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Revisiting irrigation efficiency before restoring ancient irrigation canals in multi-functional, nature-based water systems

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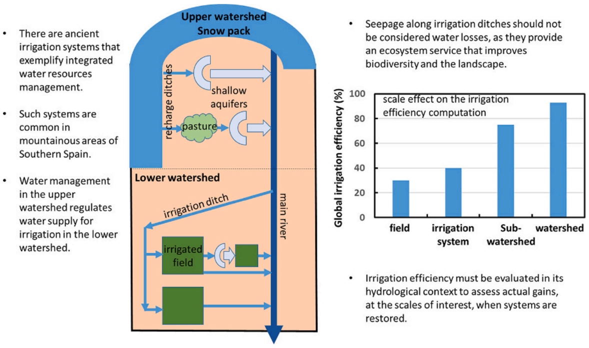
HIGHLIGHTS

- Irrigation systems of medieval origin are still in operation in Spain.
- Ancient irrigation systems provide ecosystem services in addition to agricultural production.
- The functionalities and efficiency of an ancient irrigation scheme in Southern Spain were characterized.
- The usual concept of irrigation efficiency can be misleading in the restoration of ancient irrigation systems.
- The irrigation efficiency concept was revised to reconcile efficiency gains of social and environmental nature.

GRAPHICAL ABSTRACT



- There are ancient irrigation systems that exemplify integrated water resources management.
- Such systems are common in mountainous areas of Southern Spain.
- Water management in the upper watershed regulates water supply for irrigation in the lower watershed.
- Seepage along irrigation ditches should not be considered water losses, as they provide an ecosystem service that improves biodiversity and the landscape.
- Irrigation efficiency must be evaluated in its hydrological context to assess actual gains, at the scales of interest, when systems are restored.

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ABSTRACT

CONTEXT: In the Middle Ages, the Muslims introduced communal water management in the Iberian Peninsula. Some irrigation systems of medieval origin are still in operation in the mountainous areas of Southern Spain. Snowmelt runoff is diverted during spring from high-altitude streams into contoured recharge ditches that convey the water to areas of high infiltration (shallow aquifers). This regulates and delays discharge into the main river, from which downstream flow is diverted, during late spring and summer, to irrigation ditches that supply terraces and fields on river plains. The Busquístar irrigation ditch and its irrigation scheme comprise one of these ancient systems.

OBJECTIVES: 1) To characterize the Busquístar system, its water source and regulation, its water users' association, its multi-functionality, and its quality as a nature-based solution for water security. 2) To review the irrigation efficiency concept applied to the restoration of ancient irrigation systems, taking into account their ecosystem services.

METHODS: i) Semi-structured interviews with stakeholders to evaluate irrigation system operation and perceptions of multi-functionality; ii) field surveys for description of the irrigation ditch and its riparian flora; iii) satellite imagery for quantifying riparian vegetation; iv) water balance for irrigation efficiency computation.

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RESULTS AND CONCLUSIONS: Crop production is the main function of the Busquístar irrigation scheme but additional ecosystem services are creation of landscape and biodiversity. Eight riparian plant communities were distinguished along the irrigation ditch. The discharge measured at its head on 23 July and 3 September 2017 represented 14 and 50% of the mean river flow in July and September, respectively. The flow measured at the first bifurcation of the ditch was about half that at the head, revealing the proportion filtered along its 6470-m long conveyance reach. The remaining flow was then diverted to 4 branches along the 3140-m long distribution reach proportionally to the irrigable area in each branch. Return flows and irrigation efficiency were estimated for the two measuring dates considering riparian and crop evapotranspiration. The estimated efficiency was highly dependent on which water uses were considered beneficial and on the scale of analysis, field, entire system or watershed.

SIGNIFICANCE: The study revealed the integrated approach behind the traditional water management in these ancient systems. The article proposes a review of the irrigation efficiency concept that allows reconciling the character of a nature-based solution with the current restoration of the system, responding to the needs of the emerging export horticulture in the area.

1. Introduction

Irrigation in Spain thrived in the Middle Ages. Muslims introduced, not only irrigation techniques, but also societal structures for communal water management (Glick, 1970; Glick and Kirchner, 2000; Trillo San José, 2005). Some irrigation schemes of Muslim origins remain in the region called Alpujarras, on the slopes of Sierra Nevada, southern Spain (Trillo San José, 2005; Mateos et al., 2007).

The water schemes in Alpujarras were conceived as networks of canals embedded in natural hydrological systems, in which snowmelt water was used, reused, and regulated by means of artificial recharge of shallow aquifers (Pulido-Bosch and Ben Sbih, 1995; Barberá et al., 2018; Jódar et al., 2018; Martos-Rosillo et al., 2019b). Although agricultural intensification is the primary function of these ancient water schemes, they are intrinsically multi-functional, including the creation of biodiversity and landscapes (Martín Civantos, 2011). These are, in fact, nature-based solutions, understood as being “solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience” (European Commission, 2020). In addition, nature-based solutions are locally adapted, and involve systemic interventions that bring diverse and natural characteristics into landscapes, and use the natural resources efficiently, features found in the ancestral irrigation practices in Alpujarras.

In contrast, modern irrigation development, including the Mediterranean region and others where rainfall cannot cover crop growth needs, has focused during decades on construction of dams and canals. The times of great constructions are, however, over and the focus has now shifted to the modernization of existing systems. Originally, that was restricted to the introduction of new physical structures and equipment. Later, it evolved into a transformation of the management of irrigation water resources, with the aim of improving the efficiency and productivity of the resources and services provided to the farmers (Playán and Mateos, 2006).

This concept of modernization, however, does not respond to the latest challenges of society, which include the depletion of resources, the deterioration of the environment, population growth and climate change. The question is: Do irrigation development agencies have a vision of how to meet today's complex irrigation demands? (Burt, 2013). For instance, the preservation of the Alpujarras nature-based solutions for earth-channel water management may come up against current EU policies targeting water savings. Under the European Agricultural Fund for Rural Development (EAFRD), “an investment in an improvement to an existing irrigation installation or element of irrigation infrastructure shall be eligible only if it is assessed *ex ante* as offering potential water savings of a minimum of between 5 % and 25 % according to the technical parameters of the existing installation or infrastructure” (European Parliament and the Council of the European Union, 2013). Applying this rule to ancient irrigation schemes such as those in Alpujarras might imply structural changes that would lead to the loss of other relevant functions, as discussed in this paper.

The objective of this study was to characterize the multi-functionality and ecosystem services of water in ancient irrigation systems using earth canals to recharge shallow aquifers in the upper watershed (regulating the river flow) and to irrigate crops in the lower watershed diverting water from the river. The study aligns with eco-hydrology as it analyses relationships between hydrological and biological processes on different scales, in order to understand water security, enhance biodiversity and explore opportunities for sustainable irrigation. The paper reviews the irrigation efficiency concept, and recommends guidelines for irrigation enhancement and restoration of canals in the light of nature-based solutions. The investigation uses as a study case the irrigation scheme of the Busquistar *acequia*, in the Trevélez watershed, Sierra Nevada, Spain. This scheme is cited in the Libros de Apeo of 1572–1575 (Dalaigue, 1995), testifying to its medieval origins and its existence before the deportation of the Muslims after the Christian conquest of this region.

2. Methods

2.1. The Busquistar *acequia*

The *acequia* (irrigation ditch) studied is part of the water system in the Trevélez River watershed. This watershed covers 150 km^2 of mountainous land on the southern face of Sierra Nevada, southern Spain (36^o 54′ to 37^{o}7’ N and 3^o 13′ to 3^o 18′ W) (Fig. 1). Around 66% and 22% of the area of the watershed are National and Natural Parks, respectively. Ground elevation varies from 430 to 3478 m a.s.l. Mean annual rainfall varies from about 500 mm in its lowest part to more than 1000 mm on the mountain summits. Rainfall distribution through the year is typical of a Mediterranean climate; the summer is dry and maximum precipitation occurs between November and February. It is estimated that about 75% of the precipitation above 2000 m a.s.l. is as snow, although data series above this altitude are lacking.

The predominant lithology in the Trevélez river watershed is graphite-micaschists of the Nevado-Filábride complex in the Baetic mountain range (Sanz de Galdeano and López-Garrido, 1998). Geomorphology is characterized by U-shaped valleys and glacial and periglacial landforms in the upper watershed. In the middle and lower watershed, the valley is narrower and presents an important asymmetry (Azañón et al., 2015; González-Ramón et al., 2015). The east slope is steeper than the west (Fig. 2a) due to the outcrop of unaltered schists on the west side. The relatively gentle west slope has allowed the formation of soils and the development of pasture, agriculture and human settlements.

