, the *Sima de Bérchules* recharge area was fully saturated meanwhile  
403 the other sectors were not used to infiltrate water that year. The altered sedimentary infill  
404 shows resistivity values greater than 1500  $\Omega\cdot\text{m}$  and a lower development than in *Sima de*  
405 *Bérchules* with maximum thicknesses of 8 and 2 m, respectively.

406 The DOI index method was applied to obtain the depth of investigation and a cut-off value of  
407 0,1 was chosen and highlighted on the profiles using a white dashed line (Fig. S1, S2 and S3 of  
408 the supplementary data). Above this contour, data show an overall high resolution meanwhile  
409 below it remains the areas with less reliability of the profile. Note that the bottom of the  
410 sedimentary infill is always located over the DOI limit.

#### 411 5.2.2 Sedimentology

412 Siliciclastic deposits of Bérchules, Márcula and Helechales *simas* are always placed in the  
413 downslope side of *Acequia de El Espino*, where the outflow gates, for diversion of the flow to  
414 flood the *simas* and recharge the aquifer, are also placed. The deposits are gravels, sands and  
415 silts arranged in an approximately lens-shaped body, of erosive bottom and concave top, of 10  
416 m in thickness (Fig. 7) that lie unconformably upon weathered schists of the Nevado-Filábride  
417 Complex (at 4,4 m in depth in core SB1; Fig. 8).

418 Gravels are clast-supported with sub-rounded clasts of schists and minor amounts of  
419 subangular clasts of quartzite and quartz. Clast size mode ranges from 0,4 to 1 cm and  
420 maximum size vary from 4 to 4,5 cm in the drilled cores. The scarce matrix is composed by

421 sand and silt-sized grains of quartz (main), plagioclase and/or amphibole (secondary) and very  
422 low amounts of clay (mica, chlorite and kaolinite). These deposits arrange in unordered or  
423 fining-upwards layers of 0,05 to 0,33 cm in thickness. Lateral and vertically, they change into  
424 medium to fine sands with sparse clasts (up to 4 cm in diameter) and variable content in  
425 clayey-silty matrix. The mineralogical composition of the sands is similar to that of the matrix  
426 of the gravels. The silty layers show a mineralogical composition like the sandy layers and can  
427 contain variable amounts of sand and low content in clays. These facies are related lateral  
428 (downslope) and vertically forming fining-upwards sequences of gravel-sand, sand-silt and, less  
429 frequently, gravel-sand-silt (Fig.8).

430 Mineralogical composition and textural features of the deposits record a short-distance  
431 transport, a source area of the sediments near the *Sima de Bérchules*, by high energy water  
432 currents that experienced a sudden loss of competence. Due to their position, the most  
433 plausible interpretation is that they are lobes rooted in the overflow gates of *Acequia de El*  
434 *Espino* with a fining-upwards trend related to the vanishing of the flow and a fining-laterally  
435 trend due to radial and downslope loss of competence. Piling up of sandy layers upon gravels  
436 in core SB1 that can be correlated to gravels on top of core SB4 (Fig. 9) records the lateral  
437 migration of successive lobes rooted in the same gate as they adapt to the morphology of the  
438 previous lobes.

### 439 5.2.3. Age of the sediments

440 Dose distributions derived from the post-IR OSL measurements are well defined with over-  
441 dispersion (OD) below 20% for samples BER-1, SB1, SB2 and SB4. Dose distribution of samples  
442 BER-2 and SB1 have an OD of 25 and 28%, respectively, suggesting that these units might be  
443 slightly affected by incomplete bleaching (i.e. grains that were not sufficiently exposed to  
444 sunlight to reset their OSL signal before been deposited and buried). This would imply that  
445 some of the grains still had a residual dose at the moment of burial deriving in a higher value

446 than the true burial dose. To try identifying the part of the population most likely to be well  
 447 bleached, the Finite Mixture Model (Galbraith et al., 1999) has been applied instead of CAM.  
 448 The model identifies two components; the lowest of which is used to estimate the burial dose  
 449 assuming the highest dose values are affected by partial bleaching. Estimated burial doses and  
 450 derived ages for the four samples are summarized in Table 1.

Sample	Depth (m)	Water content (%)	Total dose rate (Gy/ka)	Burial dose (Gy)	Age (years)
BER-1	1,0	17	3,17 ± 0,09	0,55 ± 0,02	170 ± 10
BER-2	1,0	17	3,17 ± 0,09	0,38 ± 0,02	120 ± 10
SB1-A	1,39 - 1,55	17	3,29 ± 0,15	1,02 ± 0,04	310 ± 20
SB1-B	3,14 - 3,24	17	3,59 ± 0,17	4,95 ± 0,14	1380 ± 80
SB2	1,54 – 1,68	17	3,31 ± 0,15	1,12 ± 0,02	340 ± 20
SB4	0,66 - 0,72	17	3,16 ± 0,15	0,69 ± 0,04	220 ± 20

451 Table 1. Summary of environmental dose rates, estimated burial doses using OSL and derived ages. Ages are  
 452 reported with 1-sigma error and expressed in years since 2016 (the year of sampling).

### 453 5.3. Infiltration capacity efficiency of *Acequia de El Espino*

454 During the hydrological year 2014-15, all the water diverted to *Acequia de El Espino* (1,57 hm<sup>3</sup>)  
 455 was infiltrated. The majority of the infiltration occurred along the channel (1,30 hm<sup>3</sup>) and 0,27  
 456 hm<sup>3</sup> were poured at the *Sima de Bérchules* in the period from April 1<sup>st</sup> to May 15<sup>th</sup>, 2015.  
 457 Between May 15<sup>th</sup> and June 15<sup>th</sup>, the diverted water was infiltrated along the channel before  
 458 arriving at *Sima de Bérchules*. As shown in Fig. 10, the water flow diverted from the river  
 459 should be higher than 150 L/s in order to reach the *Sima de Bérchules*. In addition, it could be  
 460 observed the similar evolution of the temporal flow variations in the two control sections  
 461 (points 2 and 13 in Fig.6A), with flow differences around the interval 120-300 L/s, revealing the  
 462 important infiltration capacity of the *acequia*.

463 Thirteen flow measurements were conducted in different points along the *Acequia de El*  
464 *Espino* on April 28<sup>th</sup>, 2015 (Figs. 6A and 11). Flow rates were comprised between 61 and 234  
465 L/s. On the way to *Sima de Bérchules* 173 L/s were infiltrated and 61 L/s at the *Sima de*  
466 *Bérchules*; therefore, all the diverted water from the river was entirely infiltrated at the schist  
467 weathered zone. Downstream of the sections with greater infiltration, numerous springs  
468 emerge (Fig. 5B) and there are ravines with dense riverbank vegetation fed by these channels.

## 469 **6. Discussion**

470 The use of water of ephemeral streams to do water harvesting was already the basis of  
471 livelihood in several arid and semi-arid areas of the Earth thousands of years ago (Evenari et  
472 al., 1971; Prinze, 1996). However, the use of Managed Aquifer Recharge, understanding it as a  
473 method to intentionally recharging and hence storing water into aquifers for subsequent  
474 recovery or for environmental benefits, is more recent. An inventory of Managed Aquifer  
475 Recharge (MAR) sites in Europe (Sprenger et al., 2017) indicated that the first MAR site in  
476 Europe was located in Glasgow (UK), where a collector pipe parallel to the Clyde River was  
477 built in 1810. However, the *acequias de careo* in Sierra Nevada (Spain) are much older and  
478 constitute a fascinating example of MAR.

