Historical Water Management in SE Spain
– with a focus on traditional irrigation strategies in the Vega of Vélez Blanco

A thesis submitted in partial fulfillment of the degree

Doctor rerum naturalium

Freie Universität Berlin • Department of Earth Sciences • Physical Geography

by

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Preface

This doctoral thesis was written in the Department of Earth Sciences at the Institute of Geographical Sciences of the Freie Universität Berlin for the doctoral program “Landscape Archaeology and Architecture” (LAA) at the Berlin Graduate School of Ancient Studies (BerGSAS). The research is part of the Topoi project A-3-5 “Functionality and effectiveness of technical water management measures.” It aims to investigate the historical development of water management strategies in the Iberian Peninsula with a special focus on human-environment interactions. The project is part of the Topoi key-topic research group A-3 “Water Management” of the Cluster of Excellence Exc 264 Topoi “The Formation and Transformation of Space and Knowledge in Ancient Civilizations.” The research group A-3 aims to investigate by interdisciplinary research the water supply in Mediterranean regions and the Near East during diverse periods from the Bronze Age to the Middle Ages. This doctoral thesis is a cumulative dissertation comprising three peer-reviewed and one unpublished publication.

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Abstract

This thesis focuses on the study of human-environment interactions, highlighting water management strategies in semi-arid northeastern Andalusia (southern Spain). The Vega of Vélez Blanco is used as a case study. The cultural landscape of the study site is characterized by irrigated agricultural terraces. The local water management is centrally organized in a traditional irrigation community. Its origin dates back at least to the 8th century AD. Due to the natural environmental settings, the Vega of Vélez Blanco has a perennial water supply. A special feature of the irrigation community are regular auctions of water shares for the irrigation of the agricultural land.

The presented work aims to analyze the social and technical structure of the water management in the Vega of Vélez Blanco. It furthermore aims to identify factors that influence the systems' stability. In addition, the influence of perennial water availability on the landscape development is analyzed.

The central research topic of this thesis is a unique archive of records of water auctions conducted in the Vega of Vélez Blanco. The data set was analyzed in correlation with local climate data by statistical analysis on different time scales. The research focuses on general water-price development and its dependence on precipitation events. Furthermore, the responsiveness of agricultural water management to long-term and short-term changes in the occurrence of precipitation is also investigated. The analysis results were validated with findings from structured interviews with local farmers concerning agricultural practices and irrigation strategies. In addition, a literature review on the historical development of water management in the context of regional landscape development was used to investigate the impact of perennial water availability on natural landscape processes.

The main results of this study show that the long-term average rainfall occurring during the months from March to June are of major importance for irrigation agriculture in the study area. If the amount of precipitation during this period is low, the demand for irrigation water increases during the growing season. Decisions about investments for additional irrigation water show a strong dependence on the economic yield of the cultivated plants and the economic power of the actor. The influence of historical events and socioeconomic development on irrigated agriculture in the Vega of Vélez Blanco is also demonstrated. In the short-term, the system reacts to external factors, but it is nevertheless characterized by long-term stability. However, the intensity of the impact of external factors on the system is difficult to assess. The results of the literature analysis show that in the study area the change from a natural to a cultural landscape started at least during the 8th century AD with the onset of intensive irrigated cultivation. It was only in the late 19th century that awareness of human-environment relations locally evolved, raising awareness of the human influence on landscape dynamics.

Zusammenfassung

Im Fokus der vorliegenden Dissertation steht die Untersuchung von Mensch-Umwelt-Interaktionen mit einem Schwerpunkt auf Wassermanagement Strategien im semi-ariden nordosten Andalusiens (Süd-Spanien). Als Fallbeispiel diehnt die Vega von Vélez Blanco. Die Kulturlandschaft des Untersuchungsgebietes ist geprägt durch den bewässerten Terrassenfeldbau. Das lokale Wassermanagement ist zentral in einer traditionellen Bewässerungsgemeinschaft organisiert. Ihr Ursprung ist im 8. Jh. n. Chr. anzusiedel. Aufgrund der naturräumlichen Gegebenheiten verfügt die Vega von Vélez Blanco über eine ganzjährige Wasserversorgung. Eine Besonderheit der Bewässerungsgemeinschaft sind regelmäßig stattfindende Versteigerungen von Wasserkontingenten zur Bewässerung der landwirtschaftlichen Flächen.

Ziel der vorliegenden Arbeit ist es, die sozialen und technischen Strukturen des Wassermanagements in der Vega von Vélez Blanco zu analysieren und Faktoren zu identifizieren, die einen Einfluss auf die Stabilität des Systems haben. Darüberhinaus wird der Einfluss der ganzjährigen Wasserverfügbarkeit auf die Landschaftsentwicklung untersucht.

Den zentralen Forschungsgegenstand der Dissertation bildet ein einzigartiges Archiv von Wasserverseigerungen die in der Vega von Vélez Blanco aufgezeichnet wurden. Der Datensatz wurde in korrelation zu lokalen Klimadaten mittels statistischer Auswertung auf verschiedenen zeitlichen Skalen analysiert. Im Fokus der Analysen steht dabei zum einen die generelle Wasserpreisentwicklung und ihre Abhängigkeit von Niederschlagsereignissen sowie die Reaktionsfähigkeit des landwirtschaftlichen Wassermanagements auf lang- und kurzfristige Veränderungen im Auftreten von Niederschlägen. Die Ergebnisse wurden mit Erkenntnissen aus strukturierten Interviews mit lokalen Landwirten zu landwirtschaftlichen Praktiken und Bewässerungsstrategien vallidiert. Zusätzlich wurde ein Review der Literaturquellen zur historischen Entwicklung des Wassermanagments im Kontext zur regionalen Landschaftsentwicklung genutzt, um den Einfluss der ganzjährigen Wasserverfügbarkeit auf die naturräumliche Entwicklung zu erfassen.

Die Hauptergebnisse dieser Studie zeigen, dass im langjährigen Mittel die Niederschläge in den Monaten März bis Juni von größter Bedeutung für den Bewässerungsfeldbau in der Vega von Vélez Blanco sind. Fallen die Niederschläge innerhalb dieses Zeitfensters gering aus, besteht ein erhöhter Bedarf an Bewässerungswasser während der Anbauperiode. Entscheidungen über die Investitionen für zusätzliche Bewässerung zeigen eine starke Abhängigkeit vom wirtschaftlichen Ertrag des angebauten Gutes und der Wirtschaftskraft des Akteurs. Ebenso nachgewiesen wurde der Einfluss historischer Ereignisse und sozioökonomischer Entwicklung auf die Bewässerungslandwirtschaft in der Vega von Vélez Blanco. Das System reagiert kurzfristig auf externe Impulse, ist dennoch in der langfristigen

Betrachtung durch Stabilität geprägt. Die Intensität der Einwirkung der externen Impulse auf das System ist jedoch schwer zu bewerten. Die Untersuchungsergebnisse zeigen, dass der Wandel von einer Natur- zur Kulturlandschaft im Untersuchungsgebiet spätestens im 8. Jh. n. Chr. mit dem Beginn des intensiven Bewässerungsfeldbaus einsetzt. Erst im späten 19. Jh. n. Chr. entwickelte sich regional ein Bewusstsein für Mensch-Umwelt Beziehungen hinsichtlich des menschlichen Einflusses auf die Landschaftsdynamik.

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1. Introduction

Many regions in Spain suffer seasonal water scarcity. The southern part of the peninsula in particular regularly struggles with shortages of water caused by arid to semi-arid climate conditions. Hence, throughout history, areas with higher surface-water availability or accessible groundwater resources have always been favorable places for settlements. In such environments, the technological advancement and institutionalization of water management have always been essential for human-environment interactions. The Roman, Moorish, and Iberian civilizations are known to have had major influences on the schemes and culture of water management on the Iberian Peninsula (Kress 1968; Glick 1970; Ostrom 1990; Brunhes 1902; Fröhling 1965). Their cultural heritage and technological influence on the management of water resources characterizes the usage of water to this day, especially for agricultural purposes. Moreover, the first evidence for the utilization of water management structures comes from pre-history. These findings prove the deeply ingrained and long history of traditional water utilization on the Iberian Peninsula (Gilman and Thornes 1985).

A prime example for the continuity of traditional water management is the water-sharing system of the Vega of Vélez Blanco. This area and its stable water management system is the main topic of this thesis. The Vega of Vélez Blanco is located at the southeastern edge of the Baetic Cordillera, at the foot of the Sierra María in eastern Andalusia. The region is dominated by a semi-arid climate with hot dry summers and a humid season from autumn to spring, with most reliable precipitation occurring during autumn (Geiger 1970; Isselhorst et al. 2018b; Rodrigo et al. 2000). The local annual precipitation averages 419 mm, and most precipitation is in the form of infrequent heavy rainfall events. This uneven distribution of precipitation is relevant for agricultural production, especially during the summer months (Isselhorst et al. 2018b).

To understand the complex local water management structures, several questions are raised in this thesis:

- How is the water-sharing system of the Vega of Vélez Blanco technically structured and socially organized?
- What kind of influence can affect the stability of this enclosed water management system?
- How did the existence of perennial water sources impact the landscape development in the region of Vélez Blanco?

The research is focused on the water supply of the irrigated agricultural terraces situated below the town of Vélez Blanco within the Vega. A unique feature of this study is the water-price analysis made possible by archive data of water auctions that regularly take place to this day in Vélez Blanco. To investigate the existence of interdependencies between natural, social, economic, and knowledge-based factors, the results of this analysis were combined with a data set of daily precipitation values and information of agricultural practices gathered by interviews with local farmers.

1.1 Implemented fieldwork and studies

During the first field campaign for this thesis in spring 2015, historical documents concerning the water-sharing system of the Vega of Vélez Blanco were digitalized in local archives. In addition, field mapping was conducted to produce an inventory of the water management facilities. In spring 2016, during the second campaign, field mapping was carried out again to improve the inventory. Historical cadastral map material of the study area was digitalized in an archive in Almería in autumn 2016. During the last field campaign in 2017, geographical information digitalized from map material and orthophotos was validated in the field. The results were mostly published in 2017 and 2018.

All work took place within the Cluster of Excellence Exc 264 Topoi. This thesis is the outcome of studies conducted within the research project A-3-5 "Functionality and effectiveness of technical water management measures." The project is part of the Topoi key-topic research group A-3 "Water Management," which aims to investigate by interdisciplinary research the water supply in Mediterranean regions and the Near East from the Bronze Age to the Middle Ages.

1.2 Structure of the Thesis

The present doctoral thesis is a cumulative dissertation that consists of four international peer-reviewed publications (see Table 1 below). The publications are integrated into the thesis structure as stand-alone chapters following their individual contents to address the thesis central research questions.