According to the FAO's classification (FAO, 1998), the main soil types in the watershed are Lithosols and Cambisols (Proyecto LUCDEME, 1993). Land use in the upper watershed is pasture, sparse scrub and some patches of pine forest, except along the highest summits, where exposed schists cover the ground. Oak (*Quercus* spp.) forests occupy the middle watershed. The lower watershed is grown with crops on the west side of the river and is covered by scrub on the east side (Fig. 2b). Riparian vegetation is found throughout the river and ravines.

The natural drainage system in the Trevélez watershed is dendritic (Fig. 3). In addition, the watershed has a complex network of man-made open channels (*acequias*) with different functions (Fig. 3). In the upper watershed the *acequias* divert water from the ravine tributaries of the main river and convey it around the slopes to water the pasture for animal grazing and recharge shallow aquifers (these are the so-called *acequias de careo*), including into neighbouring watersheds. Other *acequias* in the middle and lower watersheds divert water from the ravines and the main river to supply small irrigation schemes (Fig. 3). Of these, the most important ones water field and horticultural crops, while others irrigate pasture. The total length of the *acequias* is of 110 km.

In our case study, we have addressed the Busquístar *acequia*, its irrigation scheme (BIS) (Fig. 3), and the water users' association (WUA) that manages it. There are historical records of the BIS and its WUA dating back to the Middle Ages (Dalaigue, 1995). The current water rights and bylaws were consolidated in 1770 and 1950, respectively (Comunidad de Regantes de la Acequia Gorda Real de Busquístar, Pórtugos y Ferreirola, 1952). The area with water rights in the Busquístar *acequia* is of 242 ha of terraced land, spread over 3 municipalities (Busquístar, Pórtugos and La Taha, with 97, 56 and 89 ha of irrigable land, respectively) at an altitude of between 900 and 1300 m a.s.l. The irrigable land belongs to 800 farmers, who make up the BIS WUA.

2.2. *Characterization of the Busquístar irrigation scheme (BIS)*

The BIS relies on the water supply from the Trevélez river, which, in turn, is regulated through the management of the *acequias de careo* in the upper watershed. Water management and the organization of the BIS was characterized based on field visits and interviews with the president and the water masters of the WUA, who assume all responsibilities for the distribution of water to all users and for the maintenance of the *acequia*. Semi-structured questionnaires helped to establish the history, traditional crops, socio-economic changes, current cropping trends, traditional and new irrigation systems, water management, traditional and local knowledge, organization of the WUA, perception of multifunctionalities and integrated water resources. Interviews were conducted in the summers of 2018 and 2020 and were one-on-one with each interviewee so that responses could be cross-checked.

The management of water in the *acequias de careo* was defined by following it up on multiple occasions, and was validated in three complementary meetings with the water masters and the cowboys who operate and maintain these *acequias,* formally or informally. The authors also interviewed officials at the Andalusian Mediterranean Basin Water Authority and at the Sierra Nevada National Park to gain knowledge of the regulations and institutional relationships affecting water use in the watershed.

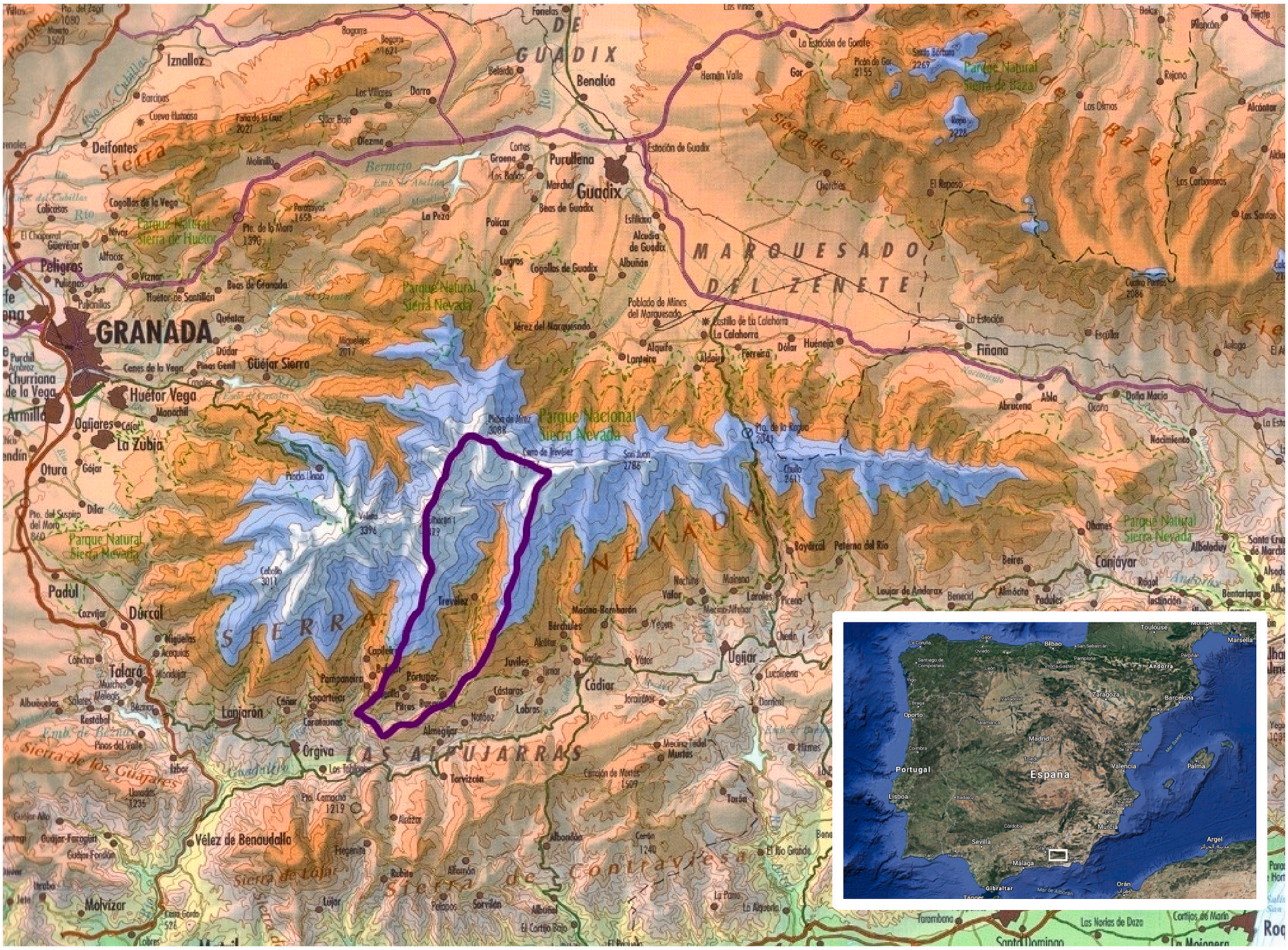

Fig. 1. Location of the watershed of the Trevélez River in Sierra Nevada (Spain).

2.3. Acequias and irrigation scheme cartography

The *acequias* in the watershed were digitized on 1:10,000 topographic-vectorial maps (Junta de Andalucía-IECA, 2007) corrected according to the authors' own observations. The cadastral map of the BIS was extracted from the SIGPAC (Junta de Andalucía-CAGPDS, 2017). The crop map in the BIS was based on the land use recorded in SIGPAC, field inspections and interviews with the president of the BIS WUA. Orthophotos acquired in, 2016 (IGN-PNOA, 2016) helped with the identification and verification of geographical features of interest. The physical description of the *acequia*, the localization of singular features and the characterization of its state was based on walking surveys along its entire length supported by smartphone GPS.

2.4. Hydrological data

The basin water authority records the Trevélez river discharge at a gauging station located in the village of Trevélez (Fig. 3), that collects the runoff from the upper and middle watershed (77 km^2). The available daily discharge data extended from 7 December 1995 to 31 May 2014 and were aggregated to monthly values. Availability of flow data after 2014 is erratic. Daily precipitation and temperature (interpolated by the kriging method using the weather stations reported in Jódar et al., 2018) were averaged across the part of the watershed upstream of the Trevélez gauging station, and aggregated to monthly values to be compared with the river discharge data.

Water diverted to the main *acequias de careo* was measured in June 2019, during peak snowmelt, using the propeller (current meter model C2 10.150 OTT, OTT HydroMet, Germany) method (Boiten, 2003).

Discharge at the Busquistar *acequia* was measured on 23 July (when the irrigation campaign was at its peak and the *acequia* operated at full capacity) and 3 September 2017 (end of the irrigation campaign) next to its inlet, using the float method (Boiten, 2003), and at the bifurcation structure where the distribution reach starts, which consists of four rectangular weirs, three in the *acequia* and another in the derived branch. Discharge equations for the rectangular weirs were taken from the US Bureau of Reclamation (1997).