479 The ancestral MAR techniques are not exclusive of Europe, as different examples of ancestral  
480 groundwater recharge systems are also described in South America (Yapa, 2016). In the  
481 Ecuadorean coastal provinces of Santa Elena and Manabi, thousands of artificial U-shaped  
482 lagoons (called *albarradas*) appear, at places occupying a few hectares of surface area. They  
483 retain and recharge water behind small earth dams (Yapa, 2016). They are dated from 4000 BP  
484 (Marcos, 2006). With the same use, in Peru, circular excavations of small size and little depth,  
485 such as the *cuchacuchas* of Ayacucho, or larger dimensions such as the *qochas*, are frequent  
486 throughout the country. However, among all the precolonial MAR systems described by Yapa  
487 (2016), the most surprising system, due to its similarity with the *acequias de careo*, is that of

488 the *amunas* (Apaza et al., 2006), also called *mamanteo* (Bardales et al., 2015; CONDESAN,  
489 2015). The recharge procedure is the same used in Sierra Nevada despite (1) having an ocean  
490 in between and (2) being the *amunas* developed several centuries before the connection  
491 between both cultures. In this sense it should be noted that the scenarios had many  
492 similarities from the physiographic, geological and climatic point of view, an aspect that may  
493 have contributed to achieving the same solution. In addition, it impresses the high degree of  
494 hydrogeological knowledge and the remarkable technological development achieved by our  
495 ancestors. *Amunas* and *acequias de careo* were made with a great precision, with minimum  
496 slopes to avoid high speeds of the water, and were provided with numerous gadgets to control  
497 the flow, the capacity of infiltration, the speed of water, to reduce erosion, etc (Espín et al.,  
498 2010).

499 Historical and archaeological research has allowed to date the *careos* in Sierra Nevada at least  
500 since the 11<sup>th</sup> century (Martín Civantos, 2010) and they are specifically documented in  
501 Bérchules since the 15<sup>th</sup>-16<sup>th</sup> century. The *Acequia de El Espino* is already mentioned and  
502 described in LAR (1573) as a consolidated infrastructure with historical rights since the Islamic  
503 period, thus, at least since the 15<sup>th</sup> century. Water management has been traditionally linked  
504 to the creation of irrigated areas with a very complex communal management. Complexity is  
505 due not only to the infrastructures or technological elements (e.g. dams, channels, reservoirs  
506 and terraces). It is mainly due to (1) social distribution of water, (2) governance of the  
507 hydrologic resource, and (3) traditional ecological knowledge produced thanks to centuries of  
508 practice, experimentation and observation of water, soils, plants and animals. The  
509 transformation took place during the first centuries of the Islamic period, mainly from the 8<sup>th</sup>  
510 to the 10<sup>th</sup> centuries, although knowing the exactly social, economic and cultural processes  
511 that took place after the Arab and Berber conquest is rather complicated. Nevertheless, the  
512 exact dating of the hydraulic system is quite difficult due to the fact that is a peasant creation,  
513 using local perishable materials and with no monumental elements representing any external

514 power. Systems were design originally once and for all (Barceló, 1989), with few possibilities of  
515 a real modification (but at the same time with a great capacity of resilience). However, they  
516 were probably built by more than one generation, and they have been maintained, cleaned  
517 and renewed continuously by the local communities as part of the governance mechanisms.

518 The attempt to date the deposits of the recharge areas linked to the *Acequia del Espino* is, in  
519 this sense, a very important and complicated experiment. Most sediments cropping out  
520 downslope, in the surroundings of the *Acequia de El Espino*, are anthropic. Their location and  
521 textural features (poor sorting and roundness, geometry of the bodies, poorly defined  
522 stratification) point to an origin related to the sudden spreading of a confined flow from the  
523 irrigation channels during the opening of the channel gates at the human-induced recharge  
524 events. The repetition of such events during some centuries led to the genesis of fan-shaped  
525 bodies, up to 10 meters in thickness. Besides, the sediment dating technique with OSL shows  
526 that the sampled sedimentary filling material is recent. Although the oldest samples might  
527 need a more accurate age analysis, the estimated ages are coherent with the historical  
528 references regarding ancient agricultural practices at the study zone. Most of the samples  
529 were deposited between 120 and 1380 BP. The oldest sample, by far, corresponds to SB1,  
530 which is dated on 636 a.C. ( $\pm 80$ ) coinciding with the end of the Visigothic period. Despite being  
531 close to the 8<sup>th</sup> century (i.e. the Arab invasion began in 711 a.C.), this sample poses an  
532 interpretation problem, given that it is very unlikely that the recharge system was  
533 implemented at that time. The 8<sup>th</sup> century was a period of political crisis and social  
534 transformation in the Iberian Visigothic kingdoms. At this time, the dissolution of the existing  
535 political power structures coming from Roman times took place, and a social feudal  
536 relationship began to be imposed. In this framework, the social implication requirements to  
537 conduct the careo recharge activities along with developing and maintaining the dug irrigation  
538 net were difficult to be satisfied. As a result of these historical constraints a historiography  
539 issue arises regarding landscape transformation and required social related structures,

540 agricultural techniques and production processes and their actual link with the Arab conquest.  
541 The rest of the sediment samples are dated between 1676 and 1896 being the result of a  
542 continued annually use of the *careo* recharge system as explained by Simón de Rojas in 1805.

543 This work also proves the efficiency of *Acequia de El Espino* as a MAR technique despite the  
544 channel is dug in hard rocks. During the hydrological year 2014/2015 this channel recharged  
545 40% of the total Berchules River runoff measured at the outlet of the basin (Martos Rosillo et  
546 al., 2017). Different research works carried out in this basin (Jódar et al., 2017, 2018, Martos  
547 Rosillo et al., 2017, Barberá et al., 2018) have shown that the *careo* recharge increases the  
548 mean groundwater runoff, and also reduces the peak of the river hydrograph while increasing  
549 the river base flow. Besides, the modification of the hydrological basin behavior leaves the  
550 aquifer discharge fingerprint in the physicochemical and isotopic characteristics of water  
551 runoff that in turns facilitates the basin behavior characterization.

552 The increase of both the river base flow and the number of springs related to the *acequias de*  
553 *careo* recharge has favored the development of agriculture practices and livestock, and hence  
554 people settlement in Sierra Nevada since the Middle Age. Besides the profits produced by this  
555 management aquifer recharge to the local people, it also benefits the basin associated  
556 ecosystems. A greater groundwater discharge along the slopes of the mountain increases the  
557 vegetation cover, the riparian vegetation and the species diversity of flora and fauna in the  
558 watershed. Therefore, the *careo* recharge is not only a MAR system but also a living example  
559 of an ancestral Integrated Groundwater Resources Management (Jakeman et al., 2016). The  
560 *careo* recharge system has overcome the drastic environmental and social changes that have  
561 taken place over the past centuries thus proving a high resilience capacity. Nowadays this  
562 ancient integrated water management system is seriously threatened by different drivers as  
563 the aging of the people preserving and maintaining the system, the migration of local  
564 population to urban areas, and inadequate agrarian and water policies.

## 565 **7. Conclusions**

566 This study has proven that the *acequias de careo* may represent the oldest MAR system in  
567 Europe. In the 11th century, there were already operational *acequias de careo* in Sierra  
568 Nevada as proved by historical written documents. In the same way, there is a documentary  
569 record claiming that in 1573 the *Acequia de El Espino* was already in operation. Moreover, in  
570 1805, the recharging procedure used in one of the irrigation ditches belonging to the Bérchules  
571 basin was fully described in historical documents. Nowadays, the *Acequia de El Espino* takes  
572 water from the upper part of the Berchules River. The diverted water is guided while  
573 recharging along the upper most part of the right river bank. The water flowing at the recharge  
574 channel is also poured into flat and highly permeable areas called *simas*. Geological and  
575 geophysical research have shown that these *simas* consist in an artificial sedimentary infill,  
576 composed of gravel, sand and silt, which is closely related with the operation of the channel.