The historical background and social organization of the water-sharing system of the Vega of Vélez Blanco is the focus of the following research articles:

Paper I:

Irrigation Communities and agricultural water management in Andalusia. A special focus on the Vega of Vélez Blanco

by Isselhorst S., Berking J., Schütt B. – published 2018

In: eTopoi. Berlin Studies of the Ancient World – Vol. 53, pp. 227-253

To compare the water management practices in the Vega of Vélez Blanco to similarly structured systems in Andalusia, a comparative analysis of irrigation communities was carried out. For this purpose, the researchers statistically analyzed a data set of 979 irrigated areas, mainly supplied by ground- and surface water within the autonomous region of Andalusia.

Paper II:

A short history of the water and society in the region of Vélez Blanco, East Andalusia

by Roth D., Beckers B., Berking J., Isselhorst S., Schütt B. – published 2015

In: Water History – Vol.8 Issue 1, pp. 59-73

This paper provides an overview of the water-related history of the Vega of Vélez Blanco from the Muslim period until today. It is focused on the development of the legal history and jurisdiction concerning water issues. Historical information was gathered through an analysis of the literature.

The research question concerning the stability of an enclosed water management system is addressed in the following research article:

Paper III:

Water pricing following rainfall distribution and its implications for irrigation agriculture. A case study from Vélez Blanco, Andalusia (1967-2006)

by Isselhorst S., Berking J., Schütt B. – published 2018

In: Agricultural Water Management – Vol. 199, pp. 34-47

This study analyzes rainfall distribution data and prices at water auctions held by the traditional irrigation community. The outcome of the statistical analyses of these data sets was validated with information gathered from structured interviews with local farmers to investigate the interdependencies between water pricing, precipitation events, temperature evolution, and local agricultural practice.

A conclusive discussion concerning the influence of perennial water sources within the area of the Vega of Vélez Blanco and its impact on the landscape transformation is given in the fourth paper:

Paper IV:

Landscape development, land-use and water management history of the headwater area of the Guadalentín drainage basin SE Spain: A review

Isselhorst S., Berking J., Schütt B. - submitted: October 9th, 2018 - rejected: December 19th, 2019

To: Physical Geography

This paper reviews the transformation from a natural to a cultural landscape in the headwater area of the Guadalentín drainage basin with a special focus on the historical development of the local water management and agricultural practices. It is based on the analyses of literature and archival sources. The results from Papers I – III above also contributed to the comprehensive discussion in this article. Due to the availability of data, most continuous information is given for the period from the 8th century until today.

This thesis is divided into seven chapters. Chapter 1 is a brief introduction to the thesis. In Chapter 2 the history of water management on the Iberian Peninsula is briefly summarized.

An introduction to the study site is given in Chapter 3. Paramount for the study site description is the paper "Irrigation communities and agricultural water management in Andalusia. A special focus on the Vega of Vélez Blanco" by Isselhorst et al. (2018a; section 3.5). It is complemented by the paper by Roth et al. (2015) titled "A short history of the water and society in the region of Vélez Blanco, East Andalusia" (section 3.6), which gives an insight into the historical background of the water management system of the Vega of Vélez Blanco. The main methods of this study are discussed in Chapter 4.

Chapter 5 presents the results of the analysis. The results of the inventory of technical water management facilities within the Vega of Vélez Blanco are given in section 5.1. The inventory consists of a brief description of the technology used for the water diversion within the Vega of Vélez Blanco. The key elements of the technical water management facilities are illustrated in the unpublished overview map of the Vega of Vélez Blanco. The map includes the most important elements of the water-sharing system, such as the locations of springs, the courses of irrigation channels, and the locations of reservoirs. Section 5.2 outlines the basic structure of the social organization of the irrigation community of the Vega of Vélez Blanco. The contents of sections 5.1 and 5.2 are unpublished. The analysis of the water-price data and their correlation with precipitation volume and information about agricultural practices is conducted in section 5.3, within the paper "Water pricing following rainfall distribution and its implications for irrigation agriculture. A case study from Vélez Blanco, Andalusia (1967–2006)" by Isselhorst et al. (2018b).

The thesis discussion is presented in Chapter 6 within the paper titled "Landscape development, land-use and water management history of the headwater area of the Guadalentín drainage basin SE Spain: A review" by Isselhorst et al. (rejected 2019). It provides an overview of the history of human-environment interactions within the study site, with a special focus on landscape development and water management.

A synthesis of the previous chapters is provided in Chapter 7. It outlines the key outcome of this thesis.

Table 1: Detailed overview of my own contribution to the publications in this cumulative thesis.

No.	Title of publication	Authors	Submitted	Published	Journal	Own Contribution	Link to Section
I	Irrigation Communities and agricultural water management in Andalusia. A special focus on the Vega of Vélez Blanco.	Isselhorst S., Berking J., Schütt B.	2016	2018	eTopoi, Berlin Studies of the Ancient World, *Vol. 53, pages* 227-253	80 %	3.5
II	A short history of the water and society in the region of Vélez Blanco, East Andalusia	Roth D., Beckers B., Berking J., Isselhorst S., Schütt B.	2014	2015	Water History, *Volume 8, Issue 1, pages 59-73*	20 %	3.6
III	Water pricing following rainfall distribution and its implications for irrigation agriculture. A case study from Vélez Blanco, Andalusia (1967-2006).	Isselhorst S., Berking J., Schütt B.	2017	2018	Agricultural Water Management, *Volume 199, pages 34-47*	80 %	5.3
IV	Landscape development, land-use and water management history of the headwater area of the Guadalentín drainage basin SE Spain: A review	Isselhorst S., Berking J., Schütt B.	2018	rejected: December 19th, 2019	Physical Geography	75 %	6

2. State of the Art

Water management is used for a variety of purposes on diverse scales from local to trans-regional. The main purposes are domestic water supply, flood protection, exploitation of wetlands, and irrigated agriculture (Orengo et al. 2014). According to Berking et al. (2016), research into water management can be separated into three basic approaches: hydrological, technological, and social. The hydrological approach concerns the natural environmental settings that control the availability of water from sources such as groundwater and surface water and the occurrence of precipitation. The technological approach is focused on facilities to capture, transport, and store water. It includes technical facilities such as canals, wells, dams and water-lifting devices. The social approach deals with the social aspect of water management. It concerns the social organization regarding the maintenance of the technical facilities and the management of water-sharing. The research by Berking et al. (2016) highlights the importance of a holistic approach to the study of water management structures to enable an understanding of the human-environment interaction that water management systems entail. Pahl-Wostl (2007) and Mitchell (2005) also emphasize the need to consider the systems' complexity when addressing issues concerning resource management (e.g., water management) so as to understand the socio-environmental interactions and interrelations of factors that are necessary to implement water management. However, studies concerning water management frequently highlight only one of the approaches mentioned above, neglecting the systems' complexity.

Selected studies of irrigation water management are reviewed below to give a brief overview of the historical development of water management on the Iberian Peninsula.

A brief history of water management on the Iberian Peninsula

The origin and development of water management on the Iberian Peninsula has been the subject of a wide range of studies on diverse scales, from local to regional and beyond. The various strategies of water management, land utilization, and accompanying technical solutions on the Iberian Peninsula were strongly influenced by the Roman and Muslim cultures (Brunhes 1902; Fröhling 1965; Glick 1970; Kress 1968; Ostrom 1990). In contrast, little is known about water management during pre-historic times (Buxó 2011; Gilman and Thornes 1985).

On the Iberian Peninsula, technical water management facilities originating from the Roman period are still present and partly in use. Monumental aqueducts and dams prove the high level of engineering skills in the Roman Empire. The aqueduct of Segovia, located in central Spain, within the autonomous region of Castile and León is a prime example of Roman water engineering. About 17 km in length, it was built during the 1st century AD to supply the town of Segovia with water from the mountains of the Sierra de Fuenfría (De Feo et al. 2013; Alföldy 2011). More evidence for the sophistication of Roman water engineering is given by a variety of dams that were built during the Roman period. Most of these dams are located in the Ebro river basin, in the Guadiana river basin, and around Toledo in the Tajo river basin. The main purpose of these dams was to ensure the water supply to settlements (Arenillas and Castillo 2003). In addition to large-scale facilities such as aqueducts and dams, the Romans also used water-lifting devices. Devices such as water wheels, Archimedean-screws, and bucket-chains are known to have been used in Roman mines on the Iberian Peninsula (Butzer et al. 1985; Glick 1970; Malouta and Wilson 2013; Watson 1983). From research into the origin of irrigation agrosystems in eastern Spain, Butzer (1985) concludes that irrigation systems were already well developed and commonly implemented during the Roman period. Orengo et al. (2014) and López (1995) also examined the advancement of technical water management skills of Roman settlers in regard to irrigated agriculture. However, these systems were most likely adopted and further developed by Muslim settlers during the 8th century AD. They implemented new water technology and social organization structures to extend and intensify agricultural production (Butzer 1985).

Today, the Arab influence is still apparent in the terminology of water management, its social organization structures, and the legal practice in regard to water (Butzer et al. 1985; Pocklington 2010; Roldán-Cañas and Moreno-Pérez 2007). While Roman settlements were usually situated close to rivers where the floodplains were utilized for agricultural cultivation, Muslim settlers also exploited areas further inland and implemented irrigation systems to enable intensive agricultural production (Butzer et al. 1985; Orengo et al. 2014). It is also assumed that Muslim settlers introduced the technique of the qanat (Span. *galería* or *foggara*) to the Iberian Peninsula (Butzer et al. 1985). Although the Romans were capable of constructing qanat systems too, there is no evidence for the existence of a qanat on the Iberian Peninsula originating from the Roman period (Gerrard and Gutiérrez 2018). A brief overview of the historical background, spatial distribution, and technical functionality of *galerías* in the area of southern Spain is given by Gerrard and Gutiérrez (2018), Glick and Kirchner (2000), Hermosilla Pla et al. (2004), Kirchner (2009) and Roth and Schütt (2000).

Especially in the dry to sub-humid regions of southeastern Spain, the implementation of water management was used to overcome the challenges of poor soil development and low water availability to improve the local conditions for the implementation of agricultural cultivation (Bellin et al. 2013; Carrión et al. 2010; García-Ruiz 2010; Latorre et al. 2001). Sediment analysis and radiocarbon dating conducted by Puy and Balbo (2013) in the irrigated area of Ricote, located about 40 km northeast of Vélez Blanco, date the construction of irrigated terraces in this area to the beginning of the 8th century AD. This dating corresponds to the early migration of Muslim settlers entering the Iberian Peninsula from the south.