Daily reference evapotranspiration (ET_o) from 2000 to 2020 (calculated as in Allen et al., 1998, and used to estimate the water requirements in the BIS) was taken from the Cadiar weather station of the Agroclimatic Information Network of Andalusia (www.juntadeandalucia.es/agriculturaypesca/ifapa/ria/). Crop and riparian vegetation water requirements were calculated for the two days on which discharge in the Busquístar *acequia* was measured. Calculations followed the FAO method by applying the single crop coefficient approach after selecting appropriate crop coefficients tabulated in Allen et al. (1998). The crop coefficient selected for the riparian vegetation considered that well-watered tall vegetation is surrounded by shorter and drier vegetation. Under these conditions, the evapotranspiration coefficient may be up to 2.5 (Allen et al., 1998). We selected a conservative value of 1.6.

The measurements of discharge in the *acequia* and the estimations of crop and riparian vegetation evapotranspiration were used to estimate

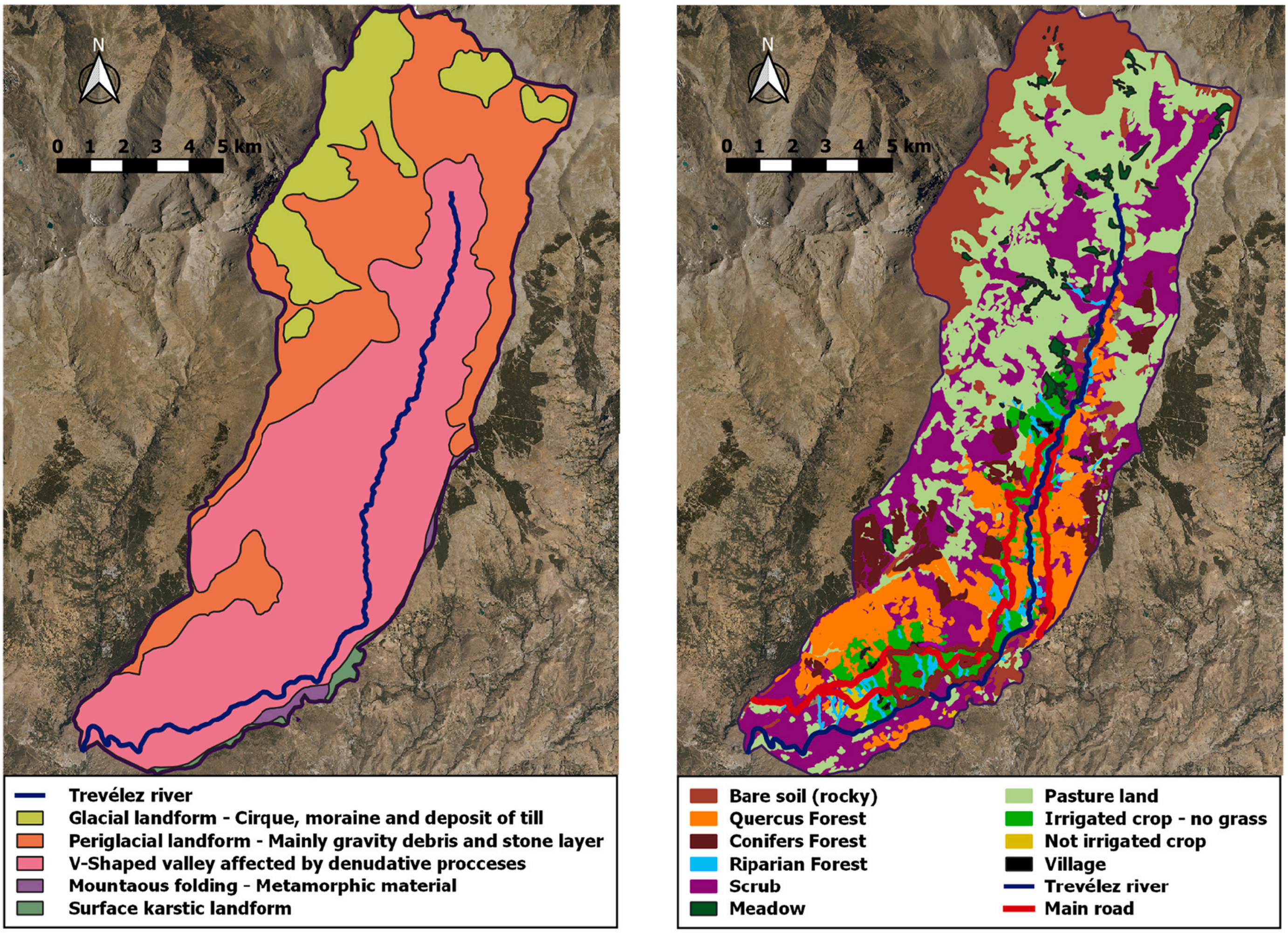

Fig. 2. (a) Geomorphology (Junta de Andalucía-REDIAM, 2013a) and (b) land use (Junta Junta de Andalucía-REDIAM, 2013b, and own elaboration) of the watershed of the Trevélez River in Sierra Nevada (Spain).

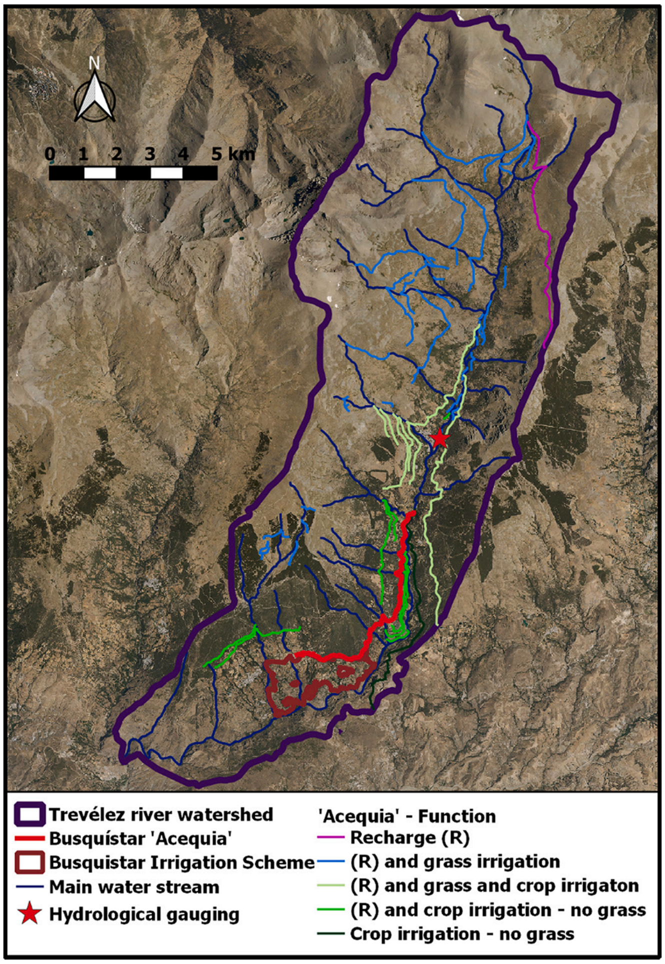

Fig. 3. Hydrology of the watershed of the Trevélez River in Sierra Nevada (Spain).

irrigation efficiency. Irrigation efficiency has several definitions in the irrigation literature. We adopted the currently most widely used definition (Burt et al., 1997):

$$\text{Irrigation Efficiency} = 100 \times \frac{\text{Volume of irrigation water beneficially used}}{\text{Volume of irrigation water diverted} - \Delta\ \text{storage of irrigation water}} \tag{1}$$

2.5. Riparian vegetation survey

Riparian flora along the Busquístar *acequia* was characterized by a botanical survey carried out on 23rd August 2020, that covered two stretches comprising 2900 m out of a total of 8400 m. The stretches surveyed were segmented based on the variation of predominant plant species. The segments were geo-localized using a smartphone GPS.

Biomass along the *acequia* was quantified using the normalized difference vegetation index (NDVI) obtained from the near-infrared and red spectral bands (pixel size of 10 m) in images acquired by the Sentinel-2 satellite on 21 August 2020 (Copernicus Programme, European Space Agency. First, we delineated two buffers (150- and 10-m wide, respectively) along the acequia on the upper side of the slope. The 10-m wide strip next to the *acequia* was assumed to benefit from the water filtering from the *acequia*. The 140-m strip above represented the natural vegetation without influence from the *acequia*. Below the *acequia*, we computed a 15-m wide buffer that was clipped when it overlapped cultivated fields and extended when the density and greenness of the vegetation (perceived on the ground, in the orthophoto or with the NDVI) was distinct from the surroundings, without any justification other than the effects of the *acequia*. For NDVI analysis purposes, the *acequia* was segmented considering the vegetation above it, the width of the riparian vegetation affected by its infiltration below it, the plant communities identified during the botanical survey, and the separation between the conveyance and distribution reaches.

