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Article in Agricultural Water Management - October 2021
DOI: 10.1016/j.agwat.2021.107240

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Reinventing the wheel – The preservation and potential of traditional water wheels in the terraced irrigated landscapes of the Ricote Valley, southeast Spain

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ARTICLE INFO
Handling Editor - Dr. B.E. Clothier

Keywords:
Irrigated agriculture
Cultural landscape
Multifunctionality of agriculture
Water management
Emission mitigation

ABSTRACT
Lifting water is crucial to irrigate agricultural terraces in the Mediterranean region. But the energy demand and emissions of modern forms of water pumping have increased, while many traditional water wheels, which lift water at zero direct emissions, have been abandoned. We explored the state of preservation and the potential for the deployment of traditional water wheels known as “norias” in the Ricote Valley of southeast Spain, where some are still in function, while also investigating the reasons for their widespread abandonment. A mixed method approach is used here to combine GIS-based methods, an expert survey, and a technological and socio-economic assessment of noria renovation.

Our findings show that norias in the Ricote Valley have mostly been replaced by thermal-engine water-lifting technologies. The reactivation of traditional irrigation technologies, many of them lying dormant but still standing, could contribute to reducing the high energy demand and the resulting emissions of irrigation systems in the Mediterranean region and beyond. It was estimated by data extrapolation that 16 renovated norias included in our analysis can irrigate 140.3 ha in the Ricote Valley, for a total achievable power of 23.8 kW. To irrigate a similar surface applying diesel motor pumps would produce up to 148 tons of emissions/year and cost up to approx. 70,000 €/year based on a price of 1.25 €/l diesel for a maximum of 8760 working hours/year. In the case of electric pumps, we estimate that up to 55 tons of emissions/year and costs up to approx. 48,000 €/year can be saved.

Therefore, we argue that rediscovering traditional technologies has potential to contribute to achieving climate actions that reduce GHG emissions (Sustainable Development Goal 13). Moreover, these technologies provide multiple functions and services for a sustainable life on land (Sustainable Development Goal 15), which needs to be considered within a holistic approach.

1. Introduction
The expansion of agriculture globally is putting high pressure on resources and biodiversity (IPBES, 2019). As much as 70% of global freshwater withdrawal and 38% of the Earth’s terrestrial surface serves agricultural production (Foley et al., 2011). While crop yields per hectare have increased significantly within the last decades and irrigated agriculture provides 34% of the global food production using 24% of the global agricultural land (Foley et al., 2011; IAASTD, 2009), decades of agricultural expansion, intensive cultivation, homogenization and irrigation have also led to environmental and social degradation (Bjornlund and Bjornlund, 2019; IAASTD, 2009; Lasanta et al., 2017a; Lomba et al., 2019). In the Mediterranean region, future warming is expected to exceed global warming rates by 25%, with
extreme summer temperatures and reduced precipitation. At the same time, Mediterranean agriculture is intensifying with increased irrigation and energetic use, and consequently with undesirable effects on water resources, biodiversity, climate and landscape functioning (Cramer et al., 2018; Martin-Gorriz et al., 2021).

In Spain, ongoing transformations in the irrigation systems can potentially reduce water consumption per hectare, but energy demand has increased by 657% between 1950 and 2008, following the widespread introduction of thermal-engine pumping systems (Soto-Garcia et al., 2013). Consequently, irrigation is responsible for 45% of GHG emissions from agriculture in Spain, conflicting with the EU’s emission targets (European Commission, 2020; Martin-Gorriz et al., 2021).

Sustainable alternatives for intensive irrigation systems are urgently needed. The revival of pre-industrial technologies and traditional ecological knowledge may help finding new sustainable solutions, e.g. improved water efficiency based on agroecological practices like cover crops, contour farming, the use of agricultural terraces and locally adapted crops or, as we will explore in this study, the reintroduction of traditional water wheels, known as norias (Altieri and Nicholls, 2012; Bernard and Lux, 2017; IAASTD, 2009; Lomba et al., 2019; Pretty, 2018).

Traditional terraced smallholder agriculture is an important component of rural Mediterranean landscapes and remains a predominant farming model in the Ricote Valley (Heider et al., 2021). It represents the outcome of the long-term convergence of human and environmental trajectories, resulting in a social-ecological system that has proven its stability and resilience over the past ten centuries or more (Balbo et al., 2016; Blondel, 2006; Lasanta et al., 2017b). The agricultural terraces of the Ricote Valley are part of a gravity-based irrigation system, which was introduced more than 1000 years ago (Puy and Balbo, 2013). Water wheels that lift irrigation water to higher agricultural terraced land, known as norias, have played a key role in the long-term sustainability of these irrigated landscapes, allowing the exponential extension of irrigated land based on a zero-emission technology.

The rural development policy within the second pillar of the common agricultural policy (CAP) of the EU aims to combine ecological and social needs with economic targets. Unfortunately, the CAP has also, perhaps unwillingly, contributed to the homogenization of rural landscapes and to the deterioration of small-scale agriculture during the last decades (Chemnitz, 2019; Heider et al., 2021; Lefebvre et al., 2015). A minimum area of 0.2 ha is needed to obtain subsidies in Spain. This, combined with the gradual withdrawal of small amounts of public aids, has further intensified these trends (BOE, 2014), accelerating the abandonment of traditional technologies, often used and maintained by smallholders.