One of the most detailed and profound studies of the social organization and technical functionality of a traditional irrigation system in southern Spain was conducted by Glick (1968; 1970). It focuses on the Huerta of Valencia during the medieval period. Highlights of the study include the detailed analysis and description of the social organization of water sharing, its legal framework, and technical inventory. The organization and management of common pool resources is the central focus of Ostrom (1990). In terms of water management, her definition of common pool resources includes natural resources such as groundwater basins, streams, lakes, and other water bodies and human-made facilities such as irrigation channels and reservoirs. Ostrom (1990) describes the long enduring self-governed irrigation systems of the Huertas of Valencia, Murcia, Orihuela and Alicante. She describes the organizational structures of the individual systems and discusses the significance of responsibilities and regulations within these systems. Also highlighted is the systems' resilience to environmental changes of natural, economic, and social origin.

However, while large water management systems such as the Huerta of Valencia are prominent examples in the history of Spanish water management, the detailed scientific exploration of small- to medium-scale systems is less common.

3. Study Site

3.1 Geographical setting

The study site is located in the region of Los Vélez, in the northern part of the Spanish province Almeria. The town of Vélez Blanco is the second largest settlement in the region. It is situated on the eastern slopes of Mount Maimón, embedded in the southern foothills of the Baetic System. The region is part of the Sierra María and Sierra de Gigante mountain ranges, where altitudes exceed 2,000 m a.s.l. The settlement of Vélez Blanco is situated at about 1,070 m a.s.l. (Figures 1 & 2; Ißelhorst et al. 2018c). The large massif that dominates most of the landscapes in eastern Andalusia originates from the Alpine oogenesis (Schütt 2001). The geology of the region is dominated by the presence of Jurassic limestone, which enables the formation of karstic systems and aquifers; to the south, the relief is characterized by Paleozoic shales and phyllites (Calvillo et al. 1983; Sánchez Martos 1988; Schütt 2001).

Figure 1: Topographic map of Andalusia, southern Spain. The white lines indicate the main catchment divides; the main river streams are highlighted in blue; and the black star marks the location of the study site (after Isselhorst et al. 2018a).

Fig. 2: Topographic map of southeastern Spain. The black star represents the location of the Vega of Vélez Blanco. The photograph is the study site viewed from the southwest (after Roth et al. 2015).

3.2 Climate

The climate at Vélez Blanco can be classified as semi-arid due to its UNEP aridity index of 0.43 (Middleton and Thomas 1997). The climate is characterized by hot summers with extremely rare precipitation events. A more humid phase occurs in spring and autumn, and temperatures are moderate during winter (Fig. 3). Following the climate classification of Köppen and Geiger (Köppen 1936), the local climate at Vélez Blanco is classified as a typical Mediterranean climate (Csa). Precipitation averages 419 mm/year and is characterized by a high inter-annual variability. The months from June to August are dominated by a distinctive dry phase, and throughout the humid phase infrequent heavy precipitation events can occur (AEMET 2014; Isselhorst et al. 2018b). Detailed analyses of the climate system are presented in sections 3.6 and 5.3.

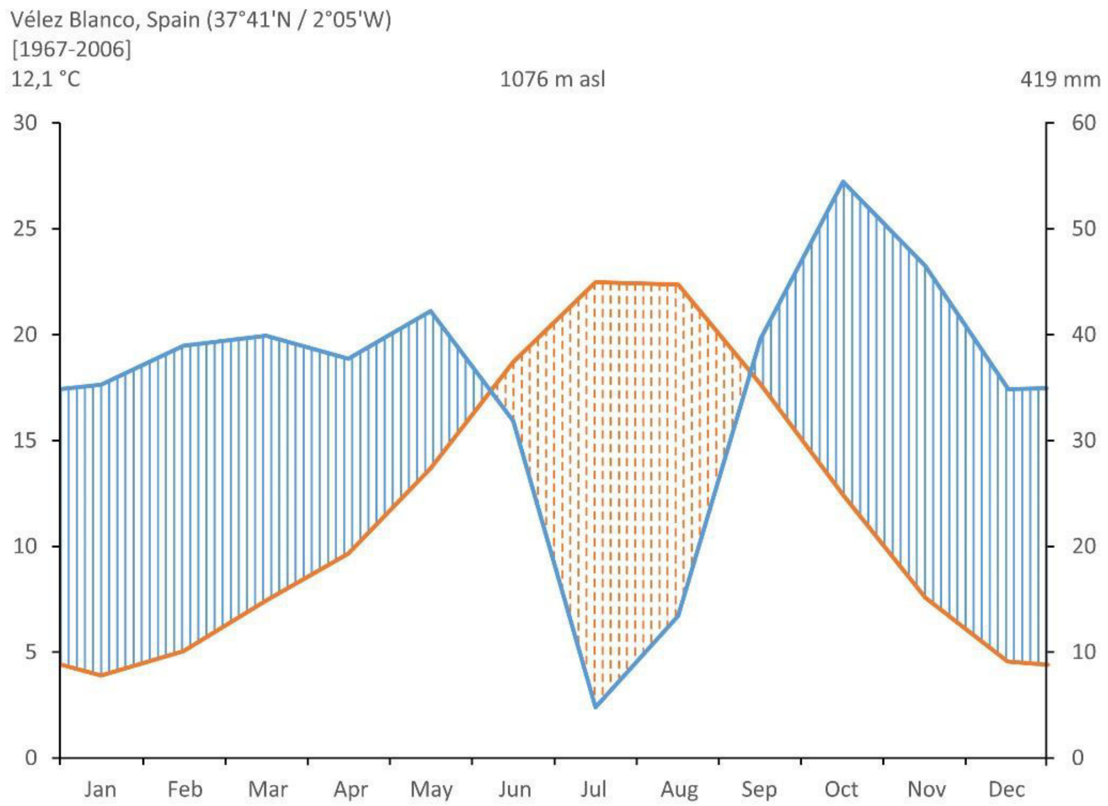

Fig. 3: Climate diagram for Vélez Blanco. Precipitation was measured at the weather station in Vélez Blanco; temperature data were recorded at the weather station in María, located about 6 km west of Vélez Blanco (Ißelhorst et al. 2018c).

3.3 Hydrology

Vélez Blanco is situated in the upper drainage basin of the Río Guadalentín. From a hydrological perspective, the Río Guadalentín is part of the Río Segura basin, most of which is located in the autonomous region of Murcia (Fig. 2). Due to the limestone karst that characterizes the mountain areas in the vicinity of the study site, kastic aquifers are present. These aquifers function as the region's water towers. Most important for the local water supply is the María-Orce aquifer in the Sierra María mountain chain (Calvillo et al. 1983; Isselhorst et al. 2018a). This aquifer feeds countless springs in the region and ensures a perennial water supply. Today, the main use of the spring water is to irrigate the agricultural terraces (Roth 2015).

3.4 Geomorphology

The Vega of Vélez Blanco is embedded in a mountain landscape dominated by the rugged terrain of the Sierra de Gigante and Sierra María. A characteristic landmark is the Muela Grande with an altitude of 1,554 m a.s.l. A sharp edge delimits the mountain's crest from the near-vertical cliff face (Fig. 4). Below the cliff is the talus slope, the first zone accumulating debris from the cliff. The steep slopes of this area are locally inclined up to 50° (Schütt 2001). As a result, landslides frequently occur. The sharp transition between the talus slope and the moderate-to-gently inclined pediment slope is marked by the pediment nick. The pediment slope consists of coarse sediment and is mainly used for rain-fed almond and olive orchards. The adjacent zone is characterized by glacis and alluvial fans consisting of fertile soils and is used for intensive terraced cultivation. The lower foothills of the Muela Grande are irrigated by water originating from the Sierra María (Isselhorst et al. 2018a). The valley that separates the Sierra María and Sierra de Gigante is incised by the Río Claro, a river originating from the high mountain area of the Sierra María. Another characteristic landscape feature is the deep incised gully structures (Span. *barranco*). A *barranco* is formed by gully and rill structures originating from the upper part of the mountain area that meet in the lower zone of the talus slope close to the pediment nick. At this point the individual erosive structures unite to form a major gully (Fig. 4). The incisions result from intensive gully erosion that cut into the slopes due to rainfall runoff. The depth of the gully incision is closely connected to the intensity of the generated runoff and soil characteristics (Iserloh et al. 2017).

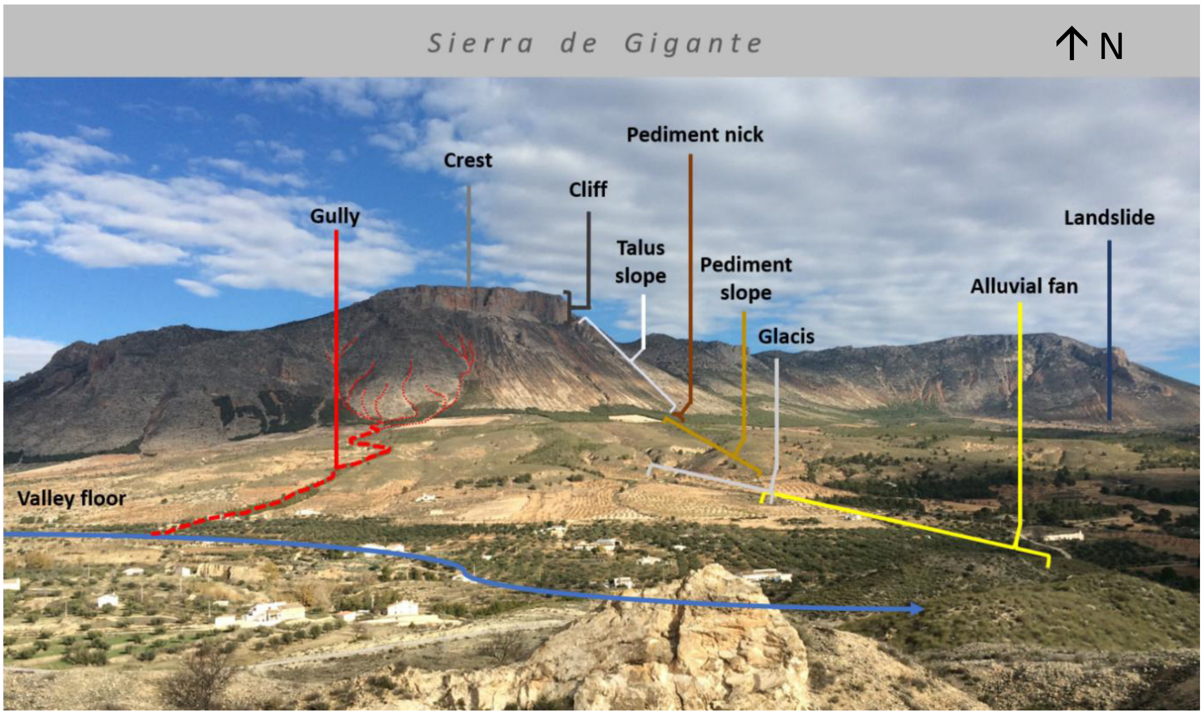

Fig. 4: Schema of the geomorphological elements that characterize the landscape in the area of the study site. Depicted is the Muela Grande. The landscape elements are indicated by individual colors (after Schütt 2001).