577 The dating of quartz grains embedded in the sedimentary filling material has revealed that  
578 these grains were sedimented between 1380 BP and today. The dating results largely  
579 corroborate the historical information, although interesting methodological questions arise  
580 regarding the possibility of setting chronologies and a sequence of human occupation, but also  
581 questions of historical nature respect to the origin of the *acequias de careo* and the role played  
582 on the development and implementation of the recharge techniques by both the indigenous  
583 (Hispano-Roman) before 711 a. C. , and Arabs and Berbers after the invasion of the Iberian  
584 Peninsula. This system, used by our ancestors as a tool for adapting to water scarcity, could be  
585 applied in other alpine basins or high altitude basins around the world as a valuable adaptation  
586 strategy to mitigate the forecasted impact of climate change. Therefore, to maintain and to  
587 improve this ancestral recharge system to survive in the future is a must providing scientific  
588 and institutional support to start new research projects, thus promoting global cooperation  
589 between scientists and practitioners involved in ancestral recharge techniques.

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Figure 1

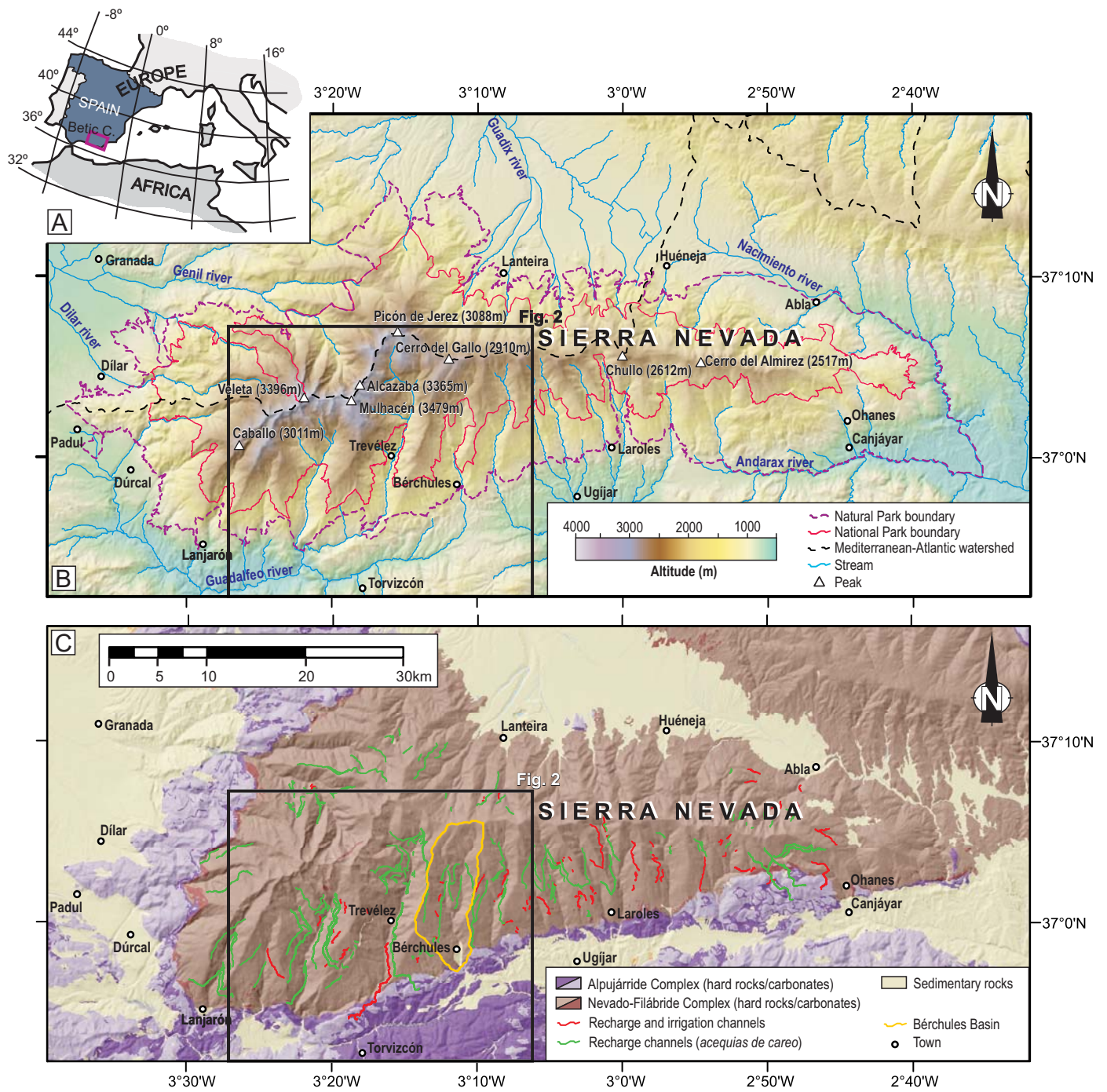


Figure2



Figure3

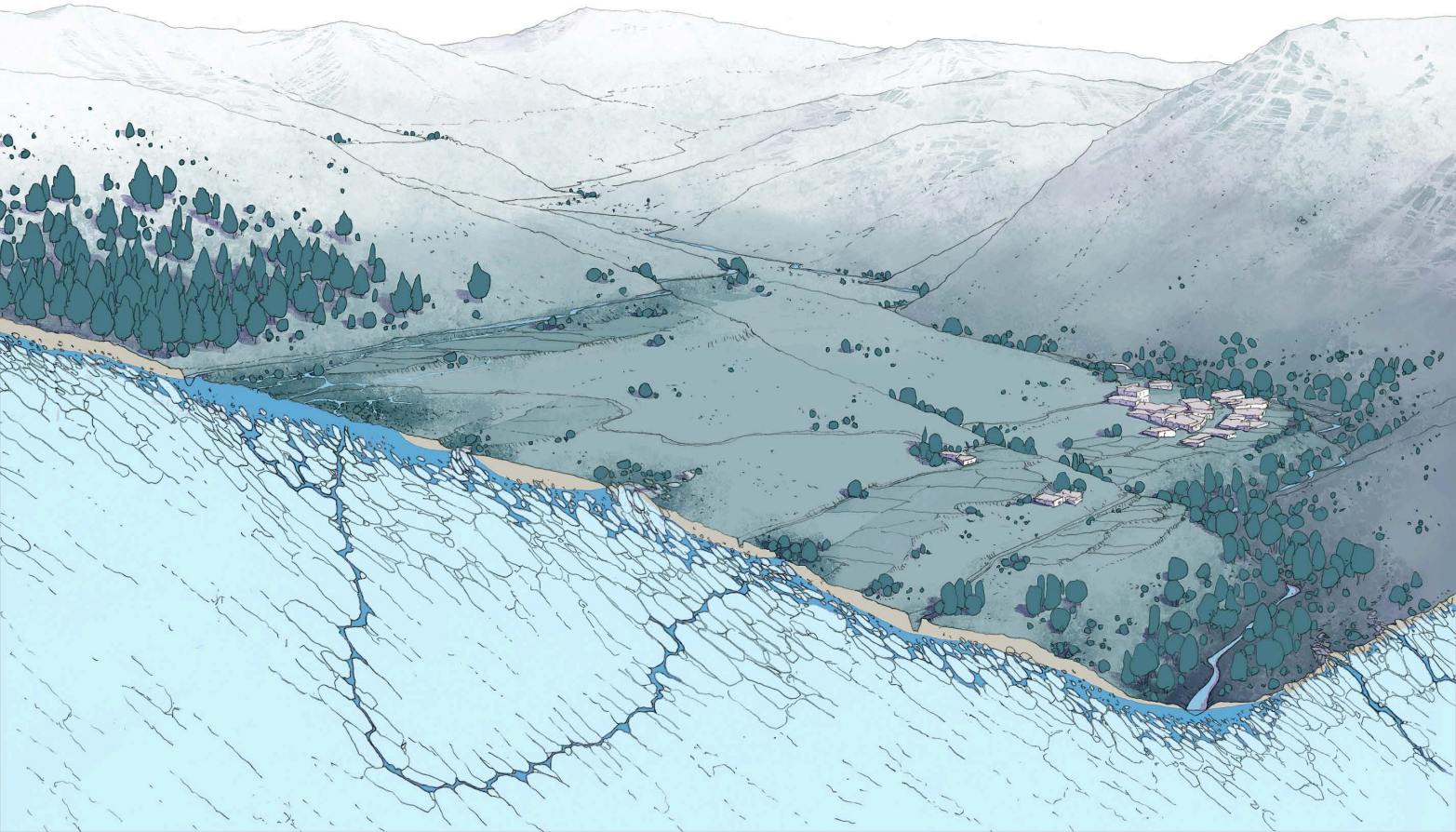


Figure4

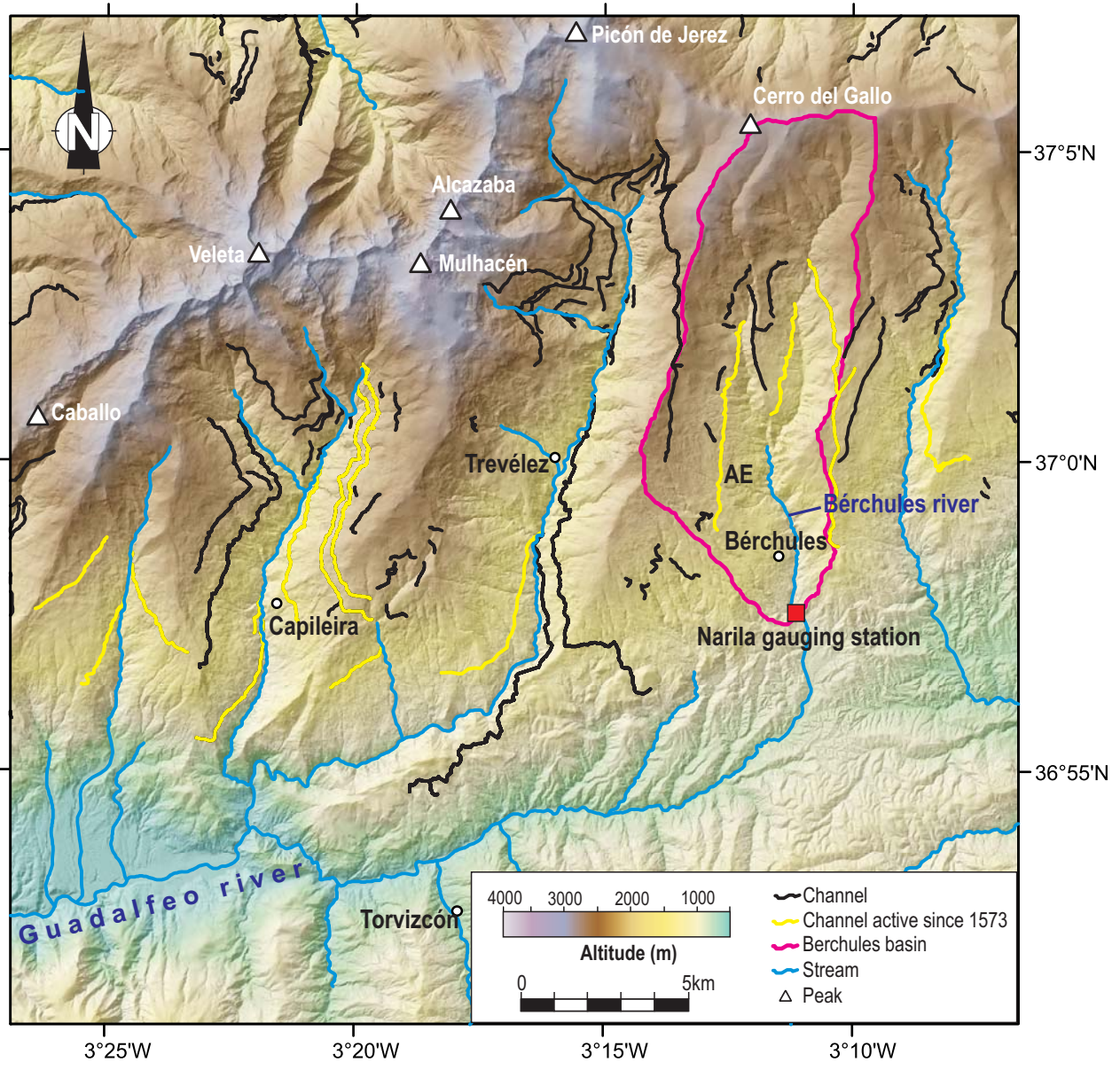
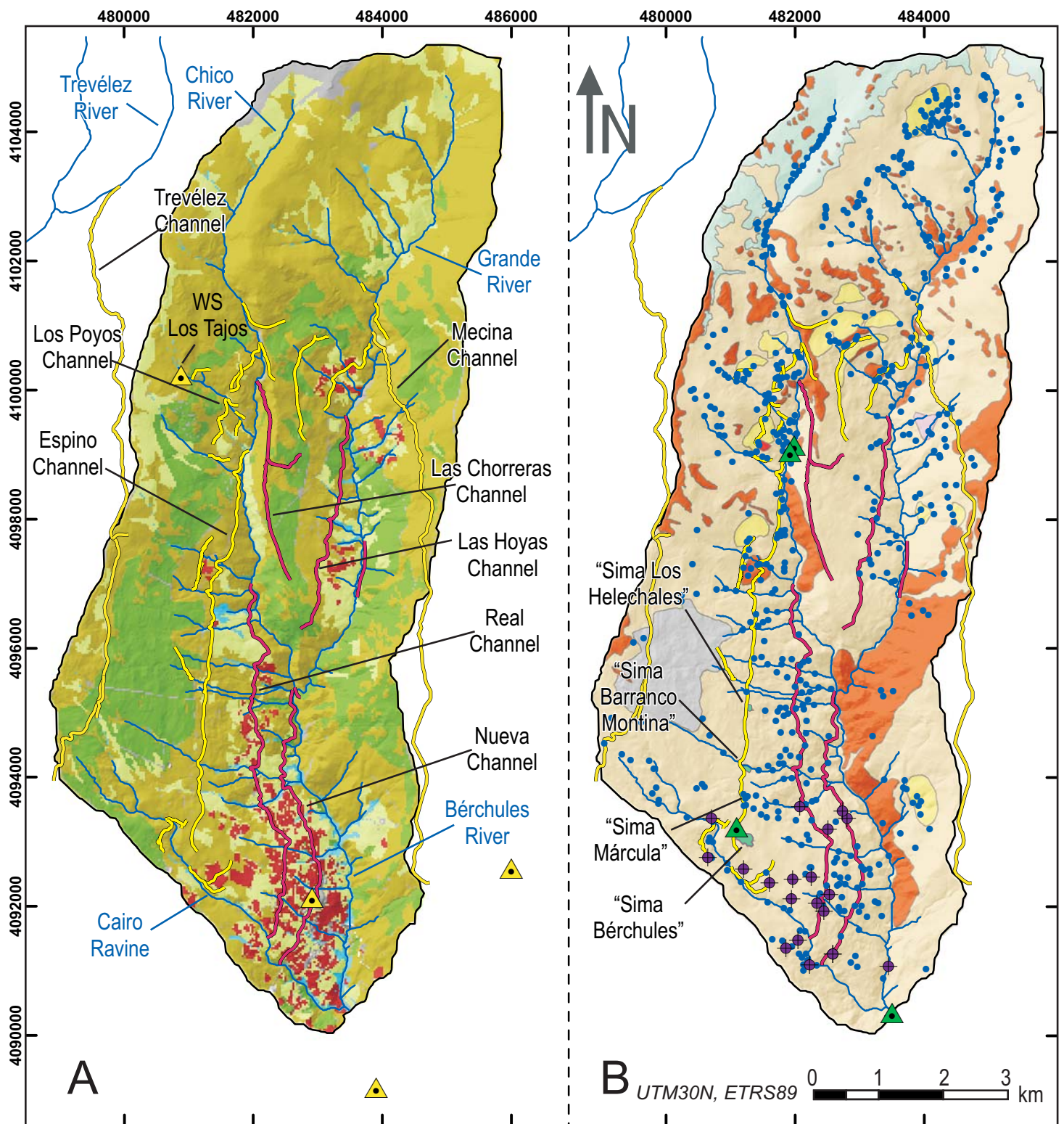