3. Results

3.1. Current state, agricultural activity and management in the Busquístar *acequia*

The length of the *acequia* is of 8400 m, running from 1320 at the river intake to 1305 m a.s.l in the location of Pórtugos, where the *acequia* ends. It has been dug into the ground throughout its entire length. The bed of the *acequia* is naturally covered by deposits of fine material transported by the water. Some small sections are concrete-lined (for instance, along the first 125 m next to the river inlet and along the 80-m stretch where the main road crosses the *acequia*), while steep slopes are traversed with bench flumes supported by retaining walls, originally built of dry stone and recently rehabilitated with masonry. These channel sections represent approximately 1% of the total length of the *acequia*. Riparian vegetation (aquatic plants, grass, scrub and tall trees) flanks the *acequia* throughout its entire length.

The distance from the intake to the first control structure is of 6470 m. This control structure is a fixed divider with 4 equal thin plate weirs, customized for a proportional supply (Fig. 4). Three flow aliquots continue in the *acequia* and the fourth diverts to the lateral that irrigates the first sector. The second control structure is another fixed divider with 3 equal weirs, also customized for proportional supply (Fig. 4). Two flow aliquots continue in the *acequia* and the third diverts to irrigate the second sector. The third control structure, at the end of the main *acequia*, is a fixed divider with 2 weirs that equally serve the third and fourth sectors of the BIS. Each sector receives one fourth of the available flow, meeting the condition of proportional supply (Fig. 4). Likewise, each sector contributes to the operation and maintenance costs with a quarter of the expenses, viz. the cost of hiring two part-time workers for the surveillance, operation and routine maintenance of the *acequia*.

The BIS WUA byelaw established its right to divert water from the river from February to October. However, for some decades, the water has run into the *acequia* all the year round, except during the maintenance month (typically in May, before the start of the irrigation campaign). Both the basin water authority and the WUA understand that water running continuously favours infiltration and better preserves the state of the *acequia*.

During the irrigation season, water rotates within each of the four sectors. In the old days, the water rotated day and night. But, now, one reservoir in each sector stores water (the diverted flow) during the night to be used during the day. In this way, 5 farmers can irrigate simultaneously in each of the first two sectors, while up to 3 farmers can irrigate at the same time in the third and fourth sectors, allowing up to 16 farmers to irrigate simultaneously in BIS.

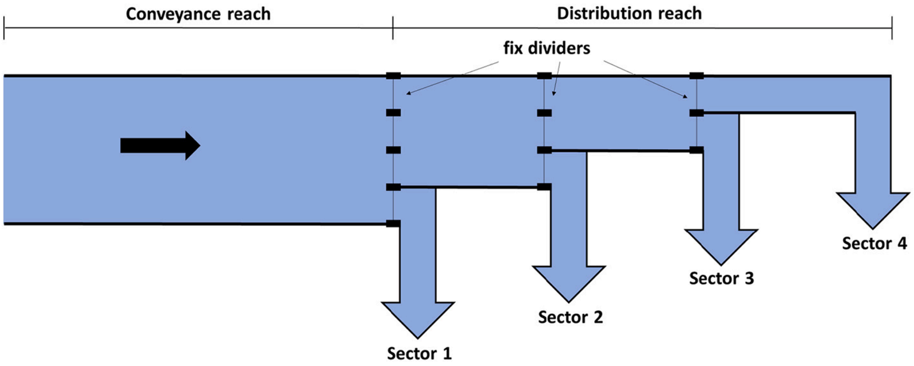

Fig. 4. Diagram representing the proportional division of the flow at the entrance of the distribution reach of the Busquístar *acequia*. Fixed dividers with 4, 3 and 2 equal thin plate weirs supply equal flows to the three sectors of the Busquístar Irrigation Scheme.

The above procedure refers to the farmers who have direct access to the *acequia*; other farms are supplied from springs below it. The locals understand that these springs are fed by seepage from the *acequia* (locally called "the mother") and by irrigation returns within the scheme. However, indirect irrigators, mostly on the lower periphery of the BIS perimeter, are not part of the WUA.

The traditional watering method was surface irrigation, which persists in some small orchards or small fodder fields. Currently, drip irrigation systems have expanded with the expansion of modern vegetable production, as well as the construction of larger polyethylene-lined regulation reservoirs. Hand-operated sprinklers are occasionally used on fodder crops and pasture. Other new cropping practices include shade netting.

3.2. *Multifunctionality of the Busquístar acequia*

The primary function of the Busquístar *acequia* is to enhance crop production in an environment in which agriculture without irrigation would not exist or would be marginal. The irrigable area is terraced land lying on slopes mostly facing south. On hundred and thirty-three ha of the irrigable land are currently unproductive (occupied by unmanaged grazing pasture), while 109 ha are devoted to horticultural crops: 53 ha with vegetables, 32 ha with fruit trees (mainly olive and almond trees), 12 ha with fodder crops, and the remaining 12 are small orchards for self-consumption. There are also chestnut and walnut trees scattered throughout the irrigation scheme, planted on the border of the fields. Tomato ("Cherry" type) is the most widely cultivated vegetable, destined for national and international markets. Its production cycle is integrated into the marketing channels of the powerful horticultural sector in the southeast of Spain. Zucchini, cucumber and green beans are also grown for the external market, but to a lesser extent than tomatoes. This new scenario is favouring the revitalization of the agricultural activity in the area, practically abandoned since the 1970s. The market for goods and inputs and the demand for labour add to the new boom in commercial agriculture that they serve. Previous inhabitants, who emigrated in past decades and during the crises of 2008 and COVID-19 (2020), are returning with enthusiasm to contribute to the new agricultural activity.

The Busquístar *acequia* fulfils other functions, however, that are less obvious to planners and water authorities but which always concerned the locals. One of these functions is to vivify the landscape and the consequent creation of biodiversity. The vegetation along the *acequia* presented a great biodiversity, with the plant communities changing along the two stretches surveyed. We distinguished eight types of riparian plant communities characterized by the predominant species, the canopy structure and a mean NDVI (Table 1). The riparian plant communities, characterized by alder and chestnut galleries, presented the highest NDVI (0.80 and 0.75, respectively), followed by those distinguished by oak and willow galleries (0.69 and 0.68, respectively). The open riparian plant communities presented a NDVI lower than 0.50. Fig. 5 depicts the sequence of the riparian communities along the two stretches studied. All included herbaceous, aquatic, and algae species. The most frequent communities in the conveyance reach were those of willow gallery, willow edge and alder gallery (Fig. 5). In the distribution reach, where the fields are close to the *acequia*, the strip of vegetation influenced by its infiltration below the *acequia* is generally narrower than in the conveyance reach, although the NDVI remains similar (Fig. 6). The most frequent ones in the distribution reach were those of open agricultural canopy, mixed frond, oak gallery and chestnut gallery

Table 1
Description and main plant species in the riparian communities along the Busquístar *acequia*. Normalized Difference Vegetation Index (NDVI) in the 10-m wide strip next to the *acequia* corresponding to each riparian community.

Community	Description	NDVI (mean/std)
Open agricultural canopy	Trees (mostly cultivated) and isolated shrubs (poplars in groups). Main spp.: *Morus nigra, Ficus carica, Ulmus minor, Celtis australis, Juglans regial, Castanea sativa, Populus nigra, Quercus rotundifolia, Hedera hélix, Crataegus monogyna, Rubus ulmifolius, Scirpus holoschoenus, Juncus inflexus, Phragmites australis, Sorghum halepense.*	0.50/0.14
Open forest canopy	Isolated natural trees and shrubs. Main spp.: *Quercus pirenaica, Hedera hélix.*	0.48/0.17
Mixed frond	Continuous frond of trees and shrubs. Main spp.: *Salix atrocinera, Castanea sativa, Quercus rotundifolia, Quercus pirenaica, Alnus glutinosa, Cytisus scoparius subsp reverchoni, Rubus ulmifolius.*	0.66/0.10
Willow edge	Medium height willow hedge plus other species. Main spp.: *Salix spp, Salix atrocinera, Castanea sativa, Rubus ulmifolius, Hedera hélix, Cytisus scoparius subsp reverchoni, Athyriom filix-femina*	0.68/0.09
Willow gallery	Gallery dominated by adult willows accompanied by other large trees and shrubs. Main spp.: *Salix atrocinera, Salix spp, Castanea sativa, Quercus pirenaica, Rubus ulmifolius, Lonicera splendida, Rosa canina, Phragmites australis, Hedera hélix, Scirpus holoschoenus, Athyriom filix-femina.*	0.68/0.13
Oak gallery	Gallery of large oaks and some trees of other species. Main spp.: *Quercus pirenaica, Quercus rotundifolia, Castanea sativa*	0.69/0.07
Chestnut gallery	Gallery of large chestnuts and some willows. Main spp.: *Castanea sativa, Salix atrocinera*	0.75/0.05
Alder gallery	Gallery of alders and some and some trees of other species. Main spp.: *Alnus glutinosa, Castanea sativa, Quercus pirenaica*	0.80/0.06