While ubiquitous in large human agglomerations, knowledge and innovations are fast eroding in rural areas, also due to rural-urban migration of the young population (Balbo et al., 2020; Tacoli and Mbajla, 2010). The resulting lack of access to existing knowledge is another major limitation for smart and sustainable development in rural areas (Copus et al., 2011), where traditional knowledge is a key dimension of sustainability. By focusing on the appreciation of regional endowments, such as biophysical, economic, cultural, social, historic and technological strengths, our paper explores smart and green specialization strategies in rural areas (Ashem et al., 2011; Thissen et al., 2013).

In the literature, norias are mostly investigated from a historic perspective (Glick, 1977; Headworth, 2004), stressing their cultural heritage values (Bravo Sánchez, 2018; Gil Meseguer, 2014), technological values (Ranegas Ortiz and Gómez Espín, 1992; Gómez Espín, 2014; Vannopoulos et al., 2015), as well as evaluating their performance (Stillwater and Awad, 1991). Indeed, water wheel sites (both mills and pumping sites) can be considered among the main drivers of economic, industrial and social development of rural agricultural spaces before the industrial revolution (Hassan, 2011; Quaranta and Wolter, 2021). It is estimated that over 350,000 of such hydro sites may have existed in Europe at one time or another. In Japan water wheels comprised 56% of total power generation until 1886 (Punys et al., 2019; Quaranta and Wolter, 2021).

The abandonment of most norias in Spain started with the generalized introduction of motor pumps over the past decades (Bravo Sánchez, 2018; Closas, 2014). The following increase of intensive groundwater extraction technologies promoted over-extraction in Spain (Closas, 2014). Indeed, most water wheels have been replaced by motors or hydro plants all over Europe (Quaranta et al., 2021).

From a current perspective, norias are valued for promoting landscape aesthetics as well as the multifunctionality of rural areas by fostering recreation and rural tourism (Gil Meseguer, 2014). Furthermore, water wheels are increasingly valued for renewable power production at low head sites and at old mill weirs. This opens up possibilities for the re-use of traditional water wheels (installed power typically below 50 kW), which have been abandoned during the past decades (Müller and Kaupert, 2004; Quaranta and Revelli, 2018; Quaranta, 2018; Quaranta et al., 2021).

This study analyses the state of norias in the Ricote Valley, while also exploring the reasons for their deterioration. Furthermore, we investigate the potential for their renovation and their potential contribution to the multifunctionality of agriculture. This leads to the following research questions:

1. What is the current state of preservation of norias in the Ricote Valley?
2. What are the reasons for the observed abandonment of norias during the past decades?
3. What is the potential of noria renovation for a sustainable agricultural system?

To address these questions, we used a mixed method approach combining GIS-based methods, an expert survey, and an assessment of the potentials of noria renovation. First, we collected available geo data to explore the state of preservation and location of norias in the Ricote Valley. Second, we combined participant observation with the inquiry of experts to identify the reasons for the deterioration of norias. Finally, we investigated the norias under a hydraulic and geometric perspective with the aim of calculating their irrigation potential (i.e. the pumped flow rate, irrigated area) as well as emission mitigation and saved costs, compared to electric and diesel pumps. We also elaborated their geometric dimensions in order to find easy and expeditious tools that can be used in future research to re-construct and estimate unknown dimensions and performance of norias. The estimation of such dimensions is important to better understand their historical deployment for irrigation in the past, but also their potential as an integral component of future pathways for sustainable agricultural systems. The results will be then discussed with focus on the Ricote Valley and could be extrapolated to other traditional agricultural landscapes in the Mediterranean region.

2. Study area

The study area is the Ricote Valley in the Region of Murcia, southeast Spain (Fig. 1). The climate in the study area is semi-arid with strong seasonality. We include in our analysis seven villages, which stretch alongside the Segura River: Albarán, Blanca, Ricote, Ojos, Ulea, Villanueva, and Archena with a population of 44,742 in 2020 (Instituto Nacional de Estadística, 2021). Part of the villages are the traditional orchards (Fig. 2). Lemon is the current primary crop cultivated in the valley, followed by olive, almond, multiple fruits, and vegetables. Many farmers cultivate their primary products for export, which leads to challenges due to price volatility and competition with modern industrial agriculture in the neighboring regions (Heider et al., 2021). Furthermore, the agricultural properties are highly fragmented due to the traditional heritage system in the study area. Most of the agricultural
properties are smaller than 1 hectare (Heider et al., 2018). Thus, smallholder farming dominates agriculture in the study area until today. The traditional orchards contain multiple levels of agricultural terraces in different sizes and shapes divided by stonewalls and crossed by small irrigation canals. These terraces are part of a hydraulic system, which was introduced by Amazigh Berber populations over 1000 years ago for flood irrigation (Puy and Balbo, 2013). Norias were added at a later stage of expansion of these agricultural systems, lifting water and expanding agricultural land to ever higher grounds. They are distributed along irrigation canals outbranched from the Segura river, which is characterized by strong seasonal differences and high flood risk (Ministerio para la Transición Ecológica y el Reto Demográfico, 2021).

Technically, the norias in the Ricote Valley originate from the “Egyptian water wheel” with buckets attached and powered by the water flow. It was originally invented by the Romans approx. between 600 and 700 BCE (Yannopoulos et al., 2015). During the Middle Ages, the expansion of Arab civilizations contributed to the broad diffusion and progressive modification of norias across the Islamic world (Martínez Soler and Banegas Ortiz, 1994). In the Ricote Valley, they probably existed prior to the 16th century, as they were well-known and widespread in Al-Andalus. However, their installation in the valley coincided with a population increase and therefore the need to increase irrigated cropland from the 16th century onwards (García Avilés, 2000; Puy, 2012). With an increasing production, the transport of locally produced crops became also important, with large numbers of muleteers in the valley deployed to export cash crops (García Avilés, 2007). The current norias are a result of the adaptation to the cultivation of new crops, rising production and rising irrigation needs for an increasing agricultural area. Therefore, they increased in size with the increasing needs for water uplift (García Avilés, 2007; Pérez Picazo and Lemeunier, 1990).