Figure 5



**Legend**

- Gauging station
- Well
- Spring
- Weather station
- Recharge channel (Acequia de careo)
- Irrigation channel
- River/stream

- Land use**
- Grassland
  - Scrub
  - Woods
  - Riparian vegetation
  - Irrigated horticultural crops
  - Bare soil

- Lithology / Hydraulic conductivity**
- Rocky basement / low
  - "Acequia de careos"-related sediments / intermediate
  - Periglacial debris / intermediate-high
  - Rockslide / intermediate-high
  - Solifluxion lobules / intermediate
  - Weathered schists and soil / intermediate

Figure6

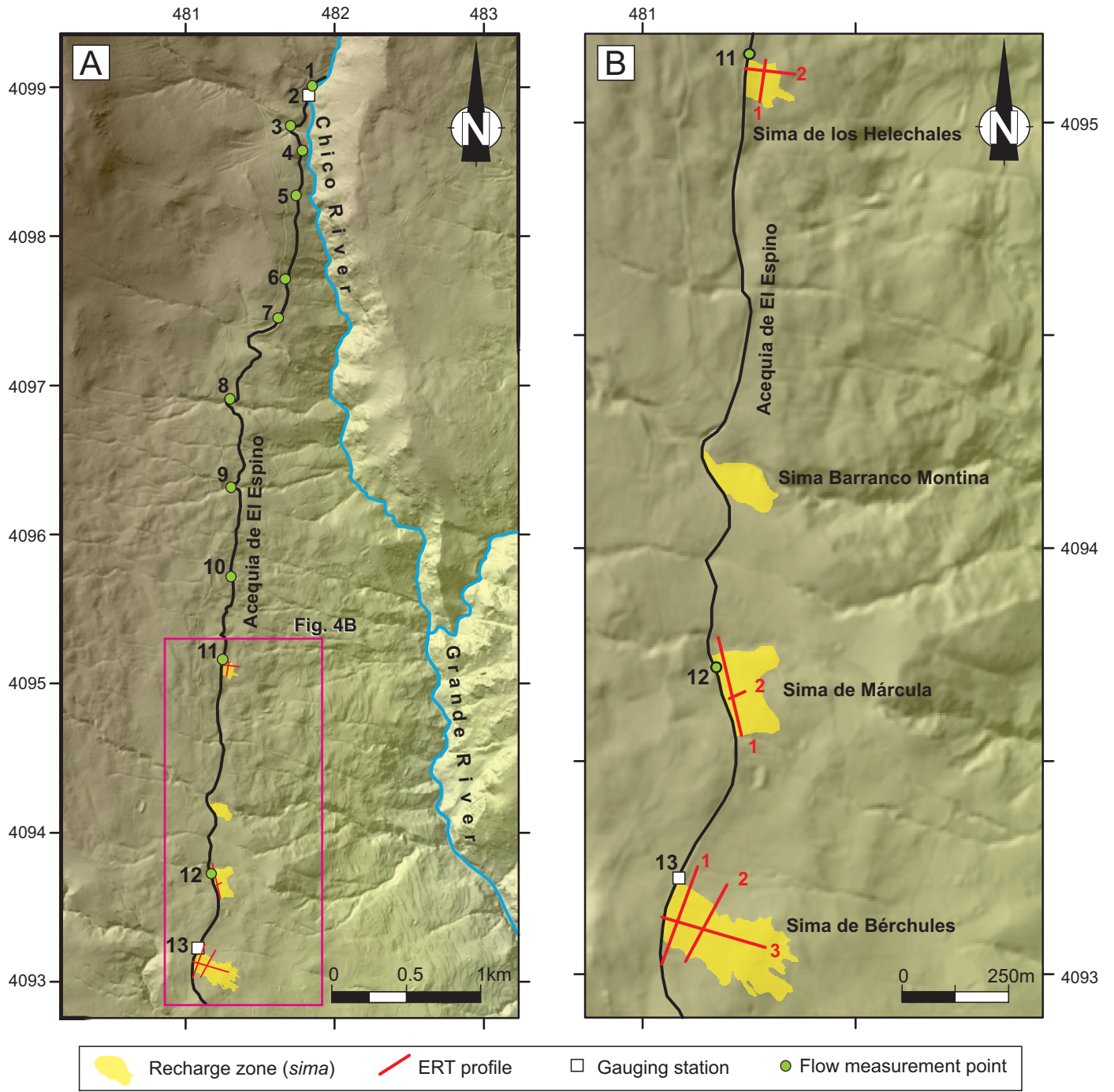


Figure7

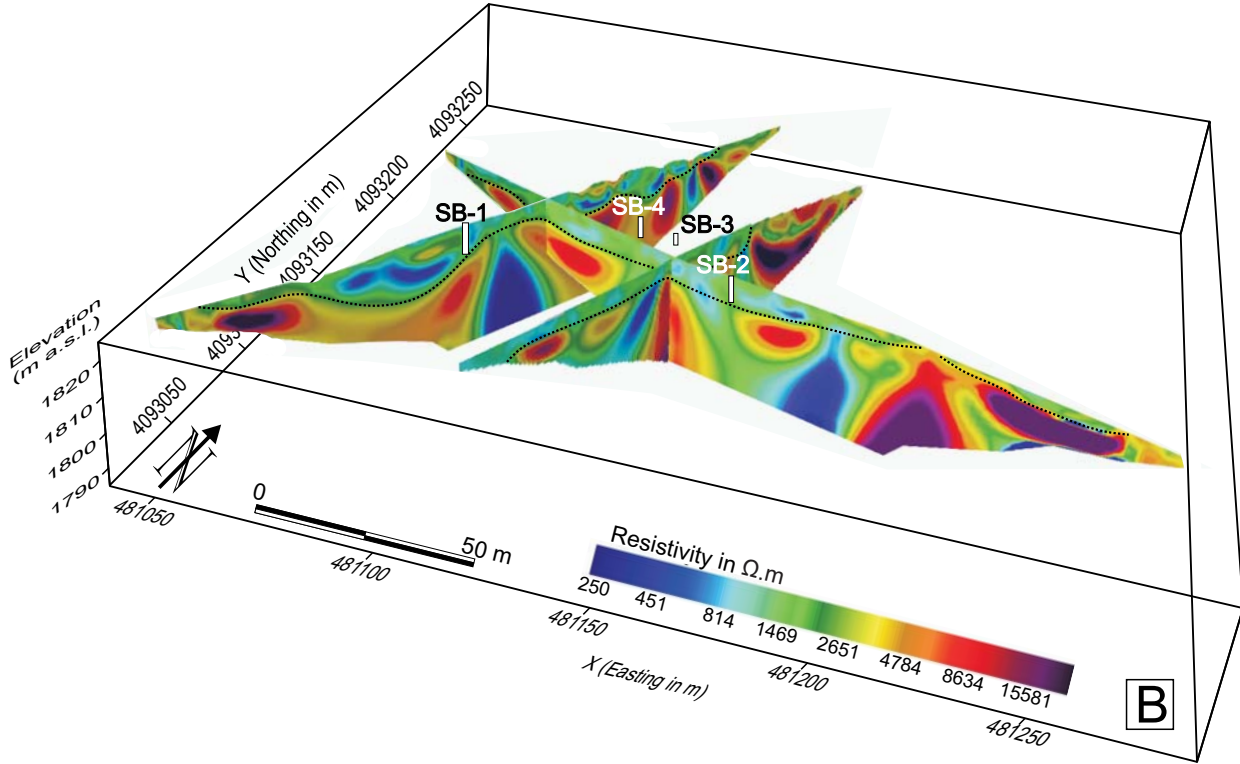
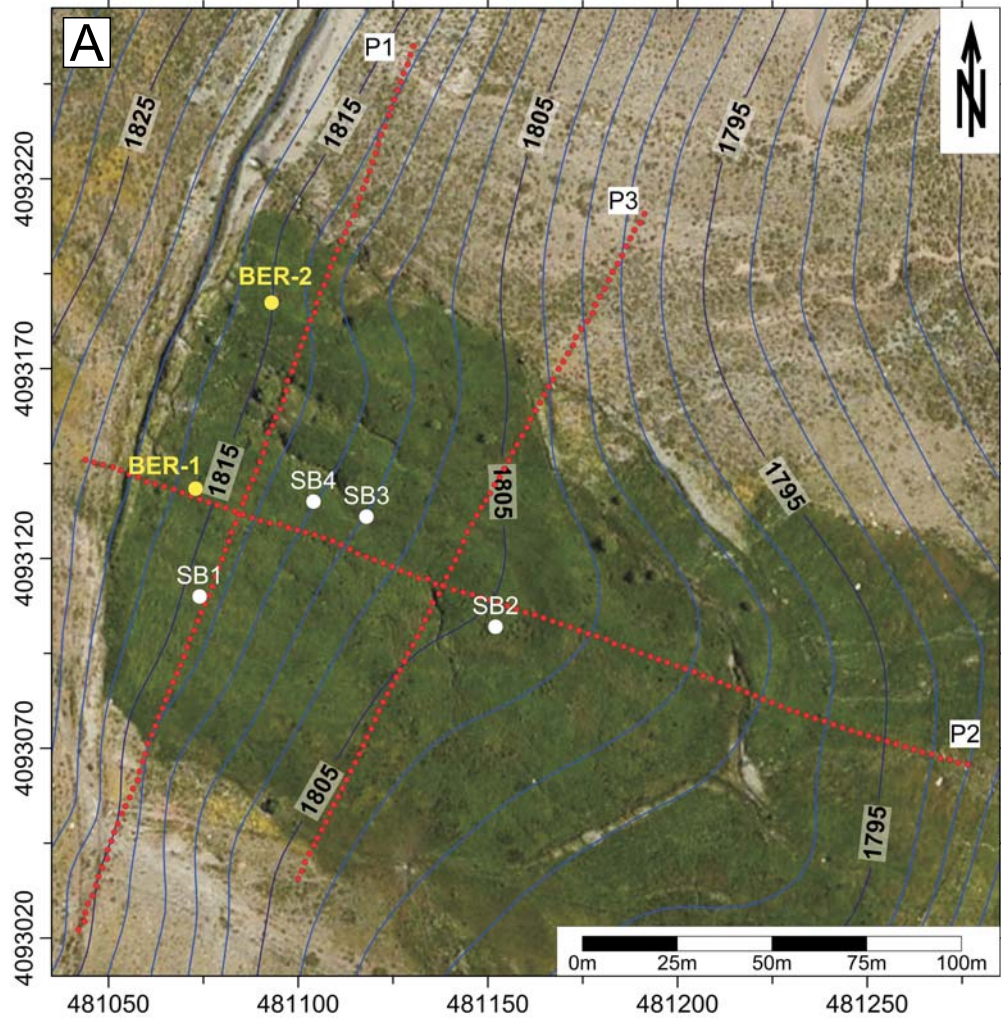