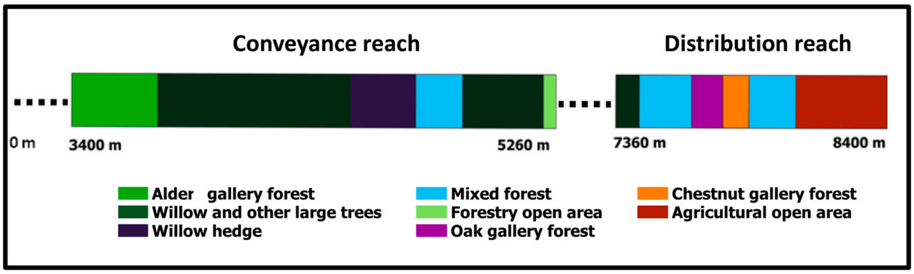

Fig. 5. Schematic representation of the plant communities (Table 2) identified along the conveyance and distribution reaches of the Busquístar *acequia*.

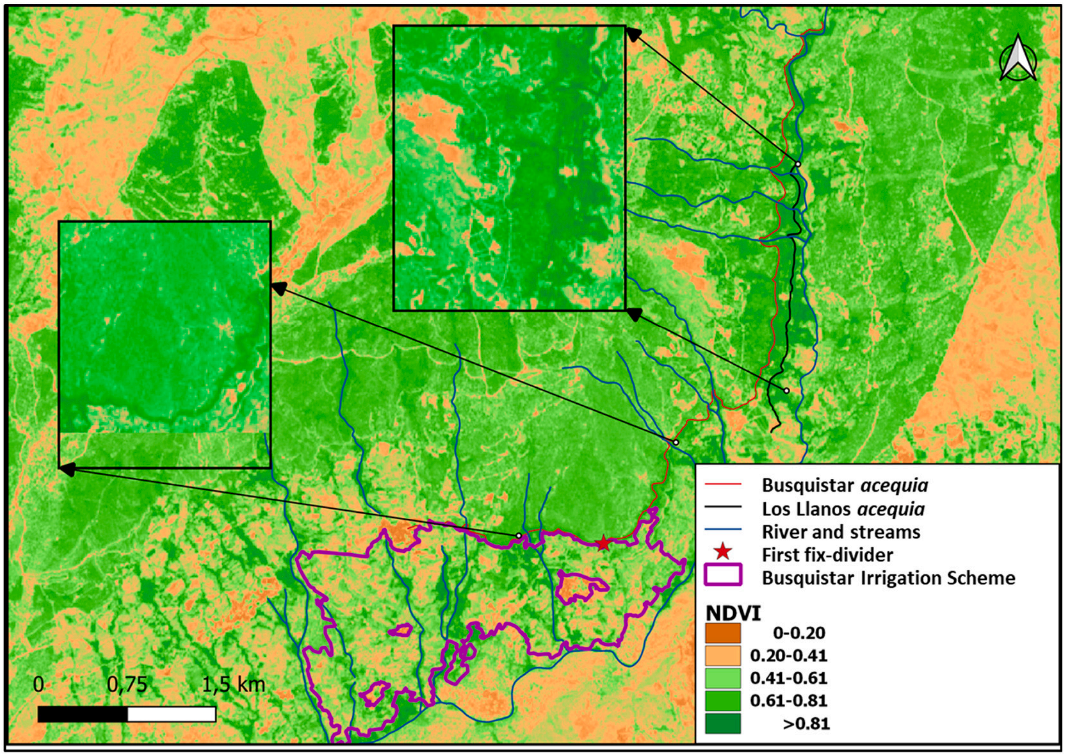

Fig. 6. NDVI image for the area surrounding the Busquístar *acequia,* with insets without any representation of the alignment of the *acequia* to facilitate visualization of NDVI.

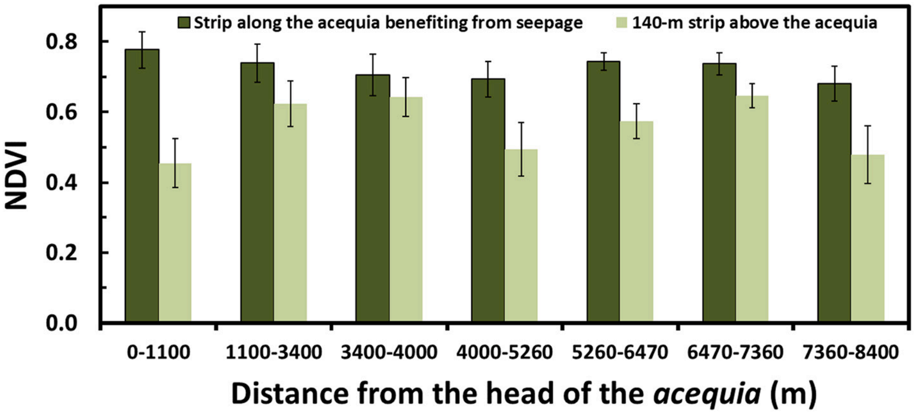

Fig. 7. NDVI of the vegetation influenced by infiltration from the Busquístar *acequia* compared with the NDVI of the strip of 140 m above the *acequia* (bars above the histogram indicate standard deviation).

(Fig. 5).

The vegetation along the *acequia* was clearly denser and greener than below and above its strip of influence. This can be seen in the NDVI map presented in Fig. 6, and more clearly in the zoomed inset, in which the line of the *acequia* has been removed. Fig. 7 compares the NDVI averaged over the previously defined stretches along the buffer containing the *acequia* with the NDVI averaged over the corresponding stretches along the 140-m strip above the *acequia*. The mean NDVI was over 0.68 in all the segments in the *acequia* buffer, which indicated fairly green and dense vegetation, and it was always significantly higher than the mean NDVI in the corresponding strip above it, evidencing the effect of the *acequia* in invigorating the riparian vegetation and generating biodiversity of plants (and likely of animals).

In addition, the return flows from the Busquístar and other irrigation schemes in the Trevélez watershed add to the artificial recharge done by means of *acequias de careo* in the upper watershed. The ancient knowledge and associated nature-based practices shared by the local communities, who understand that deliberate and non-deliberate return flows are reused downstream, contribute to the regulation of the Guadalfeo basin, of which the Trevélez river watershed is part (Fig. 1), as described in the next section. Note that the Guadalfeo basin is closed to protect the Rules reservoir, which serves the touristic and agricultural sectors of the highly populated southern coast of Spain.

3.3. Water balance in the Busquístar acequia

Fig. 8 displays the average monthly discharge at the Trevélez gauging station with corresponding precipitations in the upper watershed. Precipitation increases from September, to peak in December; staying between 40 and 60 mm month^{-1} from February to May; and decreasing to very low values during the summer. However, the discharge peaks in May–June (maximum mean 2.3 m^3 s^{-1}) and it stays relatively high during the summer despite the scanty precipitation (Fig. 8). The lag between the maximum precipitation and discharge reflects the snow regime of the watershed as has been described in snow-dominated regions (Barnett et al., 2005). Winter precipitation as snow is stored in the middle and upper watershed to melt and runoff during the spring. The water discharge during July and August, well after the snow has melted and precipitation is small, is explained by the subsurface flow and springs gushing from shallow aquifers fed previously by the *acequias de careo* (Barberá et al., 2018; Martos-Rosillo et al., 2019b). Table 2 presents the discharge diverted to the 11 *acequias de careo* monitored in June 2019. The total discharge was of 1.258 m^3 s^{-1}, which represented about 50% of the mean river discharge in June, and 150% of the river discharge measured on the same day (0.830 m^3 s^{-1}).

Table 2
Discharge measured in June 2019 at the head of the *acequias de careo* in the Trevélez River upper watershed.