The traditional irrigation system, made of historic elements such as norias, irrigation canals, and agricultural terraces, shapes a cultural and multifunctional landscape, which represents the local water culture of the region (García Avilés, 2014, 2000; Gil Meseguer, 2010). At the same time, it illustrates pre-industrial ingenuity and creativity for water use prior to the introduction of thermal-engine machines. Therefore, such systems do not represent only tangible heritage, but also the intangible heritage and technological knowledge needed for their design and maintenance. This knowledge has been transmitted over centuries. Today, a touristic route with information panels follows the Segura River along the norias of Abarán, which have been declared of cultural interest (spn. Bien de Interés Cultural, BIC) (Ayuntamiento de Abarán, 2012).
3. Data and methods

To answer our research questions, we implemented a mixed method approach that integrates two strands of analysis (Fig. 3). In the first strand, we (a) explored the state and location of norias in the Ricote Valley using GIS technologies including in-situ correction, (b) identified reasons for the deterioration of norias using participant observation supported by a literature review and (c) conducted an expert survey to identify additional reasons for deterioration and quantify the importance of each reason. In the second strand, we (a) calculated the irrigation potential of the norias in the Ricote Valley, estimated the unknown geometric dimensions, (b) their potential to mitigate emissions, and (c) their potential to produce power. Fig. 3 shows the mixed method research design with two strands. The first strand combines an explanatory design (phase 1 and 2a) to deepen the findings of the quantitative geo data analysis about the current state and location of norias with an exploratory design (phase 2a and 3) to identify reasons for the deterioration and quantify them. In the third phase, we integrated quantitative and qualitative data using the reasons identified during participant observation in the expert survey. In phase 2b in the second strand, we explored the future potential of the traditional technologies integrating our collected geo data (phase 1) and focusing on traditional and innovative usages. We integrated both strands in the discussion (phase 2b and phase 3). The priority is given to quantitative research methods (Kuckartz, 2014).

3.1. Data and data collection

To identify the location of the norias in the Ricote Valley, we used an official list provided by the region of Murcia (i.e. Consejería de Turismo, Cultura y Medio Ambiente). Based on this list, we created a geo-database of norias. In this database, we collected available data about the characteristics of the norias (i.e. diameter, width, number of paddles, irrigated area, lifted water volume) combining information from research (Bravo Sánchez, 2018), local working groups (Martínez Soler and Banegas Ortiz, 1994) and on-site information from the Region of Murcia (i.e. information panels).

We validated each location in-situ in the orchards of the Ricote Valley in summer 2019. For the validation, we uploaded our database to ArcGIS Online and used the ArcGIS Collector App to validate and edit data. During this process, we aggregated the condition of each noria and created four categories to describe it. The category in use describes a noria that is still working and lifts irrigation water to an irrigation canal on a higher elevation; Conserved describes a site, where the base and the wheel of the noria are still existing; Destroyed describes a site, where the wheel of the noria is non-existent but the base is still present; Disappeared describes a site, where wheel and base are non-existent. Data visualization was conducted in SAGA-GIS (Conrad et al., 2015).

3.2. Exploring reasons for the deterioration of norias

In the next step, we explored the reasons for the deterioration of the norias in the Ricote Valley. To integrate local perspectives, we used participant observation and a survey of eleven experts. During participant observation in the study area, we communicated regularly with local stakeholders and participated in agricultural activities (Thomas, 2019). We combined insights from participant observation with a literature review. Based on this, we selected possible reasons for the deterioration of norias, which were included in the expert survey. Experts were selected based on their expertise on the topic, location, and their availability. Eleven experts with administrative, scientific, legal, and economic backgrounds participated in the survey (see Table 1). In June 2019, we requested the experts to evaluate the importance of preselected reasons for the deterioration of norias in the Ricote Valley on a scale from 0 (not important) to 4 (very important), and they could also add other reasons. For the evaluation, we (a) created new categories that combined the preselected and added reasons; (b) calculated the weighted arithmetic mean of the new categories, considering the number of persons mentioning each added reason; and (c) included only reasons with a value higher than 2 (moderate importance).

3.3. Exploring the potentials of noria renovation in the Ricote Valley

In this section the procedure to estimate the power developed by a noria, its lifted flow rate, and the saved emissions compared to an electric or diesel pump, is explained. These quantities are a function of
the geometric and hydraulic characteristics of the norias, so they have to be known or estimated (Fig. 4).