Figure 8

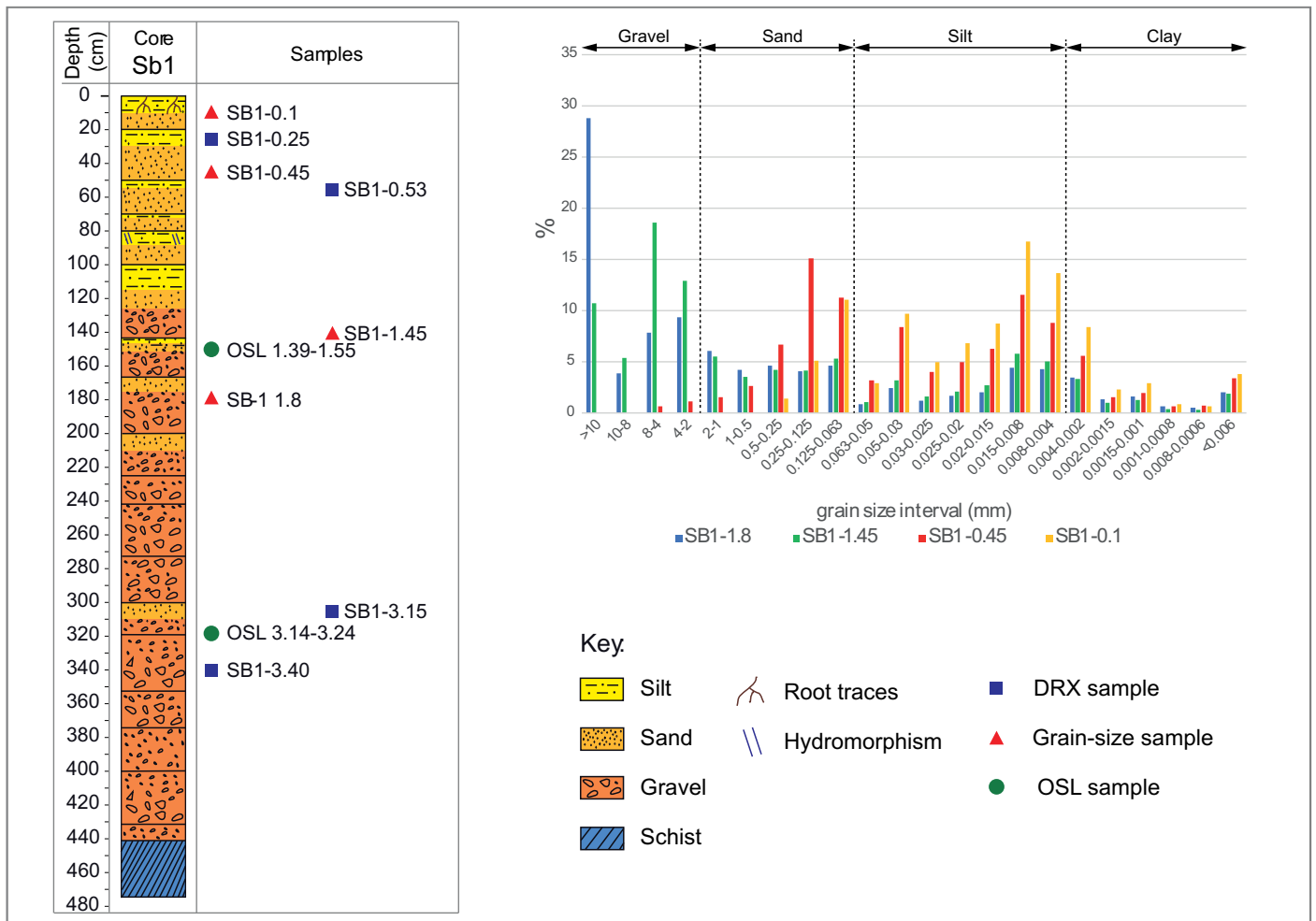
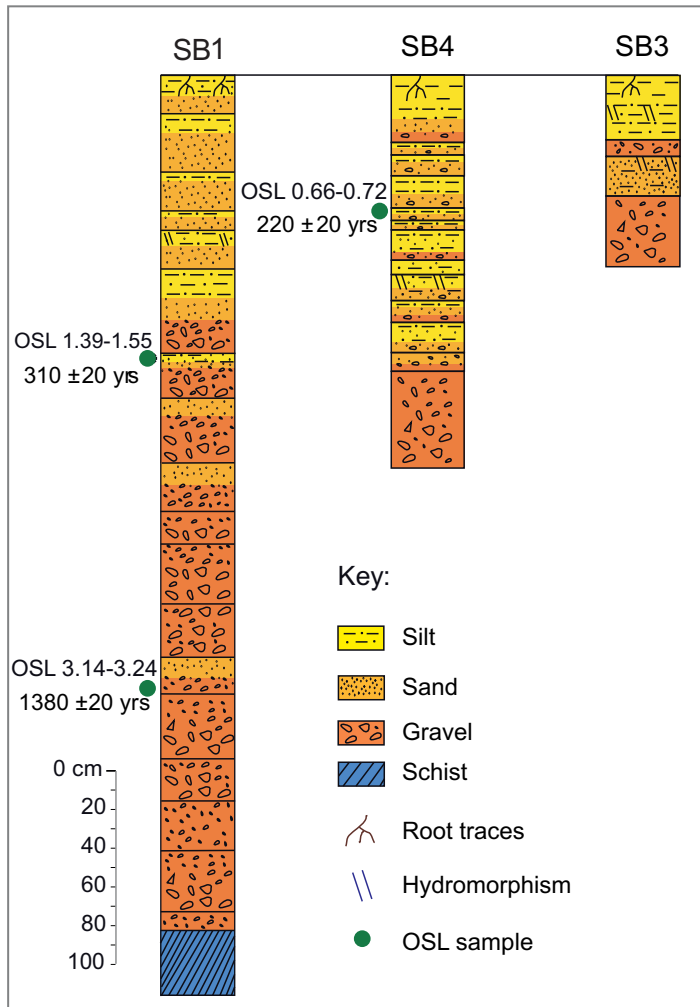
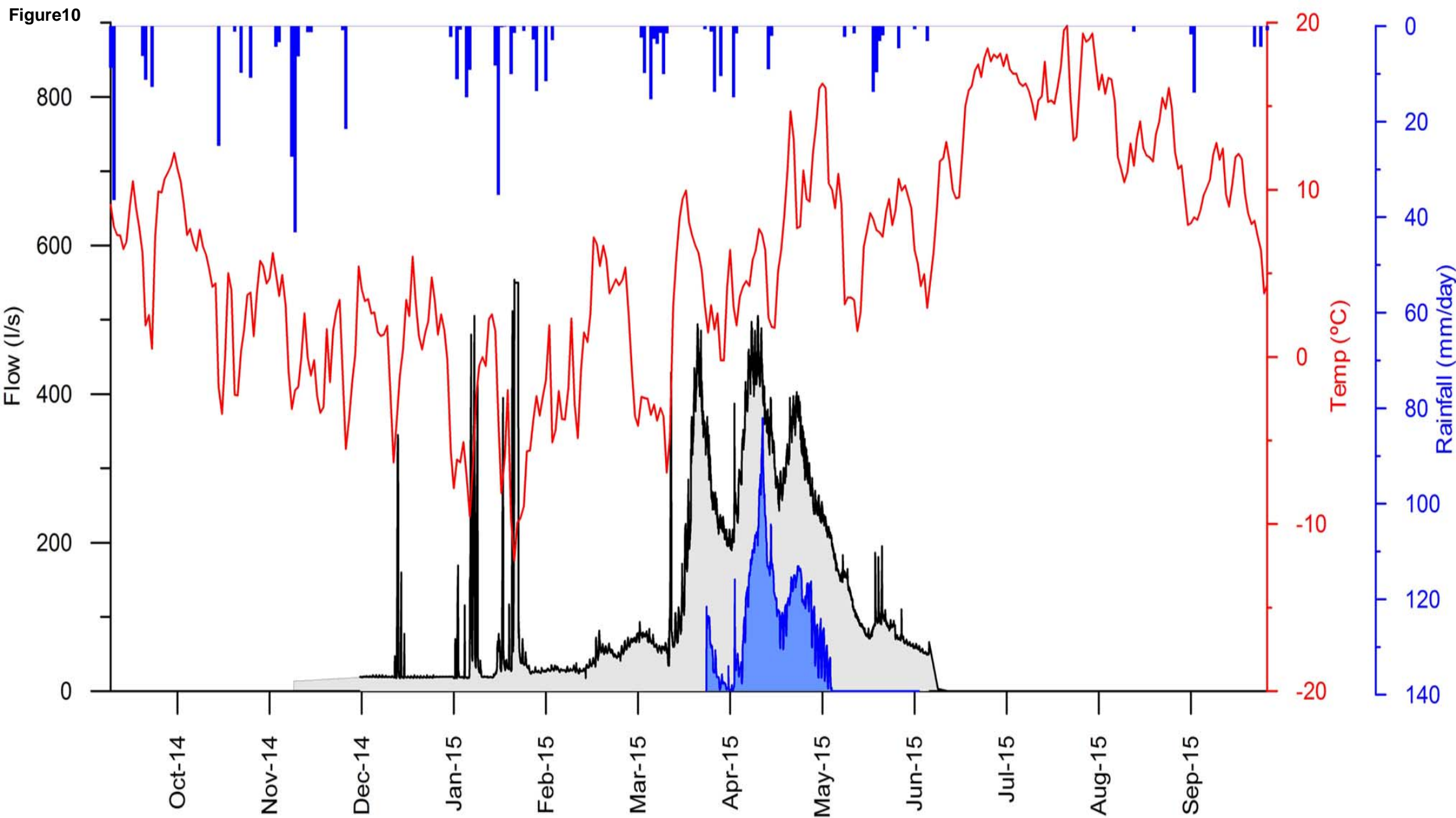