Acequia de careo	Discharge (L s^{-1})
de las Lagunas	89
Gorda de Trevélez	176
del Mingo	10
de los Posteros	10
Nueva	115
Desconocida	37
Real de Cástaras	300
del Puerto	143
de Bacares	192
del Cura	59
Calvache	127
TOTAL	1258

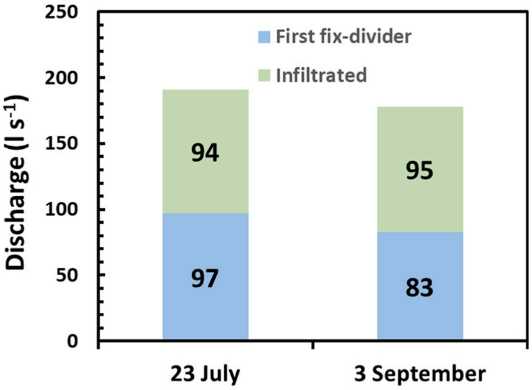

Fig. 9. Discharge at the entrance of the Busquístar *acequia* and at the head of the distribution reach measured on two dates in 2017.

The discharges measured at the head of the Busquístar *acequia* on 23rd July and 3rd September 2017 were of 0.191 and 0.178 m^3 s^{-1} (Fig. 9), respectively, representing 14 and 50% of the mean river discharge in July and September, respectively (the discharge data on those specific dates were not available). Note that another five small *acequias* divert water from the Trévelez River downstream of its gauging station and before it joins the Guadalfeo River (Fig. 3).

The discharge measured at the first bifurcation was of 0.097 and of 0.083 m^3 s^{-1} on 23rd July and 3rd September 2017, respectively, about half of the discharge at the head (Fig. 10). That is, 0.094 and 0.095 m^3 s^{-1} filtered through the bed and walls of the *acequia* along the

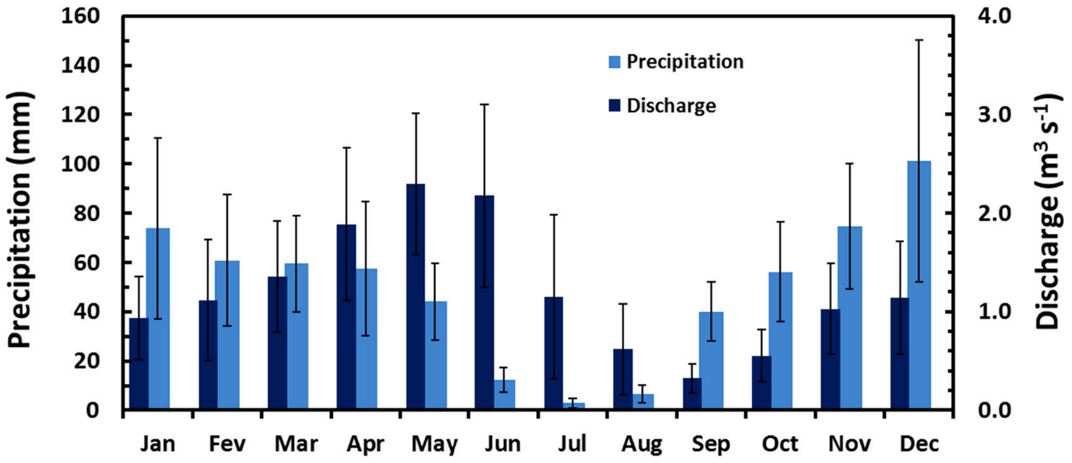

Fig. 8. Monthly mean discharge of the Trevélez River at the gauging station and monthly mean precipitation in the watershed upstream of the gauging station (bars above the histogram indicate standard deviation).

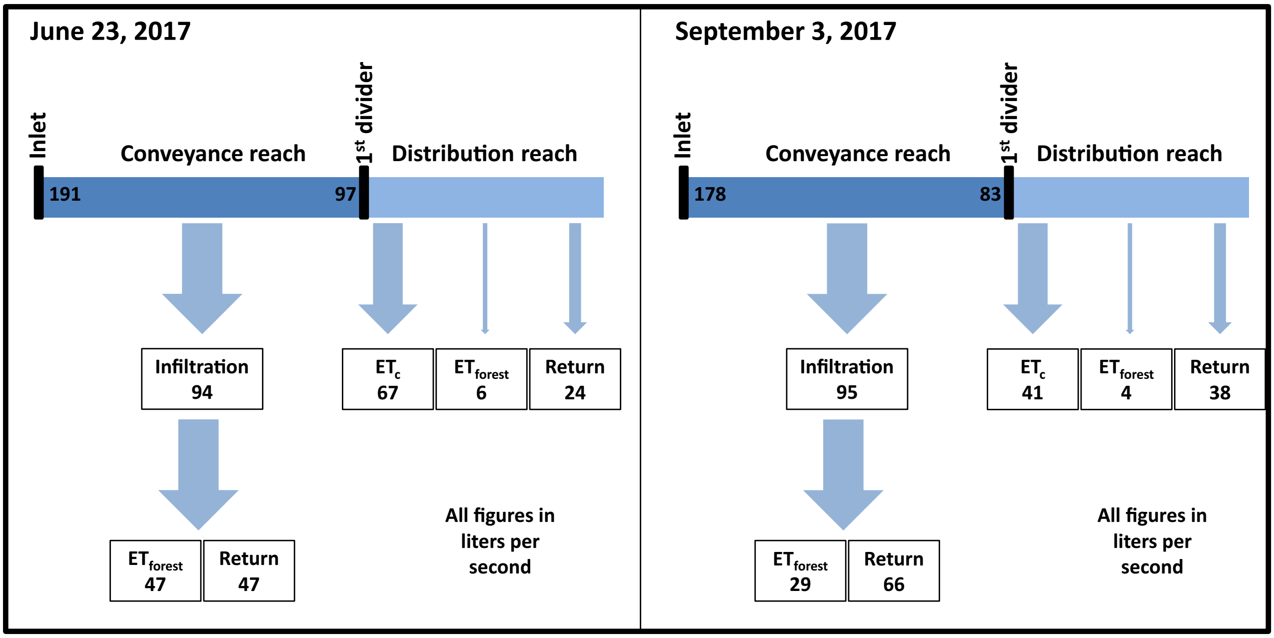

Fig. 10. Diagram of the water balance in the Busquístar Irrigation Scheme. All figures in liters per second.

conveyance reach (Fig. 9). The remaining flow continued in the *acequia* to be diverted to other 4 branches along the 3140-m long distribution reach.

The evapotranspiration of the riparian buffer estimated for 23rd July and 3rd September 2017 was of 47 and 29 L s^{-1}, respectively, in the conveyance reach (45 ha), and of 6 and 4 L s^{-1}, respectively, in the distribution reach (4.7 ha). The evapotranspiration of the crops in the BIS on the same days was of 67 and 41 L s^{-1}, respectively. Therefore, on 23rd July, the Busquístar *acequia* returned to the hydrological system 47 and 24 L s^{-1} in the conveyance and distribution reaches, respectively, and on 3rd September, 66 and 38 L s^{-1}, respectively (Fig. 10). These return flows are reused internally or downstream with a time lag, as discussed below.

4. Discussion

Traditional, community-based water management in the Trevélez River watershed has three key features. First, the diversion of snowmelt from ravines to *acequias de careo* excavated in the upper watershed. These *acequias* convey water to areas of high infiltration. From there, the water flows below ground to lower areas of the watershed, to emerge as springs and/or re-enter main streams. Then, water can be diverted from main streams to irrigation channels. Second, this circulation of water delays the process from snow melt to the emergence of recharged water close to the irrigated land, thereby increasing stream water available for irrigation during summer, when rainfall is insufficient to support agriculture. Third, water losses in both the *acequias de careo* in the upper watershed and the irrigation channels that supply irrigated fields in the lower watershed have environmental benefits because they support biodiversity that provides scenic, cultural and economic values.

Conventional water policy (often taken as a technical issue subject to optimization and the best expert-addressed knowledge) confronts the holistic view of ecosystems and the role of water in the social organization of the traditional community-based water management in Alpujarras. This, in effect, goes beyond the modern concept of integrated water resource management. For instance, water planners would consider the conveyance efficiency of about 50% observed in the Busquístar *acequia* as poor (Bos and Nugteren, 1990). Therefore, conventional irrigation modernization projects would focus on reducing seepage losses by lining the *acequia*, or substituting it with a pipe (Berbel et al., 2019). In fact, this is the improvement recognized by the EU, which conditions access to the European Agricultural Fund for Rural Development (EAFRD) for irrigation restoration and modernization to ensuring water savings of 5 to 25% (European Parliament and the Council of the European Union, 2013, Article 46, point 4). However, such a project would jeopardize the functions of ancient canals i.e. regulating the watershed flow through the spring and summer by feeding springs for irrigation, and creating biodiversity and landscape.