Compared to the hillside of the Muela Grande, the slopes of the Vega of Vélez Blanco are characterized by a more enhanced cultural imprint on the landscape caused by irrigated agricultural terraces (Fig. 5 A). The intensive farming has left its marks on the landscape. Terraced cultivation is also practiced on the steeper slopes of the hillside. The upper area of the Vega of Vélez Blanco is characterized by short terrace treads and high terrace walls (Fig. 5 B). Since this area is not necessarily irrigated, it is predominantly used for almond and olive orchards. With decreasing elevation and declining slope gradient, the terrace tread extends in the central and lower part of the Vega of Vélez Blanco (Fig. 5 C & D). In this area, plots of land are irrigated regularly and cultivation is dominated by horticulture, grain farming, and olive orchards. The agricultural terraces typically consist of a stone wall that traps the irrigation water and sediment transported by (rainfall) runoff to enable soil development behind the terrace wall. To stabilize the terrace wall, olive trees are usually planted on its ridge (Fig. 6).

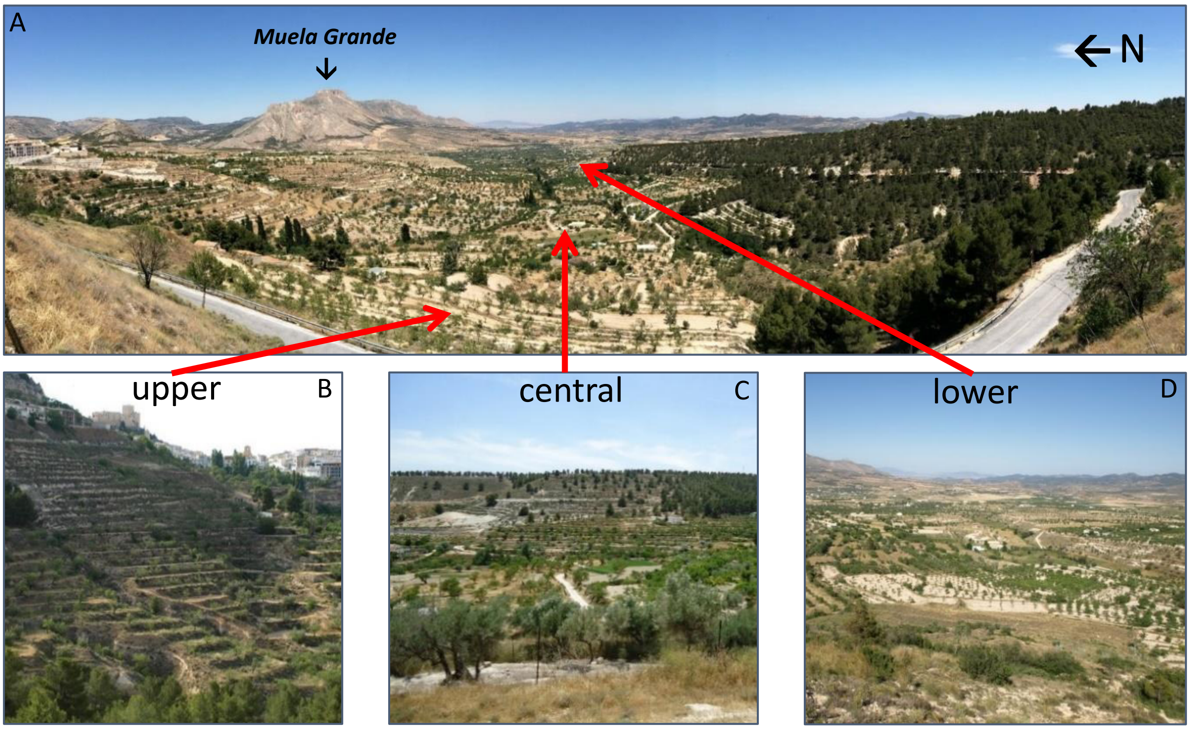

Fig. 5: A: View over the Vega of Vélez Blanco in an eastern direction. B: Picture of the steep terraced slopes in the upper part of the Vega; the central part of the slope is incised by a *barranco*. C: The central part of the Vega is characterized by gently inclined slopes with medium-sized terraces. D: The lower part of the Vega is dominated by large agricultural terraces located on shallow slopes.

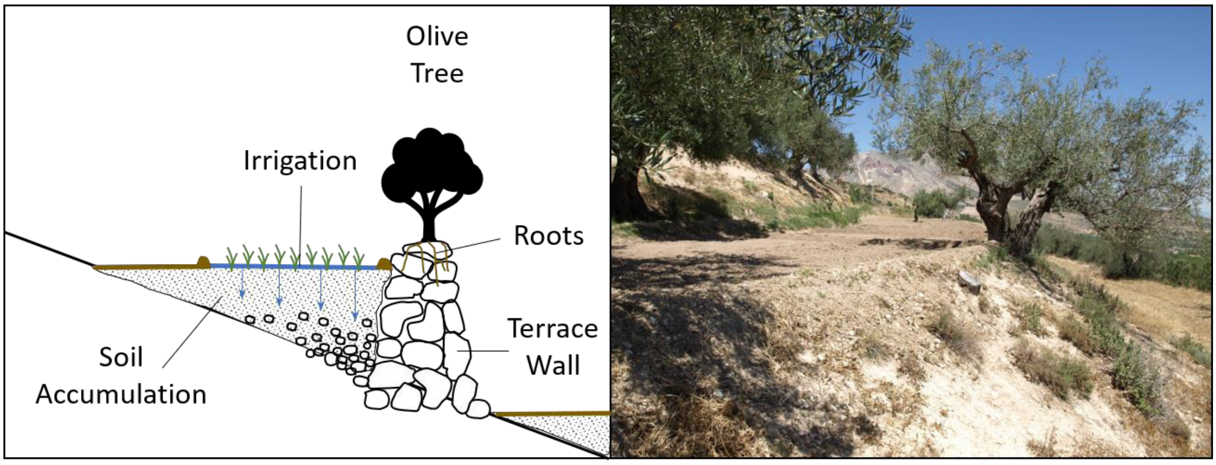

Fig. 6: An agricultural terrace. *Left*: Technical structure of an agricultural terrace under irrigation. *Right*: An agricultural terrace within the Vega of Vélez Blanco.

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3.5 Irrigation Communities and agricultural water management in Andalusia. A special focus on the Vega of Vélez Blanco

Abstract

Data from a freely available data set about Andalusian irrigation communities were comprehensively analyzed and combined with a local time series of precipitation and temperature data and put into historical context. Andalusia’s annual precipitation lies between 150 – 1000 mm*yr^{-1}, making it one of driest areas in Europe, nevertheless, extensive agricultural land use is practiced on about 50 % of its surface area. Due to the high seasonal and inter-annual variability of precipitation, irrigation measures are a necessity to enable intensive cultivation. The largely prevailing water scarcities, especially during the summer months, are one likely reason for the evolution and continuation of water cooperations practicing irrigation strategies, which have probably existed since Roman times and certainly since Islamic times. The study presented here gives an overview of water management practices in Andalusia as practiced at present by more than 500 irrigation communities. Additionally, the study highlights in this regard the Vega of Vélez Blanco in northeastern Andalusia as a case study with a traditional and a still functioning water distribution and network system.

3.5.1 Introduction

Numerous studies exist on the long history of irrigation strategies on the Iberian Peninsula, with its different historical influences from Roman, Moorish, Iberian and other Mediterranean cultures and schemes (Glick 1970; Ostrom 1990; Kress 1968; Fröhling 1965; Brunhes 1902). Irrigation is for the agriculture on the Iberian Peninsula, and especially for its semi-arid south, a necessity to cope with water deficits and seasonal water scarcities. Irrigation institutions and communities which have existed in wide areas of Spain at least since Medieval times are an outstanding characteristic of the area. This especially applies to Andalusia, which was the heartland of the Almoravid dynasty during Medieval times, with Granada as the capital of Al-Andalus, the area of the Iberian Peninsula longest governed under Muslim influence until the Christian reconquest. Locally, these irrigation governance systems which were installed during Medieval times function only slightly altered up until today. Prominent examples of traditional water management systems in southeastern Spain can be found in Valencia, Murcia and Alicante (Glick 1970; Ostrom 1990). Beyond this, more than 500 irrigated areas administrated by irrigation communities currently exist in Andalusia. In total, irrigated farmland generates about 50 % of the annual agricultural income of Andalusia (Junta de Andalucía 2013). Many of the irrigation communities share elements of the technical infrastructure of their water management systems, like tunnels for tapping groundwater or widely distributed channels of irrigation networks. Rotation based water allocation is a common feature. In some of these communities water is even still traditionally auctioned, as it is known from Valencia, for example, meaning that additional water rights can be bought from the irrigation community by its members during regular auctions.

In this study, Andalusian irrigation communities are compared based on the aggregation and reassessment of information on their size, number of irrigators, productivity, water balance and local climatic conditions. On this basis, the representativeness of a concrete case study will be evaluated, namely the irrigation community of Vélez Blanco.

The community of Vélez Blanco located in northeast Andalusia will be presented in detail as a good-practice-example for the preservation of governance structures and techniques of water management, complementing this comprehensive study.

Geographic location of Andalusia

With an area of 87 597 km² and a population of 8,4 million people, Andalusia is the second largest and most populated autonomous region of Spain (Junta de Andalucía o. J.). Its landscape can be subdivided topographically into three main units: the Sierra Morena, the Guadalquivir Valley and the Baetic System. The *Sierra Morena*, a low mountain range with elevations between 800 - 1000 m a.s.l., separates Andalusia from the northern *Castillian Meseta*, in Spain's interior. The landscape of Andalusia is dominated in its central and western-parts by the fertile basin and alluvial plain of the *Rio Guadalquivir*. To the west, the Guadalquivir meets the Atlantic Ocean at the Gulf of Cádiz where the river delta is characterized by fertile wetlands. The rough terrain of the *Baetic Mountains* shapes the south-east of Andalusia. With elevations above 3,400 m a.s.l. in the area of the Sierra Nevada, this high mountain range forms a natural barrier between the Mediterranean coastline and the Andalusian hinterland (Fig. 1).

Fig. 1: Topographical map of southern Spain. The autonomous region of Andalusia is highlighted. Elevation data are based on SRTM 3 data. Major divides are marked by white lines (Ministerio de Agricultura, Alimentación y Medio Ambiente 2016; Jarvis et al. 2008).