The first step consisted of finding the mathematical relation between diameter and number of blades, also called paddles. The number of paddles is known for 11 norias. By plotting the number of paddles versus the diameter (Fig. 5), the following equation was found:

\[ n = 3.42D + 24.87 \]  

(1)

where \( n \) is the number of paddles and \( D \) is the diameter (m). Eq. (1) exhibits a coefficient of determination \( R^2 = 0.76 \). By Eq. (1) the number of paddles can be estimated as a function of the wheel diameter, and then choosing a multiple of 4 (common practice both for norias and also for water wheels). By knowing diameter and number of paddles, the circumferential distance between two adjacent paddles can be calculated. Eq. (1) is an expeditious equation that can be generalized and used to estimate the number of blades of any noria. Eq. (1) is in line with some equations to estimate the number of paddles (as a function of diameter) commonly used for water wheels designed to power mills or generate electricity (Quaranta and Revelli, 2015) for overshot water wheels. In our case, the coefficient \( c \) for the Noria de la Hoya was estimated to be \( c = 4.3 \text{ m}^{1/2} \text{ min}^{-1} \). By Eq. (2), the rotational speed \( N \) of each noria can be estimated from the diameter. Eq. (2) practically expresses the Froude hydraulic similarity concept, where velocities scale as the square root of linear dimensions. With such estimated \( N \), the tangential speeds range between 0.5 and 0.7 m/s, which is consistent with the fact that, in general, the optimal tangential speed of stream water wheels (i.e. water wheels driven by the kinetic energy of flowing streams) is one half of the river velocity. In our case, this would correspond to 1–1.4 m/s, a common flow velocity in rivers and canals (Quaranta, 2018).

The other analysed dimension was the container dimension. For the Noria de la Hoya, the container equals the distance between two paddles, which is intuitive. Width and depth of the container are one quarter of the wheel width. These proportions can be applied to all the norias whose container dimensions are not known.

By knowing the container dimensions and the rotational speed, the lifted flow rate \( Q \) could be estimated, considering that it is known for two norias (Noria de la Hoya and Noria Grande). The estimation of the lifted flow allows to calculate the power developed by the wheel (Eq. (3))

\[ P = \rho gQH \]  

(3)

where \( P \) (W) is the power, \( g \) is the gravity acceleration (9.81 m/s²), \( \rho = 1000 \text{ kg/m}^3 \) is the density of water, \( Q \) is the lifted flow rate (m³/s) and \( H \) (m) is the pumping head (in the case of norias, \( H = D \)).

From Eq. (3), it can be seen that, for a certain power, the higher the pumped head \( H \) is, the lower must be the lifted flow \( Q \). Therefore, \( Q \) is inversely proportional to the head \( H \) (i.e. the diameter). Furthermore, the lifted flow \( Q \) is proportional to the cross-section area \( A \) (m²) of the container that catches the water from the river below the noria. Therefore, it is possible to define the coefficient \( q \) expressed in Eq. (4):

\[ Q = qA/H \]  

(4)

From Eq. (4), \( q = 5.83 \text{ m}^2/\text{s} \) for the Noria de la Hoya and \( q = 5.02 \text{ m}^2/\text{s} \) for the Noria Grande, so that an average value of \( q = 5.4 \text{ m}^2/\text{s} \) can be taken as reference. The fact that the values of \( q \) for the two norias are similar, confirms the method is reasonably generalizable. Therefore, the value of \( Q \) for the other norias was estimated as...
Q = 5.4 \frac{\text{kg}}{\text{m}^3} and implemented in Eq. (3) to estimate the power developed by the norias.

4. Results

4.1. Current state and location of norias in the Ricote Valley

We identified the location of 24 norias in the Ricote Valley as well as their current condition (phase 1). The condition and location of each noria in the Ricote Valley is shown in Fig. 6. Three norias (12%) are still in use to lift irrigation water. All of them are located in Abarán (green). 13 norias (54%), classified as conserved, are distributed across the valley. Four norias are destroyed (17%) and four have disappeared (17%). Examples for each category are given in Fig. 6.

4.2. Reasons for the observed deterioration of norias during the past decades

As expected, most of the norias (88%) in the Ricote Valley are no longer in use. The eleven consulted experts identified multiple reasons for their deterioration in the Ricote Valley. The most important reasons are 1) use of new technologies; 2) lack of valorization of traditional technologies; 3) high maintenance costs; 4) expansion of infrastructures and urbanization.

Most norias have been replaced by motor pumps during the past decades, contributing to the high energy demand and related emissions of Spanish irrigation systems. According to experts, the lack of valorization of traditional technologies plays an important role and can be explained by an increasing loss of the relationship between local populations and agriculture. In particular, the young generation is less interested in continuing the agricultural activities. This leads to a lack of transmission of traditional knowledge between generations and loss of interest in heritage conservation. The noria as an instrument of production and a material heritage, which is passed down from parents to children along with the land, suffers the same neglect as the land it irrigates. In the words of a local farmer: “Today’s traditional agriculture in the valley survives because of small technical improvements and sentimental value, but the generation after mine no longer understands this sentimentality”.

Furthermore, the high maintenance costs had a large effect on the deterioration of the norias. Many norias have been financed by their users. Often users are organized in local users’ communities (i.e. irrigators communities). These communities are responsible for the maintenance of norias, and repairation costs are usually distributed between users. But the local irrigators communities are facing increasing economic challenges. Most users have a low income from agricultural activities without price premiums or subsidies. For example, the common agricultural policy (CAP) does not grant aid to owners of small plots. A minimum area is required to qualify for subsidies and in the Ricote Valley, only a few farmers fulfill this requirement. Additionally, the number of users decreases due to land abandonment. As a local farmer describes: “Small farms with traditional agricultural or livestock production systems are disappearing, absorbed by agribusiness, they have been preserved where their products are valued and the farmers can earn an appropriate income with their production”.

Finally, the expansion of infrastructure and urbanization led to the displacement of agricultural activities. While norias in the Ricote Valley were originally constructed within the traditional orchards, several of them are now located next to main roads or within urban areas. This is the case for the Noria Grande de Abarán and the Noria “La Tía Vicenta” surrounded by sealed surfaces in small urban recreational areas.