In this work, we have proposed to revisit the irrigation efficiency concept using the definition by Burt et al. (1997) (Eq. 1). Implicit in this definition is the consideration of both temporal and spatial scales in the efficiency concept. A key feature in this equation is that the water volume in the numerator is of a beneficial use. It therefore allows the consideration of the multiple functions of water use as long as they are beneficial. Thus, exactly what is meant by beneficial is the issue to be defined. Crop production is the main use considered to be beneficial in irrigated systems, although biodiversity and landscape creation can also be valued, not only by the local population but also by society at large. Recharge for downstream use that may occur through deep percolation and runoff on the farm is likely to result in low efficiency at that scale. However, if efficiency is computed on the BIS scale, those on-farm return flows become part of storage of irrigation water, so their efficiency remains high. For instance, the conveyance efficiency on the two dates of discharge measured in the Busquístar *acequia* was of 51 and 53% (on 23rd July and 3rd September, respectively). The combined distribution and on-farm efficiencies (considering crop evapotranspiration as the only beneficial use) were estimated at each date at 69 and 43%, respectively, with the irrigation efficiency of the *acequia* system being 35 and 23%, respectively. The difference between the two dates was due to the decrease in evapotranspiration as the summer advanced, while the decrease in the diversion at the *acequia* entrance was a lower proportion. However, should riparian evapotranspiration also be considered as a beneficial use (since it creates biodiversity, beauty and cultural landscape), the irrigation efficiency of the *acequia* system would increase to 63 and 42%, respectively. Furthermore, if the domain of the analysis were to extend to the lower Trévelez watershed, then part of the *acequia* and farm return flows should be considered as water stored in the system for a future beneficial use elsewhere. Assuming that only half of that volume could be recovered beneficially, then irrigation efficiency would rise to 77 and 60%, respectively. Note that this is a rather conservative assumption given the geology of the area that prevents deep percolation through the underlying impermeable rock also favours groundwater discharge from shallow aquifers into the river (Jódar et al., 2018; Barberá et al., 2018; Martos-Rosillo et al., 2019b).

The above discussion adds to the debate on the scale effect on irrigation efficiency. The degree of reuse of return flows affects system performance, which depends on its hydraulic arrangement and the performance of the irrigation units (Mateos, 2008). The analysis by Vivas et al. (2016) in a watershed neighbouring that of Trevélez one, showed that, by including internal reuse of return flows, the irrigation efficiency on the watershed scale was significantly greater than that on the sector scale. The scale effects have implications to the investment in water saving (Perry et al., 2017; Ward and Pulido-Velázquez, 2008).

Furthermore, supra-community management in the Trevélez watershed is an ancient practice intrinsic to i) the *acequias de careo* on the upper watershed; ii) the local consciousness of the reuse of irrigation return flows downstream of the watershed; and iii) the inter-watershed transfer of water inwards from its neighbouring watershed on the east outwards to its neighbouring watershed on the west. Such transfers are a common feature of all important watersheds along the southern side of Sierra Nevada (Martos-Rosillo et al., 2019a).

Note that both intra- and supra-community water management employs nature-based solutions to meet the multiple functions of the water system while providing complementary ecosystem services and maintaining a high system efficiency. For instance, within the *acequia* system, some farmers use the water that flows from springs fed by upstream irrigation return flows. This obviates the need to the build surface reservoirs or install impermeable lining in channels. Along the *acequias*, seepage functions as subsurface irrigation of the riparian vegetation (without the installation of any irrigation system) and contributes to the recharge of shallow aquifers feeding the springs at a lower altitude. The *acequias de careo* also exert this function on wider territorial, spatial and temporal scales. Ancestral experience led to the identification of highly permeable areas, where a significant fraction of the annual runoff is stored temporally to eventually be used in springs or as a river flow. This natural solution for intra-annual water regulation substitutes the construction of dams and conveyance conduits to supply downstream users (Ozment et al., 2015), thus it is a paradigm of the “water sowing and harvesting” notion (Martos-Rosillo et al., 2021; Albarracín et al., 2021). Finally, the steep slope and unaltered hard rock outcropping on the east side of the watersheds along the south face of Sierra Nevada renders *acequias de careo* ineffective there but not for transfer to the western sides of neighbouring watersheds (González-Ramón et al., 2015; Martos-Rosillo et al., 2019a). This win-win solution is surprising given the common reluctance of rural communities to allow the transfer of water outside their territories (Zhuang, 2016), and reflects the wise vision of water management in the ancient communities that developed it.

This discussion is particularly important in the transition to the new agriculture that is developing in the region. Should it adopt the standards of modern irrigation or adapt traditional knowledge? Public policy should favour this new agriculture that is repopulating the region, but it could move a step ahead of promoters to protect the cultural landscape, by 1) regulating the transformation of water distribution and storage systems, 2) regulating soil management (including conservation of terraces), and 3) motivating the creation of second-order water user associations. The first two points are important for the conservation of biodiversity and landscape; the third point could be the ultimate water planning measure to preserve the integration of the *acequias de careo* into watershed water management. One additional and potentially relevant function of is carbon sequestration. Watering the slopes of southern Sierra Nevada has favoured the growth of pasture and forest over very large areas where soil has likely become enriched in carbon (Rodríguez-Murillo, 2001), all this in an environment in which otherwise vegetation would be sparse and dry in the summer.

There are signs of a good understanding between the farmers' community and the water and National Park authorities. For instance, although the formal water rights limit the diversion period to the end of October, at the initiative of the WUA and with the agreement of the National Park authority, nowadays water keeps flowing in the Busquístar *acequia* also during autumn and winter, with a discharge that can infiltrate along its length. The single purpose is to extend the period of recharge of the connected aquifers. A second example relates to current regulations (derived from the European Union Water Framework Directive) establishing that all water users must measure the water they use (de Medio and España, 2001). The application of this norm has been delayed in spite of environmentalist having denounced the failure to meet it, and advocating the importance of water accounting. The solution arrived at by the authors' research team was to rate existing hydraulic structures for discharge measurement.

5. Conclusions

Conclusions of this study are:

- The ancient open channel irrigation schemes in Alpujarras are living examples of water multi-functionality and eco-hydrology.
- The emerging export horticulture in the Alpujarras region is both an opportunity and a threat for preserving these ancient water schemes.
- A revision of the irrigation efficiency concept may reconcile criteria for restoring canal systems and investing in efficient irrigation under EAFRD and in compliance with nature-based solutions for water management.

In addition, the analysis identifies the value of regulating the transformation of water distribution and storage systems to facilitate the new export horticulture while preserving biodiversity, soil and landscape. We also suggest the creation of a second-order water user's association to preserve the integration of up- and downstream water beneficiaries and facilitate modern water management compatible with the nature-based attributes of the ancient system.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Albarracín, M., Ramón, G., González, J., Iñiguez-Armijos, C., Zakaluk, T., Martos-Rosillo, S., 2021. The ecohydrological approach in water sowing and harvesting systems: The case of the Paltas Catacocha Ecohydrology Demonstration Site. Ecuador. Ecohydrol. Hydrobiol. 21, 454–466. https://doi.org/10.1016/j.ecohyd.2021.07.007.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage, Paper No. 56, Rome, Italy.

Azañón, J.M., Galve, J.P., Pérez-Peña, J.V., Giaconia, F., Carvajal, R., Booth-Rea, G., Jabaloy, A., Vázquez, M., Azor, A., Roldán, F.J., 2015. Relief and drainage evolution during the exhumation of the Sierra Nevada (SE Spain): is denudation keeping pace with uplift? Tectonophysics 663, 19–32.

Barberá, J.A., Jódar, J., Custodio, E., González-Ramón, A., Jiménez-Gavilán, P., Vadillo, I., Pedrera, A., Martos-Rosillo, S., 2018. Groundwater dynamics in a hydrologically-modified alpine watershed from an ancient managed recharge system (Sierra Nevada National Park, southern Spain): insights from hydrogeochemical and isotopic information. Sci. Total Environ. 640, 874–893.

Barnett, T.P., Adam, J.C., Lettenmaier, D.P., 2005. Potential impacts of a warming climateon water availability in snow-dominated regions. Nature 438 (17), 303–309. https://doi.org/10.1038/nature04141.

Berbel, J., Expósito, A., Gutierrez-Martín, C., Mateos, L., 2019. Effects of the irrigation modernization in Spain 2002–2015. Water Resour. Manag. 33, 1835–1849.

Boiten, W., 2003. Hydrometry. Lecture notes UNESCO-IHE Delft, Swets and Zeitlinger B. V., Lisse, The Netherlands.

Bos, M.G., Nugteren, J., 1990. On irrigation efficiencies. ILRI Publication 19, 4th Ed. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, p. 117.

Burt, C.M., 2013. The irrigation sector shift from construction to modernization: what is required for success? Irrig. Drain. 62, 247–254.

Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A., Eisenhauer, D.E., 1997. Irrigation performance measures: efficiency and uniformity. J. Irrig. Drain. Eng. 123, 423–442.

Comunidad de Regantes de la Acequia Gorda Real de Busquístar, Pórtugos y Ferreirola, 1952. Ordenanzas y Reglamentos para el Sindicato y Jurado de Riegos. Busquístar, Granada, Spain.

Dalaigue, M.C., 1995. La red de acequias de la Alpujarra Alta. In: Lunwerg Editores, S.A. (Ed.), El agua y la agricultura en Al-Andalus, p. 143.

European Commission, 2020. Nature-based Solutions. https://ec.europa.eu/info/research-and-innovation/research-area/environment/nature-based-solutions_en (accessed 22 November 2021).

European Parliament and the Council of the European Union, 2013. Regulation (EU) No 1305/2013 of the European Parliament and of the Council of 17 December 2013 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD) and repealing Council Regulation (EC) No 1698/2005. Official Journal of the European Union, pp. 347–548, 20.12.2013.

FAO, 1998. World Reference Base for Soil Resources. FAO World Soil Resources Report 84. Food and Agriculture Organization of. the United Nations, Rome, Italy.

Glick, T.F., Kirchner, H., 2000. Hydraulic systems and technologies of Islamic Spain: History and archaeology. In: Squatriti, P. (Ed.), Working with Water in MedievalEurope: Technology and Resource-Use. Brill, pp. 267–330.

Glick, T.H., 1970. Irrigation and Society in Medieval Valencia. Harvard University Press, Cambridge, Massachusetts.

González-Ramón, A., Martos, F.M., Marín, C., Martos Rosillo, S., Pedrera Parias, A., Ruiz Constán, A., Durán Valsero, J.J., 2015. Factores geomorfológicos condicionantes de la hidrogeología de la cuenca alta del Río Bérchules (Sierra Nevada, Granada). Simposio del Agua en Andalucía, T I. Málaga, pp. 283–294.

IGN-PNOA, 2016. Plan Nacional de Ortofotografía Aérea. Instituto Geográfico Nacional, Gobierno de España. http://centrodedescargas.cnig.es/CentroDescargas/index.jsp (Accessed on 26 November 2021).

Jódar, J., Carpintero, E., Martos-Rosillo, S., Ruiz-Constán, A., Marín-Lechado, C., Cabrera-Arrabal, J.A., Navarrete-Mazariegos, E., González-Ramón, A., Lambán, L.J., Herrera, C., González-Dugo, M.P., 2018. Combination of lumped hydrological and remote-sensing models to evaluate water resources in a semi-arid high altitude ungauged watershed of Sierra Nevada (southern Spain). Sci. Total Environ. 625, 285–300.

Junta de Andalucía-CAPDS, 2017. Visor SIGPAC Andalucía. Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible (CAPDS), Junta de Andalucía. https://www.juntadeandalucia.es/organismos/agriculturaganaderiapescaydesarrollosostenible/servicios/sigpac/visor/paginas/sigpac-descarga-informacion-geografica-shapes-provincias (accessed on 26 November 2021).

Junta de Andalucía-IECA, 2007. Localizador de Información Espacial de Andalucía. Instituto de Estadística y Cartografía de Andalucía (IECA), Junta de Andalucía. https://www.juntadeandalucia.es/institutodeestadisticaycartografia/lineav2/web/ (accessed on 26 November 2021).

Junta de Andalucía-REDIAM, 2013a. Red de Información Ambiental de Andalucía. Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía. https://descargasrediam.cica.es/repo/s/RUR?path=%2F04_RECURSOS_NATURALES%2F02_GEODIVERSIDAD%2F03_GEOMORFOLOGIA%2FGeomorfologia_General%2FInfGeografica%2FInfVectorial%2FShapes%2FETRS89 (accessed on 26 November 2021).

Junta de Andalucía-REDIAM, 2013b. Red de Información Ambiental de Andalucía. Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía. https://descargasrediam.cica.es/repo/s/RUR?path=%2F01_CARACTERIZACION_TERRITORIO%2F06_USOS_COBERTURAS%2F06_SIOSE%2F04_SIOSEA_2013%2F02_SIOSEA13_OCUPACION_SUELO%2FSioseA13_OS_Detalle%2FInfGeografica%2FInfVectorial%2FShapes (accessed on 26 November 2021).

Martín Civantos, J.M., 2011. Working in landscape archaeology: the social and territorial significance of the agricultural revolution in al-Andalus. Early Medieval. Eur. 19 (4), 385–410.

Martos-Rosillo, S., González-Ramón, A., Ruiz-Constán, A., Marín-Lechado, C., Guardiola-Albert, C., Moral, F., Jódar, J., Pedrera, A., 2019a. El manejo del agua en las cuencas de alta montaña del Parque Nacional de Sierra Nevada (Sur de España). Un ejemplo ancestral de Gestión Integral del Agua. Bol. Geol. Min. 130 (4), 729–742.

Martos-Rosillo, S., Ruiz-Constán, A., González-Ramón, A., Mediavilla, R., Martín-Civantos, J.M., Martínez-Moreno, F.J., Jódar, J., Marín-Lechado, C., Medialdea, A., Galindo-Zaldívar, J., 2019b. The oldest managed aquifer recharge system in Europe: new insights from the Espino recharge channel (Sierra Nevada, southern Spain). J. Hydrol. 578, 124047 M.

Martos-Rosillo, S., Durán, A., Castro, M., Vélez, J.J., Herrera, G., Martín-Civantos, J.M., Mateos, L., Durán, J.J., Jódar, J., Gutiérrez, C., 2021. Ancestral techniques of water sowing and harvesting in Ibero-America: Examples of Hydrogeoethical systems. In: Advances in Geoethics and Groundwater Management: Theory and Practice for a Sustainable Development. Springer, pp. 489–492.

Mateos, L., 2008. Identifying a new paradigm for irrigation system performance. Irrig. Sci. 27, 25–34.

Mateos, L., Vivas, G., Giráldez, J.V., González-Dugo, M.P., 2007. Origin, Tradition and Decline of the Ancestral Irrigation Systems in the High Alpujarra, Spain. ICID 22nd European Regional Conference, 2–6 September 2007, Pavia, Italy (CD-ROM Version).

de Medio, Ministerio, España, Ambiente-Gobiernode, 2001. Real Decreto Legislativo 1/2001, de 20 de julio, por el que se aprueba el Texto refundido de la Ley de Aguas (Artículo 55.4.Boletín Oficial de Estado176 de 24 de junio de 2001).

Ozment, S., DiFrancesco, K., Gartner, T., 2015. The Role of Natural Infrastructure in the Water, Energy and Food nexus, Nexus Dialogue Synthesis Papers. IUCN, Gland, Switzerland.

Perry, C., Steduto, P., Karajeh, F., 2017. Does Improved Irrigation Technology Save Water? A review of the evidence. FAO, Cairo. http://www.fao.org/3/b-i7090e.pdf.

Playán, E., Mateos, L., 2006. Modernization and optimization of irrigation systems to increase water productivity. Agric. Water Manag. 80, 100–105.

Proyecto LUCDEME, 1993. Mapa de Suelos 1:100000, Lanjarón-1042 (1:50000). In: ICONA (MAPA), Dpto. Edafología (Universidad de Granada), Madrid, Spain.

Pulido-Bosch, A., Ben Sbih, Y., 1995. Centuries of artificial recharge on the southern edge of Sierra Nevada (Granada, Spain). Environ. Geol. 26, 57–63.

Rodríguez-Murillo, J.C., 2001. Organic carbon content under different types of land use and soil in peninsular Spain. Biol. Fertil. Soils 33, 53–61.

Sanz de Galdeano, C., López-Garrido, A.C., 1998. Nature and impact of the neotectonic deformation in the western Sierra Nevada (Spain). Geomorphology 30, 259–273.

Trillo San José, C., 2005. A social analysis of irrigation in Al-Andalus: Nazari Granada (13th-15th centuries). J. Mediev. Hist. 31, 163–183.

US Bureau of Reclamation, 1997. Water Measurement Manual, 3rd ed. US Government Printing Office, Denver, CO, USA.

Vivas, G., Giráldez, J.V., Mateos, L., 2016. Water management in an ancestral irrigation system in southern Spain: a simulation analysis. Irrig. Sci. 34, 343–360.

Ward, F.A., Pulido-Velázquez, M., 2008. Water conservation in irrigationcan increase water use. Proc. Natl. Acad. Sci. U. S. A. 105, 18215–18220.

Zhuang, W., 2016. Eco-environmental impact of inter-basin water transfer projects: a review. Environ. Sci. Pollut. Res. 23, 12867–12879.