Climatic characteristics

The climate in most parts of Andalusia is Mediterranean and corresponds to a *Csa* climate, only in the southeast of Andalusia is climate significantly drier and corresponds to a steppe climate (Köppen 1936). In general, the climate mostly consists of a pronounced dry season during summer months, while most of the rainfall events occur from autumn to spring. The annual precipitation is characterized by rainfall events that most likely occur during the autumn months and to a lesser extent during winter and spring (Geiger 1970; Rodrigo et al. 2000).

Regional differences in the climate of Andalusia are predominantly controlled by the topography and the distance to the coastline. In consequence, the strong seasonality of the Mediterranean climate is overlapped regionally by maritime influences due to the geographical position adjacent to the Mediterranean Sea in the south and the east, and the Atlantic Ocean in the west. This especially applies to the spatial and temporal distribution of rainfall: In Andalusia high regional variations of annual precipitation occur, ranging between less than 150 mm in the area of Cabo de Gata in the southeast and more than 1,000 mm in the Sierra de Grazalema in the western Baetic Mountain range, whereas annual precipitation in the area of Vélez Blanco locally averages 420 mm (Pita López 2003). Precipitation amounts also show a high seasonal and annual variability. In general, the occurrence of rainfall in Andalusia is controlled by two types of pressure cells, the Azores high and Atlantic lows with their related fronts (Rodrigo et al. 2000). Particularly during the wet season from autumn to spring, precipitation of low intensity is mainly brought to western Andalusia by low pressure cells or rain bearing clouds from the Atlantic ocean (Schütt 2004; Sumner et al. 2001). As shown by isotope analyses of Andalusian aquifers, groundwater recharge is mainly caused by more intense winter precipitations originating from the Atlantic ocean (Julian et al. 1992). The steppe-like climate of south-east Andalusia is also characterized by wet seasons in autumn and spring, but with precipitation appearing reliably only in autumn. During this time the precipitation maxima is caused by the Balearic low from the Mediterranean Sea, a thermal depression of stationary character that emerges in September due to the thermal difference between land and water masses (Lautensach 1964). The winter in this region is usually marked by a dry phase (Geiger 1970). In this area, dryness is mainly caused by the *Baetic mountains* which function as a barrier for precipitation coming from the west (Junta de Andalucía 2013).

Aspects of agricultural production in Andalusia

Despite the fact that most areas in Andalusia struggle with water scarcity, agricultural production has a long history and is an important economic sector. More than 50 % of the region’s surface is used as farmland, of which arable crops and olive groves are the main cultivation forms, while fruit farming and vineyards are - today - of minor importance. In general, agricultural cultivation can be subdivided into dry and irrigation farming, with irrigation faming practiced on approximately 25 % of the agricultural land (Tab. 1). Due to the severe dry season from June to August, irrigation farming is a frequently used tool to enable cash crop farming.

Tab. 1: Main agricultural cultivations of Andalusia, Spain. The category "arable crops" comprises the cultivation of vegetables and cereals (Junta de Andalucía 2013).

	Cultivated Area		Irrigation Farming	
	[ha]	[%]	[ha]	[%]
Arable Crops	1,564,387	49.1	322,620	20.6
Olive Groves	1,358,757	42.7	359,366	26.5
Fruit Cultivation	229,515	7.2	105,649	46.0
Vineyards	26,299	0.8	2,837	10.8
Other	4,609	0.2	2,560	46.9

The Vega of Vélez Blanco

In the village of Vélez Blanco, eponymous for the adjoining Vega, irrigation water is still obtained by public sale at auctions, which take place twice a week during summer months. Due to its special character of governance the Vega of Vélez Blanco is described separately in this study. The remarkable - and in Andalusia today singular - water governance system in the Vega of Vélez Blanco was already the object of various publications (Roth et al. 2015; Navarro Sánchez 2010; Schütt 2001; Tyrakowski 2001; Navarro López et al. 2012; Real Orden de 18 de Enero de 1902/1903).

The Vega of Vélez Blanco is located in northeast Andalusia, downslope from the town of Vélez Blanco, a small town in the easternmost part of the autonomous region of Andalusia (Fig. 2). At an altitude of 1,070 m a.s.l. the town is embedded in the mountainous region of the *Sierra de Maria*. This mountain range is primarily composed of Jurassic limestone, and is part of the southern foothills of the Baetic mountains (Schütt 2001). The springs located above the town have their source at the eastern slopes of the *Mount Maimón and* ensure a perennial water supply to the town and adjacent agricultural areas. The springs are fed by an extensive aquifer situated in the karstic limestone formations of the Sierra de Maria. The environs of Vélez Blanco are characterized by terraced slopes where intensive irrigation farming is practiced; this area is also known as the *Vega of Vélez Blanco*. Within the irrigated area traditional cultivation such as olive and almond groves can be found, as well as vegetable gardens and orchards. In the lower parts of the Vega of Vélez Blanco cultivation of intensive irrigated vegetables is also practiced.

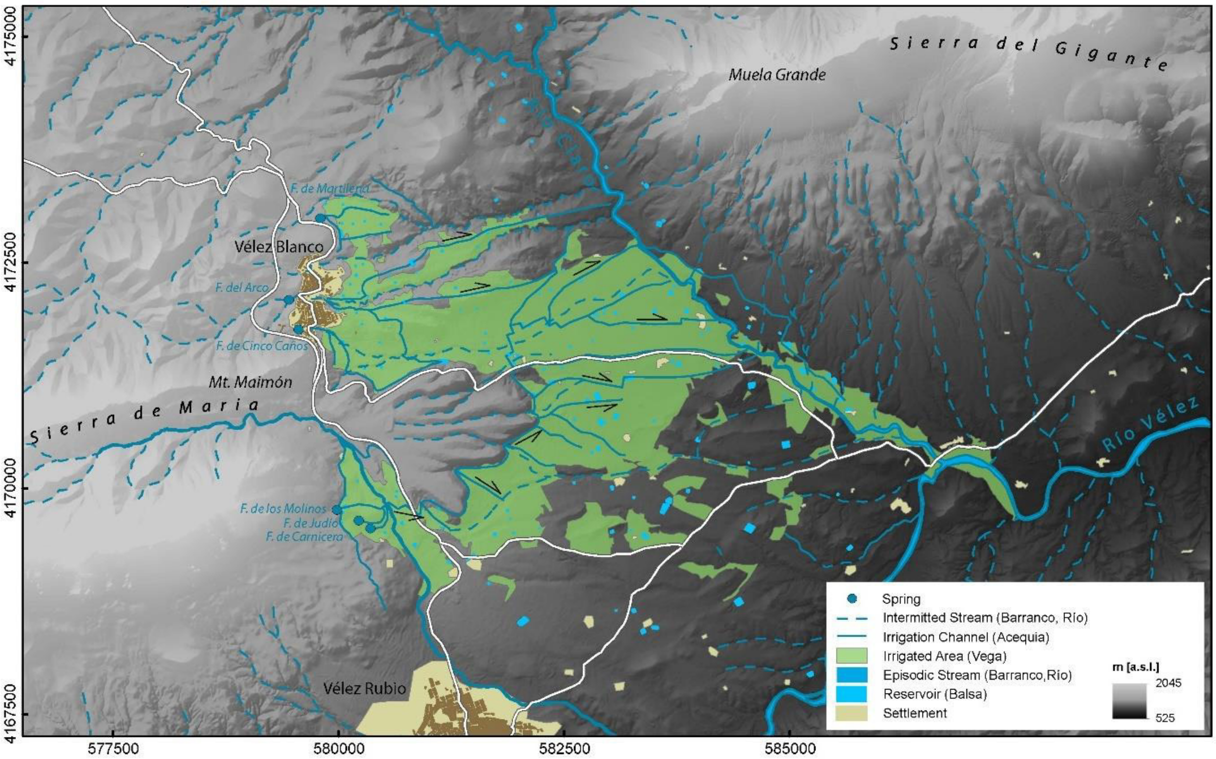

Fig. 2: Location of the Vega of Vélez Blanco. The depiction of water management infrastructure is simplified and illustrated by solid blue lines (irrigation channels) and light blue polygons (reservoirs). Elevation data are based on Lidar data (5 m resolution) (Centro Nacional de Información Geográfica (CNIG)).

3.5.2 Components of Andalusia´s water management history

Water utilization

Water scarcity is a serious problem in wide areas of Andalusia. The main water supply for irrigation farming originates from surface and groundwater, with surface water supplied by streams, lakes and reservoirs (Fig. 3) (Consejería de Agricultura, Pesca y Desarrollo Rural). Irrigation water originating from desalination of seawater and water treatment is of minor importance (Consejería de Agricultura, Pesca y Desarrollo Rural). In addition to the physical availability of water, good technical and administrative management practices are required to achieve a sustainable distribution.

While surface water needs management techniques for its transportation, distribution and storage, such as aqueducts, channels and reservoirs, groundwater additionally needs technical facilities for its exploitation. In Spain a traditional technique for groundwater exploitation is the so called *galería*.

This technique is similar to that of the *qanat* systems which originate from Persia (Mays 2010). *Galerías* are frequently used to exploit water from an upslope aquifer by tapping into the waterbody with a tunnel or conduit that leads the water to a foreland outflow facility, from where it is transferred into small artificial reservoirs (*span. balsa*) where it is temporarily stored (Beckers et al. 2013; Roth et al. 2001). From there the water is distributed by networks of channels to serve the fields below. Often these systems are traditionally managed by so called irrigation communities or irrigation associations (subsequently the term irrigation community will be used as an equal term for both irrigation community and irrigation association).