All consulted experts considered the preservation of norias important, arguing for their high historical, cultural, touristic, and technological value and they agreed that the conservation of norias should not be sustained by the users alone. Eight out of eleven experts think that renovation and maintenance should be co-financed between users, local and regional authorities.

Based on our findings, we have identified three main management
patterns for norias in the Ricote Valley. In the first pattern, norias are still in use and irrigate the surrounding agricultural area. However, due to land abandonment or urbanization, the agricultural area has been reduced, and the irrigators community is confronted with higher costs per farmer for maintenance. In the case of the Noria de la Hoya in Abarán (Fig. 4) and to solve the difficulties in the irrigators community, a single landowner, who owns much of the land irrigated by the noria, agreed to maintaining it. Furthermore, Noria de la Hoya has been declared of cultural interest (BIC), and benefits from support by the regional administration. In the second pattern, norias are no longer used for irrigation, but are maintained for reasons of heritage conservation. This is the case of Noria Grande de Abarán, maintained in function although the irrigated land is lost to urbanization. It has been declared as asset of cultural interest (BIC) and the regional administration became responsible for maintenance. However, the change of responsibilities can represent an additional challenge, hampering the transmission of local traditional knowledge, necessary for cost-effective maintenance (Asociación Cultural La Carraila, 2019).

In the third pattern, the noria is surrounded mostly by abandoned land or has been substituted by motor pumps and is neither used, nor renovated or maintained. In these cases, responsibilities for maintenance and preservation are weakly defined. In the following section, we will describe our results about the potential of noria renovation, also exploring whether power production might be a sustainable usage pattern of norias in the Ricote Valley.

### 4.3. Assessment of the potentials of noria renovation for a sustainable agricultural system

By means of the procedure explained in the method section, it was possible to re-construct the geometric dimensions and the pumping characteristics of norias (number of blades, container dimensions, speed, pumped flow and developed power). The Noria de la Hoya and the Noria Grande de Abarán were the reference ones, because most of their dimensions are known. The proposed methodology can be used in general to estimate preliminary dimensions of any noria, as long as their dimensions are known. This is the case for 15 norias (see Table 2). In our calculations, if width and diameter of a given noria were not known, the noria was not considered. Therefore, the following dimensions can be estimated, in general, knowing diameter and width:

- number of paddles
- immersed length of the paddles (m)
- rotational speed (revolutions per minute, rpm)

![Fig. 7. Saved emissions per year versus the pumped flow based on 15 norias.](https://example.com/fig7)

**Table 2**

| Name                                         | Estimated construction year | Height (diameter) (m) | No. of paddles | Irrigated area (hectares) | Lifted flow (l/s) | Rotational speed (rpm) | No. of containers | Power (W) |
|----------------------------------------------|-----------------------------|----------------------|----------------|--------------------------|-------------------|------------------------|------------------|-----------|
| Noria de la Hoya (de D. García)              | 1818                        | 8.2                  | 1.1            | 48                       | 26.0              | 42.2                   | 1.5              | 96        | 3397      |
| Noria Grande de Abarán                       | 1807                        | 11.9                 | 1.2            | 64                       | 17.3              | 25.0                   | 1.2              | 128       | 2923      |
| Noria de Candélon                           | 1850                        | 6.0                  | 0.5            | 40                       | 1.0               | 12.4                   | 1.8              | 80        | 728       |
| Noria La Norica                             | 1850                        | 5.0                  | 0.4            | 40                       | 0.9               | 9.3                    | 1.9              | 80        | 458       |
| Noria y acueducto de Félix Cayetano          |                             | 6.0                  | 0.7            | 48                       | 3.4               | 22.7                   | 1.8              | 96        | 1335      |
| Noria de la ‘Viuda de Don Juan de Teodoro’  |                             | 8.2                  | 0.4            | 56                       | 1.8               | 6.3                    | 1.5              | 112       | 505       |
| Noria de Miguelito Núñez                     |                             | 8.2                  | 0.4            | 56                       | 0.4               | 6.3                    | 1.5              | 112       | 505       |
| Noria de Ribera                             |                             | 7.0                  | 0.5            | 42                       | 0.3               | 9.3                    | 1.6              | 84        | 640       |
| Noria del Olivar                            |                             | 8.5                  | 0.7            | 48                       | 3.4               | 20.2                   | 1.5              | 96        | 1684      |
| Noria de D’ Elia Carrillo                   |                             | 4.8                  | 0.3            | 44                       |                   | 5.9                    | 2.0              | 88        | 276       |
| Noria del Conde de Villa-Felices            |                             | 9.0                  | 0.6            | 56                       | 0.4               | 12.9                   | 1.4              | 112       | 1138      |
| Noria de los Semolicas                      |                             | 10.0                 | 0.6            | 60                       | 5.3               | 11.6                   | 1.4              | 120       | 1138      |
| Noria del Otro Lao o Noria de D. Matías Martínez | 4.5                      | 0.8                  | 48             | 16.8                      | 35.5              | 2.0                    | 96               | 1566      |
| Noria de “Los Chirichines”                  | 1910                        | 7.5                  | 0.8            | 52                       | 20.7              | 27.5                   | 1.6              | 104       | 2023      |
| Noria ‘La Tía Vicenta’                      |                             | 10.0                 | 0.8            | 56                       | 14.0              | 20.6                   | 1.4              | 112       | 2023      |
| Noria del Acebuche                          |                             | 12.2                 | 0.8            | 74                       | 14.5              | 29.0                   |                  | 3481      |
working hours (see Table 3). In case of different numbers of working hours, the obtained results from Fig. 7 scale proportionally. It must be noted that the mitigated pollution estimated here must be interpreted considering the additional benefits that the use of a renovated noria can generate, rather than a motivation to build a noria instead of using a motor pump, since the choice of technology should also consider the practical aspects of flexibility, maintenance, installation and fabrication.