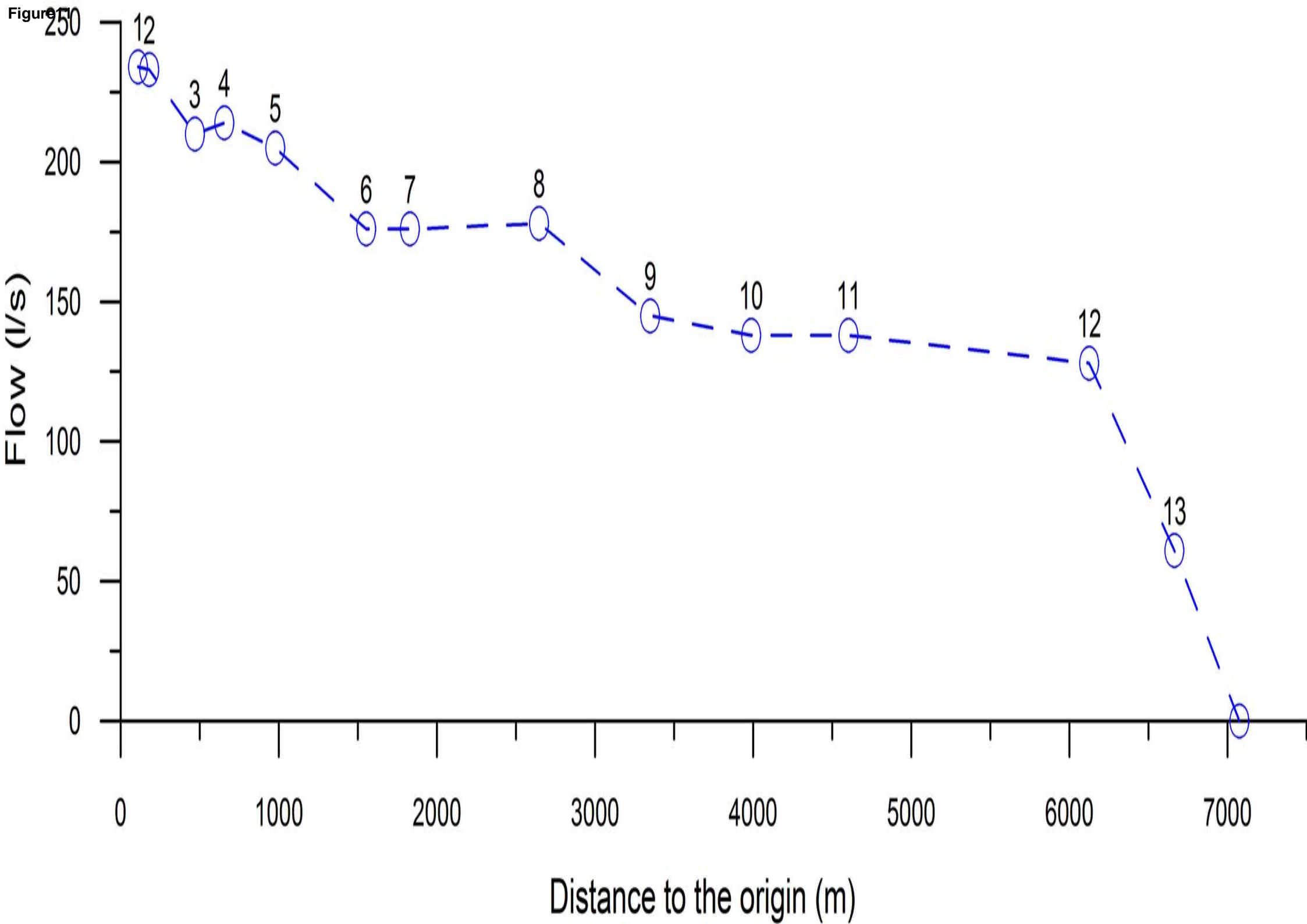
Figure9





## Legend

- 
- Volume of water infiltrated in *acequia Espino*
 Flow in gauging station 2 (Fig. 6)
  Temp. Tajos W.S. (Fig. 5)
- Volume of water infiltrated in *Bérchules Sima*
 Flow in gauging station 13 (Fig. 6)
  Daily rainfall Tajos W.S. (Fig. 5)



**Table1**[Click here to download Table: Tabla\\_1.docx](#)

<b>Sample</b>	<b>Depth (m)</b>	<b>Water content (%)</b>	<b>Total dose rate (Gy/ka)</b>	<b>Burial dose (Gy)</b>	<b>Age (years)</b>
<b>BER-1</b>	1,0	17	3,17 ± 0,09	0,55 ± 0,02	170 ± 10
<b>BER-2</b>	1,0	17	3,17 ± 0,09	0,38 ± 0,02	120 ± 10
<b>SB1-A</b>	1,39 - 1,55	17	3,29 ± 0,15	1,02 ± 0,04	310 ± 20
<b>SB1-B</b>	3,14 - 3,24	17	3,59 ± 0,17	4,95 ± 0,14	1380 ± 80
<b>SB2</b>	1,54 – 1,68	17	3,31 ± 0,15	1,12 ± 0,02	340 ± 20
<b>SB4</b>	0,66 - 0,72	17	3,16 ± 0,15	0,69 ± 0,04	220 ± 20

Table 1. Summary of environmental dose rates, estimated burial doses using OSL and derived ages. Ages are reported with 1-sigma error and expressed in years since 2016 (the year of sampling).

Figure 1. Geographic and geological setting of Sierra Nevada (A) Geographic location of the study area. (B) Boundaries of the National and Natural parks of Sierra Nevada. (C) Geologic map of Sierra Nevada showing the distribution of the main *careo* channels. In this map the boundary of the Bérchules watershed is indicated with a yellow line.

Figure 2. Sierra Nevada terraces, irrigations and recharge channels, and related deposits (A) Overview of terraced crops in Bérchules village; (B) *Acequia de Trevélez* with the backdrop of the Mulhacén and Alcazaba peaks; (C) Member of the Bérchules river Irrigation Community arranging the diversion dyke of *Acequia de El Espino*; (D) Overview of the beginning of *Acequia de El Espino*; (E) and (F) different views of *Sima de Bérchules* during the recharge period of the aquifer; (G) Drilling works for soil sampling at the *Sima de Bérchules*.

Figure 3. Scheme of the management aquifer recharge system using the *acequias de careo* during the snowmelt period in spring for recharging the aquifer (Illustration: Rocío Espín).

Figure 4. Location map of the recharge channels in the study area. Channels already documented in 1573 and still in use are highlighted in yellow (LAR, 2013); AE: *Acequia de El Espino*.

Figure 5. Land covers map (A) and hydrogeological map (B) of the Bérchules watershed.

Figure 6. (A) Map of the *Acequia de El Espino* showing the location of the flowrate measurement points, the gauging stations, and the recharge zones (i.e. *simas*); (B) zoom of the previous map corresponding to the lower part of the *Acequia de El Espino*, showing the location of the *simas*, the ERT profiles, the cores and the samples.

Figure 7. Location of the ERT and IP profiles in *Sima de Bérchules* (A) and 3D view of the 2D resistivity models inverted. The position of the cores is marked.

Figure 8. Stratigraphic section and grain size analysis of SB1 core.

Figure 9. Stratigraphical sections of SB1, SB4 and SB3 cores. No horizontal scale.

Figure 10. Flow rates in the gauging stations 2 and 13 (Fig. 6) of the *Acequia de El Espino*. The meteorological data come from the weather station of Los Tajos.

Figure 11. Flow rates measured along the *Acequia del Espino* on April 28, 2015; gauging stations 1-13 are located at Fig. 6.