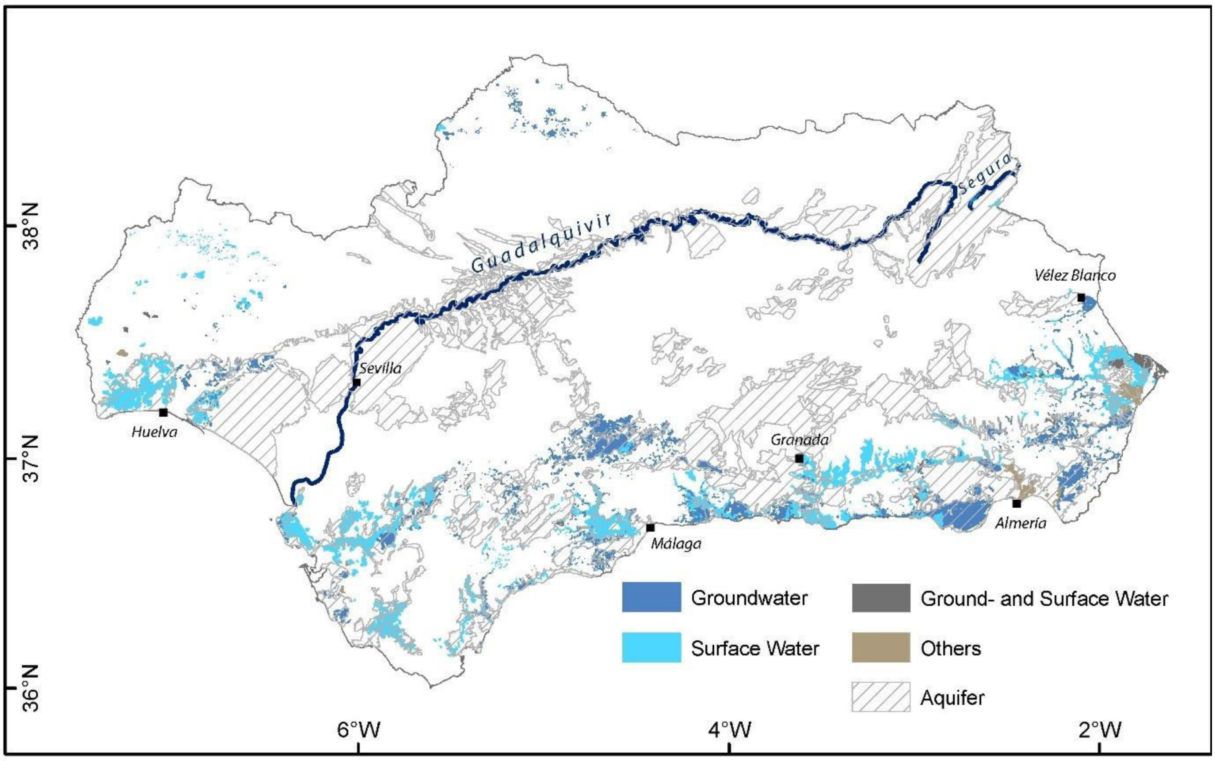

Fig. 3: Areas under irrigation in Andalusia, subdivided by the origin of the water. Locations of aquifers are indicated with grey stripes.

Historical development of the water management's legal framework and administration

In Spain, the first evidence for the implementation of water management structures dates to the Roman times, while most of the present structures were established during the Muslim period (8th cent. BCE) (Fröhling 1965; Kress 1968). The Moors introduced the autonomous management of water allocation systems and improved water availability by technical advancement during Medieval times (Boelens and Post Uiterweer 2013). Since then, a variety of transformations of administrative organization, legal ownership and local water law took place, but fundamentally the Moorish structures still provide the basis for the current Spanish water management practices and structures (Glick 1970). The first standardized guidelines for water regulation were adopted with the initial Water

Act in 1866 (Fornés et al. 2007). At this time, the first low degree state regulations on spatial organization and usage of water were introduced. Subsequently, a significant turn in the spatial organization of administrative water management units took place between the 1920s and 1960s with the foundation of river basin authorities (*Confederaciónes Hidrográficas)*. From here on, the drainage basins of the main streams of Spain were treated as hydrological units, defined by their natural catchment area instead of territories limited by political borders (Sánchez-Martínez et al. 2012) (Fig. 4).

The Water Act of 1985 has had the most significant influence on the current Spanish water management practices. Its implementation led to an almost completely revised organization of water property rights and administrative management structures. The new legislation declared all surface water as well as renewable groundwater bodies as public goods, except those where private ownership was adjudged by prior legislation (Sánchez-Martínez et al. 2012).

Fig. 4: A: Hydrological basin level administration units (Confederaciones Hidrográficas) of Spain; boundaries are defined by the major divides (black lines). The location of Vélez Blanco is indicated by the red point. The political border of the autonomous region of Andalusia is highlighted by the red line. 1-Islas Baleares, 2-Cuencas Mediterráneas de Andalucía, 3-Cuencas Atlánticas de Andalucía, 4-Cuencas Internas de Cataluña, 5-País Vasco, 6-Cantábrico, 7-Miño-Sil, 8-Galicia Costa. B: The overview map illustrates the political borders of the Spanish autonomous regions. The area of Andalusia is marked in red (M. de A. Gobierno de España Alimentación y Medio Ambiente 2016).

The multiplicity of the water management regulations implemented over time have led to the high complexity of the present administrative water management structures in Spain (Fig. 5). Large scale systems, which operate on basin levels are directly supervised by the central government (central management), while systems of a smaller scale are usually administrated by regional and local institutions or private associations (decentralized management). It is assumed that a number of these irrigation communities were founded at least during the Muslim Period. Today only few of these sub-systems still exist with their historical administration structures, while most of them were transformed by external influences.

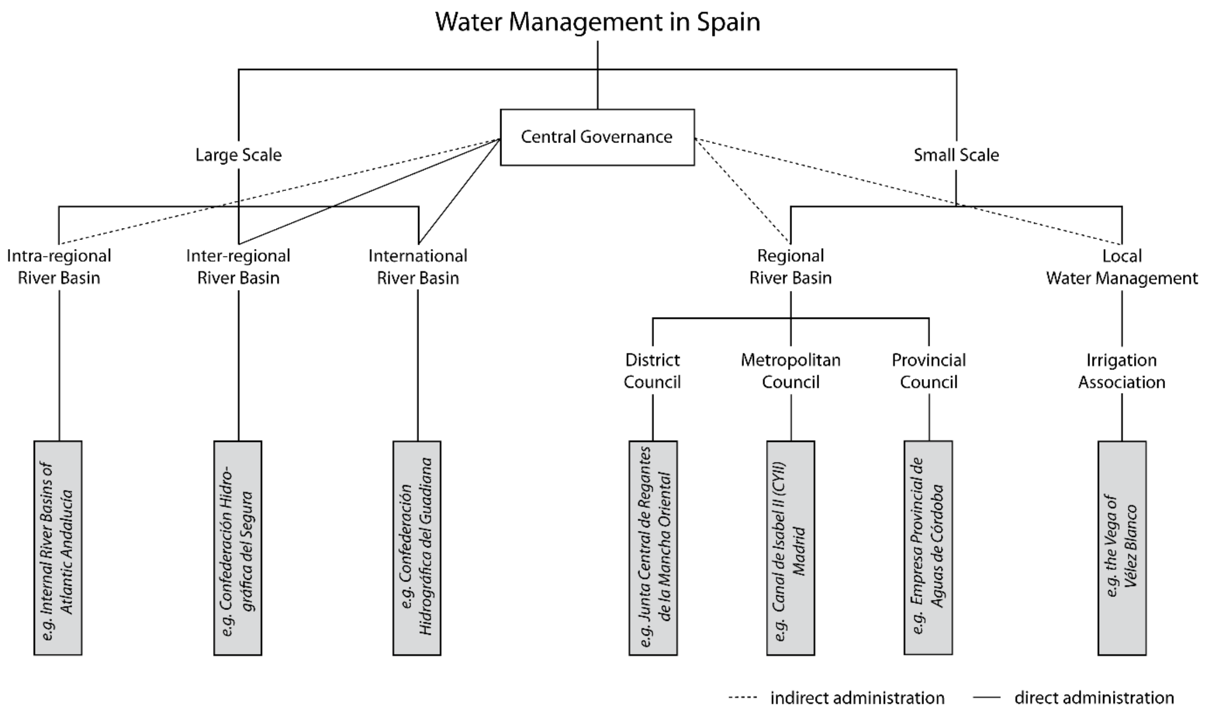

Fig. 5: Exemplary organization of the water management in Spain (based on Sánchez-Martínez et al. 2012)

At present, a total of 586 irrigated regions exist in Andalusia, administrated by so called irrigation communities (span. *Comunidades de Regantes*). Most of the irrigation communities are of private origin and show a wide variety in size, water availability and crops cultivated (Consejería de Agricultura, Pesca y Desarrollo Rural). Also the management of the irrigation communities varies. In principal, they can be distinguished by their characteristics in terms of legal relationships between land, owner and water law. According to Butzer et al. (1985) two basic types of linkages between landownership and water law exist historically: On the one hand, there is the Syrian system, where land property is inseparable from irrigation rights, implying that each land plot is legally entitled to an amount of (irrigation) water proportional to the area. On the other hand, the Yemenite system separates the ownership of water and land, so that they can both be sold independently.

Furthermore, the irrigation communities can also be differentiated by the local organization systems of water sharing. A frequently used method is the water allocation by rotations, where each eligible user is entitled to receive irrigation water in a fixed turn of time units or volume (Glick 1970). Another type is water allocation on demand, where landowners need to apply for irrigation water. The auctioning of water was a common method in the past, but is rarely found nowadays (Geiger 1970). Prominent examples in south-eastern Spain where water was auction in the past are the irrigated areas of Elche, Alicante and Lorca (Brunhes 1902, Geiger 1970, Ostrom 1990), while most of the irrigation communities abandoned the auction-based system.

The water management system of the Vega of Vélez Blanco

With regard to its location, the Vega of Vélez Blanco (Fig. 6) represents a good example for the modern reorganization of the traditional administration. While politically the town of Vélez Blanco is part of Andalusia, its hydrological administration is task of the *Confederación Hidrográfica del Segura, which* is situated in the autonomous region of Murcia. But since the local springs are traditionally managed by the local irrigation community, the national water management has just a marginal influence on this system (Navarro Sánchez 2010).

Based on knowledge about similarly structured systems in the area of south-eastern Spain, it is assumed that the local water management structures in the Vega of Vélez Blanco can at least be dated to the Muslim period (Roth et al. 2015). Its uninterrupted irrigation history enables the investigation of an irrigation community that is only marginally affected by large scale restructuring plans and external institutions. Even today the local water allocation is organized in a mixed system that consists of irrigation rotations and water auctions (Navarro Sánchez 2010). Within this system, each farmer with legal water rights has a fixed amount of irrigation time that is assigned to the land owned or hold; landownership and irrigation rights are originally bound to each other (Roth et al. 2015). Likewise, the irrigation community is part of the rotation system, so they also get water out of the rotations. This surplus is periodically sold during public auctions where everybody who is connected to the channel network of the Vega of Vélez Blanco is allowed to buy a fixed amount of irrigation water (Tyrankowski 2001). Especially during dry periods in summer months, additional irrigation water is frequently needed to gain good harvests or in some years even to avoid crop failure.

Fig. 6: View into the Vega of Vélez Blanco (line of sight westerly direction). The mountain Muela Grande can be seen in the background.

3.5.3 Materials and Archives

To determine the characteristics of the average Andalusian irrigation community, the data set "*Inventario de Regadíos 2008*" was used. It also includes the irrigation community of Vélez Blanco, for which several values are highlighted for comparison. The selection of numeric attributes enabled the evaluation of local hydrological and economic features within the irrigated areas.