If electric pumps would be considered, the saved emissions would be between 14 and 55 tons/year (Table 3), assuming that the electric pump emissions are 265.5 gCO$_2$/kWh (European Environment Agency, 2018). The saved emissions of Noria Acebuche could not be estimated with the methodology proposed in the method section, due to its unknown width. Indeed, the width of the noria is used to estimate the container dimensions, as well as the pumped flow, and it has to be known. Therefore, in case of unknown width, the pumped flow can be estimated by inverting the equation proposed in Fig. 8 as a function of the irrigated area.

For each noria, the irrigated area was known from official data, so that Fig. 8 shows the irrigated area versus the pumped flow. The higher the pumped flow, the higher is the area that can be irrigated. We calculated that 16 renovated norias could irrigate 140.3 ha saving between 14 and 148 tons of CO$_2$ per year compared to the usage of motor pumps covering the same surface (see Table 3). The 140.3 ha represent 6.21% of the agricultural terraced land in the Ricote Valley (2259.72 ha) based on an estimation from a previous study (Heider et al., 2021). It has to be considered that approx. 40% of agricultural terraced land was abandoned in 2019.

Economic savings and benefits: The use of norias would offset the cost of diesel by between 17,606 and 70,424 €/year for the production of 23.8 kW (16 norias) of power for between 2190 and 8760 working hours/year, based on the estimated need of 0.27 l of diesel per kWh and on an estimated cost for diesel of 1.25 €/l. In the case of electric pumps, the use of norias would offset the cost of electricity by between 11,998 and 47,993 €/year for the same production and working hours mentioned above based on an estimated electricity cost of 0.23 €/kWh (Eurostat, 2021). Alternatively, if the norias would be deployed for power production instead of water pumping and the produced electricity would be sold, we estimate a benefit of between 2608 and 10,433 €/year. This was calculated by multiplying the total power of 16 norias by working hours by the energy price. The result is based on an estimated price of 0.05 €/kWh paid by Spanish electricity companies to private producers (Guijarro Ruiz, 2021). Such savings should be factored in towards the maintenance of norias.

However, an initial investment is needed to obtain these services. After this investment, a noria is likely able to sustain more than half of its maintenance costs, only considering economic savings from diesel consumption compared to engine-based technologies. Maintenance costs of a noria add up to c. 5000 €/year. Considering the average diesel savings of 2750 €/year, a noria could offset 55% of these costs. If a noria is alternatively used to produce electricity instead of water pumping, gains from selling energy could offset approx. 8% of its maintenance costs. We estimate that these calculations will change in favor of norias in the near future with increasing CO$_2$ prices.

Renovation costs depend on the individual preservation state of each noria and have to be assessed by an expert individually. Therefore, we discuss construction costs. The construction cost of a noria without irrigation canals lies between 8000 and 15,000 € per meter of diameter. According to this, a noria with a height of 8 m costs between 64,000 and 120,000 €, depending on the materials used. (The described construction and maintenance costs are based on personal communications with Miguel Ángel Molina Espinosa, technical engineer specialized in hydraulic machines and norias).

4.4. Renovated norias as drivers of the multifunctionality of agriculture

Above, we have shown the potential of noria renovation. Renovating norias can promote sustainable rural development and the multifunctionality of agriculture (Cairol et al., 2009; IAASTD, 2009; Renting et al., 2009) (Fig. 9). An increasing renovation of traditional irrigation technologies like norias would contribute to lower the high energy demand for pumping and mitigate emissions, helping to further approach the EU emission targets. However, the potential of the norias in the Ricote Valley for electricity production is limited due to their high

![Fig. 8. Irrigated area versus pumped flow based on 15 norias.](image)

![Fig. 9. Norias as drivers for the multifunctionality of agriculture combining social (yellow), economic (orange), and ecological (green) needs.](image)

### Table 3

Estimated potential benefits summed up for 16 norias with known dimensions in the case of noria renovation in the Ricote Valley for four scenarios. The scenarios represent seasonal variabilities of working hours.

| Scenario (hours) | Working hours | Energy (kW) | Saved emissions diesel (t/year) | Saved emissions electr. pump (t/year) | Saved cost diesel (€/year) | Saved cost electricity (€/year) |
|-----------------|---------------|-------------|-------------------------------|-------------------------------------|---------------------------|---------------------------------|
| 100%            | 8760          | 208,663     | 148                           | 55                                  | 70,424                    | 47,993                          |
| 75%             | 6570          | 156,497     | 111                           | 42                                  | 52,818                    | 35,994                          |
| 50%             | 4380          | 104,332     | 74                            | 28                                  | 35,212                    | 23,996                          |
| 25%             | 2190          | 52,166      | 37                            | 14                                  | 17,606                    | 11,998                          |
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diameter and low rotational speed compared to modern water wheels used for electricity generation. Nevertheless, we stress the multifunctional character of the norias and the multiple positive services they can provide if maintained. The norias in the Ricote Valley have been used to lift irrigation water on the multiple levels of agricultural terraces, contributing to food security. Some of them are still in use while also being part of a popular touristic route (Ayuntamiento de Abarán, 2021). Thus, norias contribute to recreation and tourism, to the aesthetics of a cultural landscape, and represent a part of the local water culture. They help to preserve traditional knowledge and create local employment. Moreover, norias contribute to biodiversity by creating micro-habitats for flora and fauna, e.g. water pools attracting birds, insects and promoting plant growth (Freshwater Habitats Trust, 2021b).

5. Discussion

Our analysis has shown that 88% of the norias in the Ricote Valley are currently not used and one of the most important reasons for the deterioration mentioned by the experts was the introduction of new technologies, especially motor pumps. Generally, motor pumps (diesel or electric pumps) can be easily bought, are cheaper, handier, of easy transport and easy adaptation on different sites, while high diameter water wheels are more complex in requirements, construction, and maintenance. Nevertheless, the renovation of norias provides important social, ecological, and economic services like irrigation without using fuel or electricity (emission mitigation), valorization of cultural heritage and social attractiveness.

In the Ricote Valley, mainly surface water (Segura River, El Molino spring, etc.) is used for irrigation representing relatively low energy consumption for water acquisition compared to groundwater extraction, external water transfer or desalination (Soto-García et al., 2013). However, energy is needed for water elevation on the different levels of the agricultural sectors within the valley. Since the 1970s boresholes substituted traditional norias using mostly diesel pumps (Closs, 2014). Until today diesel pumps and electric engines are mainly used for the provision of irrigation water including extraction and transport on different elevations (Espinosa-Tasón et al., 2020).

A similar trajectory of abandonment to that described for the norias in the Ricote Valley, has been observed for water mills across Europe and beyond. This trend is alarming, considering the high cultural and historical value of norias and water mills. Exploring their history and potential seems fundamental not only for better understanding the past, but also in defining innovative sustainable strategies for the future of agriculture, tourism and rural communities worldwide. The trend seems set, but needs to be consolidated, as many water wheel sites are experiencing a revival, both for electricity generation and thanks to a deeper understanding of their cultural value (Quaranta and Revelli, 2018).

The expert survey has shown that all experts considered the preservation of norias in the Ricote Valley important, including experts from the local irrigators communities. Furthermore, local associations, like the cultural association La Carraila, are active in the protection and recuperation of the cultural heritage in the Ricote Valley (i.e. norias). However, the maintenance of several norias poses some challenge, due for example to different ownership regimes. Some of them are owned by irrigators communities, others by a group of private individuals, and others by a single owner. Therefore, flexible coordination, cooperation and financial support is needed.

Based on our assessment, we estimate that 16 renovated norias included in our analysis can irrigate 140.3 ha in the Ricote Valley. To irrigate a similar surface applying diesel motor pumps would cost between 17,606 and 70,426 €/year for the consumption of between 14,085 and 56,339 l diesel/year and produce between 37 and 148 tons of emissions/year depending on the working hours. In the case of electric pumps, we estimate that between 11,998 and 47,993 €/year of electricity costs can be saved as well as between 14 and 55 tons of emissions/year. Therefore, renovation and re-use of traditional irrigation technologies could help to reduce the high energy demand and the resulting emissions of irrigation systems in the Mediterranean region and beyond.

Moreover, our results show that 16 renovated norias in the Ricote Valley could produce 23.8 kW. Modern water wheels used in the same context could be more efficient and less expensive. It must be noted that the achievable power in flowing river contexts (i.e. by exploiting the river kinetic energy) is generally limited (Quaranta, 2018), while low head sites are more attractive. Indeed, water wheels can be considered optimal machines to generate electricity, typically in head sites below 6 m and river flows below 1 mc/s per metre width (Quaranta, 2020). They generally work with 70% efficiency, but only if adequately designed to operate in that context. Based on our analysis, the re-use of a noria to generate electricity in the context of this study is feasible, but comes along with several disadvantages: (1) the power developed by a noria in the Ricote Valley is below 3 kW, and 1.5 kW on average; (2) they are designed to lift water, not to generate electricity, thus their efficiency is lower when used for electricity generation; (3) their rotational speed is very low due to the large diameter (2 rpm), thus, a large gearbox would be needed, including additional power losses and costs, with an efficiency decrease. Therefore, the average power value may further reduce. However, if modern stream water wheels (Quaranta, 2018) were used for electricity generation, replacing the norias, it is expected that the developed power would be higher than that estimated for the norias in this study. An additional study would be needed to better investigate this option, since the site characteristics have to be explored in detail. Therefore, we understand the usage of norias for power production as an additional opportunity adding up to its multifunctionality.

As we have shown, power production may not be viable as a stand-alone solution for the norias in the Ricote Valley, but their role as drivers for a multifunctional agriculture becomes clear by considering all the quantitative advantages of using water wheels compared to engines shown in this study: (1) lower emissions, (2) land irrigated, (3) diesel and electricity savings, (4) energy production. Their deployment would reduce the high energy demand and emissions in the Spanish irrigation system, while also enabling economic savings and benefits. On top of that are all the qualitative advantages like (5) shaping the local cultural landscape while also (6) providing areas for recreation and (7) preserving the local water culture (Gil Meseguer, 2014), (8) creating water-rich micro-habitats that support biodiversity in agriculture as well as (9) attracting an increasing number of external visitors and (10) public support for heritage protection. This includes the two most valued agroecosystem services in the Region of Murcia: biodiversity and recreation opportunities (Zabala et al., 2021). Nevertheless, we must consider that overall construction, installation and operational costs would be higher than for diesel or electric pumps.