Archives

The data set "*Inventario de Regadíos 2008"* is a state inventory of the irrigated areas in Andalusia. It is generated by the *Confederación Hidrográfica del Guadalquivir* as part of the national hydrological plan and includes detailed information on a total of 979 irrigation areas supplied by fresh water that mainly originates from ground or surface waters. Additional water sources such as desalinated seawater and treated wastewater are of minor importance. Data about local irrigation communities relevant for this study were extracted from this inventory; subsequently only data on areas supplied by ground or surface water remained. The variables used for statistical analyses are briefly introduced in table 2. They were chosen as representative characteristics for comparison.

The detailed information on cultivation and handling of the irrigated areas is based on interviews with local landowners and staff members of irrigation communities (Consejería de Agricultura, Pesca y Desarrollo Rural) [1].

Data Preparation

The data are not normally distributed; hence all data sets were statistically edited by determining extreme values. Extreme values were calculated based on the individual interquartile range of each factor. The minimum value in table 2 represents the 0.25 quartile while the maximum value marks the 0.75 quartile; extreme values that exceed the statistical boundaries defined by the interquartile range are not equal to bias within the data set. Therefore, these adjusted data were interpreted carefully. In general, all values show a high degree of dispersion. To determine measures of central tendencies, basic statistics were calculated for the processed data. Mean values extracted from the data set represent the properties of the average Andalusian irrigation community.

Water balance

Data on local water consumption and demand allow the analysis of local water balances. By plotting the parameters of consumption and demand, the individual water balance of an irrigation community is visualized. Local water consumption is calculated using information about locally cultivated goods and their respective water demand, hence amounts of water demand are estimated within the data set.

Irrigation volume

The local irrigation volumes were calculated by the quotient of water prices per area (€*ha^{-1}) and water costs per volume (€*m^{-3}). The local average volume of irrigation water was determined in cubic meters per hectare (m^3*ha^{-1}). This value allows the classification of irrigated areas in terms of its irrigation intensity. As the calculated irrigation volume is similar to the value of local water consumption, these values were applied to verify the data set.

[1] Only values given for the Comunidad de Regantes de las Aguas del Maimón de la Villa de Vélez Blanco were selected as characteristic for the Vega of Vélez Blanco.

Precipitation and temperature

The annual precipitation for each irrigation community was extracted from the global Worldclim precipitation data set with a spatial resolution of 1 km². The Worldclim 30 arc-seconds dataset is generated by the interpolation of climate information from a large number of weather stations with a temporal resolution for the precipitation records of at least 30 years (1960-1990) (WorldClim - Global Climate Data). This data set is known to give reliable results and is widely used in the scientific community (Hijmans et al. 2005; Avellan et al. 2012).

A dataset of daily precipitation measurements (1969 – 2014) from the weather station in Vélez Blanco was used to illustrate the seasonal variations of precipitation; for monthly data, the daily precipitation measurements were summed up (AEMET 2014). Temperature measurements from the weather station in María, situated about 6 km west of Vélez Blanco, were used to represent the seasonal variation of the monthly mean temperature (AEMET 2014). Mean values were calculated based on daily minimum and maximum temperature data.

Based on these data sets, mean values were calculated and boxplot diagrams for each month were created to outline the variation of monthly precipitation amounts and mean temperature during the hydrological year (Nov. 1^{st}- Oct. 31^{st}). Moreover, data about cycles of irrigation, blossom and harvest of olives were consulted from the literature to exemplarily show the importance of precipitation variability for plant growth.

3.5.4 Results

Characteristics of Andalusian irrigation communities

In Andalusian irrigation communities land property size per farmer averages 2.76 ha and is in general irrigated annually by 3,700 m³ water per hectare (m^3*ha^{-1}). The estimated water surplus of approximately 215 m^3*ha^{-1} indicates that the average irrigation community has a positive water balance. In total, annual mean productivity rates of agricultural cultivation of more than 3,700 m^3*ha^{-1} are achieved by irrigation farming (table 2).

The direct comparison of the Vega of Vélez Blanco with the average Andalusian irrigation community shows that the number of irrigators per ha in the Vega of Vélez Blanco is higher than in the average Andalusian irrigation community, while the average property size per farmer is more or less identical in both groups (table 2). In contrast, the average amounts of annual water consumption and demand, as well as those of productivity and irrigation volume, are lower in the Vega of Vélez Blanco than in the respective means of the average Andalusian irrigation community.

Tab. 2: Results of the statistical analysis of the Inventario de Regadíos of 2008. Since all data show high standard deviation, mean values should be handled with care. AIC: Average Irrigation Community.

	Irrigation Communities Andalusia (n=301)				Vega of Vélez Blanco
	Mean (AIC)	Standard Deviation	Min.	Max.	
Property Size per Farmer [ha]	2.76	12.52	0.04	15.13	2.76
Irrigators per ha	2.50	3.03	0.01	28.03	0.36
Water Consumption [m^3*ha^{-1}]	3732.8	457.88	2953	4500	3000
Water Demand [m^3*ha^{-1}]	3517.4	521.63	2732	4620	2682
Water Balance [m^3*ha^{-1}]	215.4				318
Irrigation Volume [m^3*ha^{-1}]	3723.0	450.07	2953	4500	3000
Production [m^3*ha^{-1}]	3711.2	444.01	2965	4505	3217
Annual Precipitation [mm]	450.43	139.55	224	870	403

Water balance

The data show that 58.7 % of irrigated areas manages by irrigation communities in Andalusia have water excess, while 41.3 % struggle with water deficits (Fig. 7); in consequence, nearly half of the irrigated areas in Andalusia suffer from a considerable water deficit, where the water demand for irrigation farming cannot be covered by local water resources. With an average annual water consumption of 3,000 m^3*ha^{-1} and a demand of 2682 m^3*ha^{-1} the Vega of Vélez Blanco has a well-balanced water budget with a small amount of excess water.

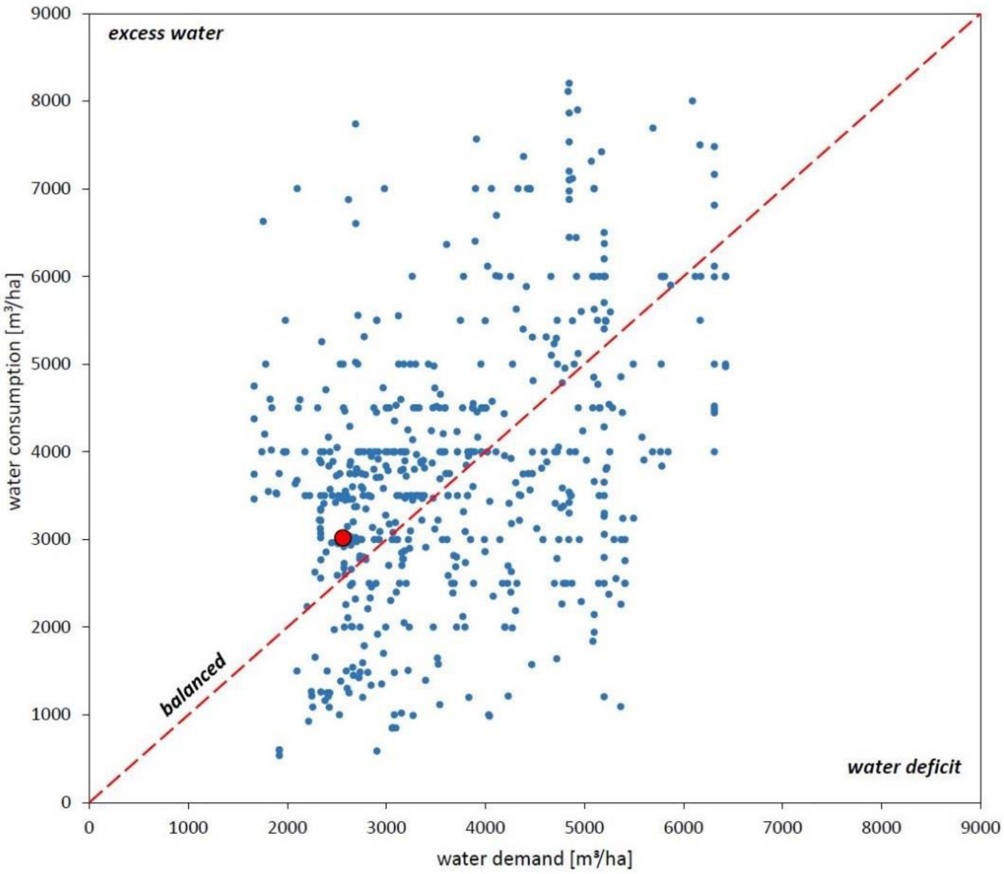

Fig. 7: Correlation of water consumption and water demand in irrigated areas managed by an irrigation community. The red line indicates the theoretically balanced water budget equilibrium. The red point marks the Vega of Vélez Blanco.

Irrigation volume and precipitation amounts

The most intense irrigation is practiced in areas used for vegetable cropping or citrus fruit plantations; in these areas annual irrigation capacity averages 400 mm*ha^{-1} and can reach up to 800 mm*ha^{-1} (Consejería de Agricultura, Pesca y Desarrollo Rural). Olive groves require less irrigation water volume, with an average amount of 290 mm*ha^{-1} and maximum amounts of 780 mm*ha^{-1} of irrigation water.

The annual precipitation amounts in the analyzed regions range between 230 – 795 mm*yr^{-1} (Fig. 8). Citrus fruits are planted in regions with annual precipitation amounting to up to 690 mm*yr^{-1}, while most plantations operate in areas with annual rainfall amounts of 300 – 460 mm*yr^{-1}. Subtropical fruits are cultivated in regions with up to 800 mm*yr^{-1} annual precipitation, where most areas receive about 410 – 590 mm*yr^{-1} of annual precipitation. The precipitation range of regions where vegetables and olives are cultivated correspond to those of the subtropical fruits, with olives showing the widest range of annual precipitation, spanning between 350 and 590 mm*yr^{-1}. For the data analyzed all means were higher than the median. Summarizing, the box-plot in figure 8 clearly shows that the amount of annual precipitation is not the controlling factor for cropping.

More important for the selection of a crop type for a region is the relation of the respective flowering period and growing season to the annual cycle of precipitation and prevailing temperatures at a location. The plants demand for water is usually increased during these phenological growth stages. Also seasonal variations in temperature have a major influence on the growth of certain plants, which especially applies for plants that are vulnerable to temperatures below the freezing point.