Finally, we want to stress that global agriculture must transform in order to address major challenges like reducing emissions, reversing biodiversity loss, adapting to and mitigating climate change, and accommodating population growth and migrant communities. Foley et al. (2011) suggest four global strategies addressing these challenges: 1) stopping the expansion of agriculture, 2) closing yield gaps, 3) increasing resource efficiency, 4) changing to a plant-based diet and stopping food waste (Foley et al., 2011). Increasing resource efficiency includes an increasing irrigation efficiency. Especially, in water-scarce regions like the study area, good water and land management practices can increase irrigation efficiency. Agroecology provides principles and practices for a sustainable management of agroecosystems (Altieri and Nicholls, 2012; Bernard and Lux, 2017; De Leijster et al., 2019; Pretty, 2018). For example, reducing water losses through mulching, cover crops and reduced tillage will increase irrigation efficiency. Beyond that, adapting to local climate conditions or climate warming by cultivating locally adapted crops would reduce irrigation needs even more (Martin-Gorriz et al., 2021).

The dominant crop in the Ricote Valley is lemon. The cultivation of
lom trees sequesters more carbon than other woody crops or vegetables (Martin-Gorriz et al., 2021) and is less exigent in irrigation than the cultivation of vegetables because it is better adapted to water stress due to irregularities in water supply (Confederación Hidrográfica del Segura, 2013). Nevertheless, the cultivation of better adapted crops like olive and almond trees could reduce irrigation even further. Furthermore, we stress the importance of crop diversification due to its multiple benefits for biodiversity, water filtration, water retention, and resilience. However, the selection of crops is highly influenced by the market price and farmers have to earn their livelihood. Prices for locally adapted crops like almond and olive are low compared to more water-demanding crops like lemon.

6. Conclusion

In this study, we investigated the location and preservation state of norias in the Ricote Valley, explored the reasons for their deterioration during the past decades, and assessed the potential of their renovation. We observed high rates of noria abandonment and deterioration in the Ricote Valley: Only 12% of the norias are still used to lift irrigation water, 54% are conserved, 17% are destroyed, and another 17% have disappeared. The most important reasons for the deterioration of norias in the Ricote Valley are 1) the use of new technologies, in particular, motor pumps have replaced norias during the last decades; 2) the lack of valorization for traditional technologies, which combined with 3) high maintenance costs for noria preservation has further contributed to their deterioration; and 4) urbanization and the expansion of infrastructures that led to the displacement of agricultural activities, such that norias, located on what used to be agricultural terraces, are now disconnected from their original context.

Based on our results, we argue that rediscovering traditional technologies helps to achieve affordable and clean energy (SDG 7) as well as climate action to reduce GHG emissions (SDG 13). Moreover, these technologies provide multiple functions and services for a sustainable life on land (SDG 15), which needs to be considered within a holistic approach instead of only concentrating on new technologies.

To assess the potential of noria renovation, we proposed four scenarios, which represent different working regimes, due to seasonal variabilities: a full year, with 8760 h/year (100%), 6570 h/year (75%, i.e. 9 months), 4380 h/year (50%, 6 months), and 2190 h/year (25%, 3 months). Based on these scenarios, 16 norias would produce the following benefits if they would replace diesel motor pumps: 16 norias could mitigate between 37 and 148 tons of emissions/year as well as between 18,000 and 70,000 €/year spent on 14,000–56,000 l diesel. If they would replace electric motor pumps, 16 norias would produce the following benefits: 16 norias could save between 14 and 55 tons of emissions/year and between 12,000 and 48,000 €/year spent on electricity. Both types of engine are currently used to lift irrigation water on the elevated agricultural terraces. Such savings should be factored in towards the maintenance of norias. Finally, we estimated that 16 renovated norias could produce 23.8 kW and 1.5 kW on average. The main reasons for the limited power production potential are: the large diameter resulting in very low rotational speed (2 rpm), as well as their design optimized to lift water, which results in a lower efficiency when used for electricity generation. However, we estimated that norias deployed for power production could produce benefits of between 2600 and 10,400 €/year if the generated electricity were sold.

Our study is limited by the availability of data. We integrated four scenarios to cover variabilities in the working hours of norias. Furthermore, cost offsets are based on current fuel and electricity prices, rather than subsidized prices. We estimate that these costs will change in favor of norias in the near future with increasing CO2 prices. We recommend renovation, but renovation costs depend on the individual preservation state of each noria and have to be assessed case-by-case by an expert. Therefore, at this stage, we approached these numbers by estimated construction costs.

Finally, we recommend the integrated preservation of norias in the Ricote Valley and beyond, stressing their role as drivers for a multifunctional agriculture. We argue that norias are much more than water-lifting devices. Noria renovation in agricultural landscapes could produce highly valued social, ecological, and economic services compared to engine-based solutions, as we have shown for the Ricote Valley. Apart from their potential to mitigate emissions, norias create freshwater micro-habitats for flora and fauna, contributing to increase biodiversity in agriculture. Furthermore, they shape the cultural landscape and preserve the local water culture while providing recreation opportunities for locals and tourists. Further research is needed to quantify these services, and we will continue our research on multifunctional agriculture, exploring the potential of agroecological practices in Spain.

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.

Acknowledgments

We thank the experts for participating in our survey and the members of the association La Carraila in Abarán for their support during our research and their effort for the preservation of norias in the Ricote Valley. This research was funded by Friedrich-Ebert-Foundation (FES, Germany) and partly supported by the CLICCS Cluster of Excellence (Grant ID: 2037) funded by the German Research Foundation (DFG).

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