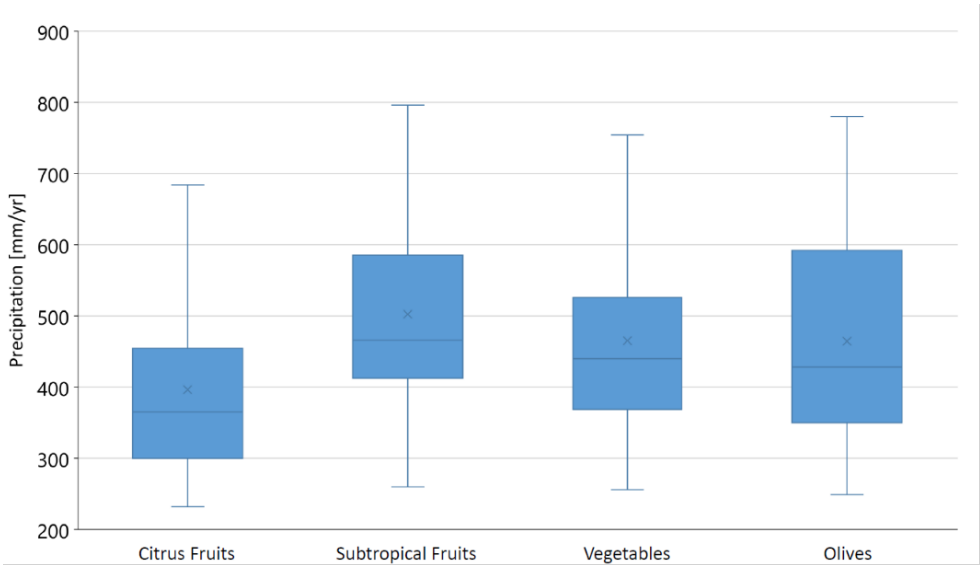

Fig. 8: Boxplot diagrams of areal precipitation ranges for irrigated areas and their respective main crops.

Precipitation and temperature variability in Vélez Blanco

In Vélez Blanco the autumn is characterized by the highest variation in monthly amounts of precipitation, with means of about 50 mm per month and extreme values of more than 240 mm (1969 - 2014; Fig. 9). During this time of the year mean temperatures rapidly fall from about 17 °C in September to less than 8 °C in November. The months of September and November also show the lowest range of mean temperatures. A significant low in average precipitation volume (less than 5 mm in average) marks the summer month of July, while the highest temperatures are reached in August. June and August show low precipitation amounts averaging less than 25 mm. Winter and Spring are characterized by constant mean precipitation amounts of about 40 - 45 mm, where the highest variation can be observed in January and April (1969 - 2014). The winter months are dominated by the lowest monthly mean temperatures which show a moderate range. Highest variations in mean temperature can mainly be observed in the transition zone of the seasons.

The comparison of precipitation and temperature data from Vélez Blanco with annual general cycles for the cultivation of olives shows that the major irrigation period in August coincides with aridity and high mean temperatures, which mark the summer months from June to August, and the low precipitation probability during this time overlaps with the flowering period of olive trees. In contrast, the water demand of olive plantations during the start of the blossoming period in May is likely to be covered by precipitation, while additional irrigation is only required during dry springs. The same holds true for the ripening process of the olive fruits in autumn.

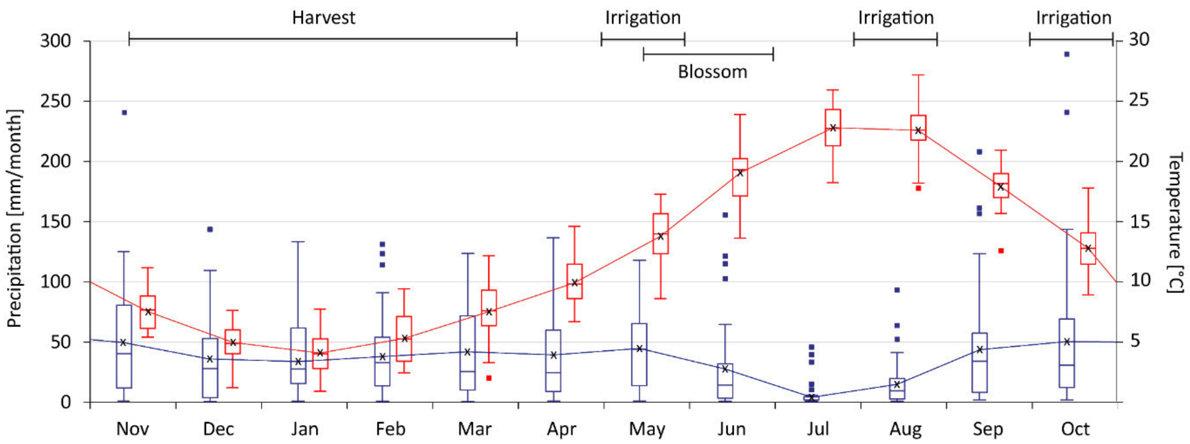

Fig. 9: Boxplot diagram of the monthly precipitation and mean temperature values (precipitation data recorded at the weather station in Vélez Blanco; temperature date recorded at the weather station in María) for a period of 45 years (1969-2014). The data is arranged in the sequence of the hydrological year (Nov. 1st – Oct. 31st). The blue boxplots and line represents the monthly mean precipitation rates, while the red boxplots and line illustrate the monthly mean temperature. Blue and red squares mark extreme values of monthly precipitation sums and

mean temperature rates. The general annual cycle of irrigation, blossom and harvest of olives are based on data from the FAO (FAO 2015; AEMET 2014).

3.5.5 Discussion

The data set of the inventory of irrigated areas in Andalusia was already used in several studies (Rodríguez-Díaz et al. 2008; Solbes 2003; Salmoral et al. 2011). These studies share a tentative handling of the data, since much of the information provided is aggregated indirectly from interviews and remote sensing analyses. Nevertheless, this archive contains comprehensive information about irrigation communities in Andalusia that is currently openly accessible (Solbes 2003).

Organization of irrigation communities in Andalusia

A literature review revealed that the degree of complexity of the administration of irrigated areas mainly depends on the number of farmers that rely on surface or groundwater. Especially irrigated areas that are supplied by surface water often need a high degree of administration, with decentralized cooperation, since these sources often supply several irrigated areas within a rivers course such as the Guadalquivir. In contrast, areas supplied by groundwater are usually of small extend and therefore need a relatively low degree of administration. Butzer et al. (1985) defines three basic scales to classify the management of irrigated areas. The smallest one is *micro-scale* irrigation with a size of less than 1 ha. Here an individual farmer or a few farmers use water from one small spring or a cistern. *Meso-scale* irrigation areas include one single or several cooperating irrigation communities that are supplied by water from at least one spring. On average, these systems contain up to several hundred farmers that together usually irrigate less than 100 ha. The largest unit are the *macro-scale* irrigation areas, which comprise several irrigation communities; up to several hundred cultivators can be included in these systems. The area under irrigation normally exceeds 50 km² and therefore necessitates a highly complex channel network for the water distribution as well as a sophisticated government structure.

Based on the numeric characteristics of the Vega of Vélez Blanco and the definitions by Butzer et al. (1985) the Vega of Vélez Blanco can be classified as a meso-scale irrigation area. This is also the classification for the average Andalusian irrigation community.

Vélez Blanco within the Andalusian irrigation communities

The comparison of the irrigation area of Vélez Blanco with the average Andalusian irrigation community reveals that the Vega of Vélez Blanco is a good representation of the average Andalusian irrigation community. The only feature that distinguishes the Vega of Vélez Blanco from other Andalusian irrigation areas is the tradition of auctioning irrigation water during summer months. The prevailing mixed system of irrigation rotations and water auctions has lasted centuries in approximately the same administrative form that is still in place today, while other irrigation communities of Andalusia abandoned this type of organization (Roth et al. 2015). A well-known example is the *Huerta de Lorca*, located in western Murcia, where water auctions where abolished in 1961 (Geiger 1970).

Since water is an important resource for the development of local economic and social structures, transformations in water availability or its quality can influence these developments (Custodio et al. 2016). As shown by Boelens and Uiterweer (2013), a change in political or economic conditions, like for example the governmental reorganization of administrative structures, can trigger transformations of organizational water management systems (Boelens and Post Uiterweer 2013). In the most recent water management history of Spain large scale water allocation programs led to a completely revised organization of local and regional water management systems. These restructuring plans have deconstructed self-governance systems in many regions that had previously worked in a self-organized way for centuries (Boelens and Post Uiterweer 2013). Substantial imbalances in regional water supply were the initial reason for this reorganization. According to the analyzed inventory, more than half of the irrigated areas of Andalusia show a positive water balance whereas water demand exceeds the natural availability in 41,3 % of the areas (Fröhling 1965; Geiger 1970; Saurí and Del Moral 2001).

Water balance

Water consumption and demand in the Vega of Vélez Blanco is approximately balanced. Thus, on average the given water resources are sufficient to supply the cultivated crops. This general statement does not include seasonality and inter-annual variations. An extended dry season as well as a drought or a sequence of years with below average annual rainfall can lead to an increased water demand and, thus, to a shift towards an unbalanced water regime

The main crop cultivated in Andalusia are olive groves. In total, they cover more than 40 % of the irrigated land of the autonomous region (Junta de Andalucía 2013). Olives require water especially during their periods of growth in May, August and October to obtain good harvests (Galán et al. 2008). To allow a harvest, the minimum amount of water required during this time totals 200 mm, while the highest crop yields are achieved with 600 – 800 mm of water provided during that time; as in most cases these water amounts are not provided by precipitation irrigation is required (FAO 2015). Most importantly, irrigation is required about two to three week prior to the flowering period of the olive (Caliandro and Boari 1992). Olive groves in irrigated areas of Andalusia that are administrated by an irrigation community receive 230 – 795 mm of annual precipitation, which should be adequate to receive low to sufficient yields without irrigation. However, due to the seasonal and inter-annual variations in precipitation amounts, irrigation is frequently required to improve harvests or secure crops. Especially during the main growing seasons in the summer months, irrigation is often used to bridge the dry season for the improvement of crop yields.

Vegetables and cereal fields cover nearly half of the cultivated surface area of Andalusia (Junta de Andalucía 2013). Based on data found in literature, vegetable crops such as tomatoes, peppers, cabbage and onions need on average 350 – 900 mm of annual precipitation to achieve adequate crop yields (FAO 2015 a-e). Within the irrigated areas of Andalusia these agricultural products are usually cultivated in regions where annual precipitation ranges from 250 - 760 mm. Here likewise, annual sums of precipitation give no reliable information about the natural water supply of the cultivated crops during its season of growth. The cultivation of most vegetables in Andalusia needs intensive irrigation.

Agricultural production in the Vega of Vélez Blanco is dominated by olive and almond groves. A small area of intensively irrigated vegetables can also be found in the lower part of the Vega of Vélez Blanco. These vegetable gardens are mainly for private consumption.

As literature sources and the case study from Vélez Blanco show, for most of the cultivated goods represented in this study the main periods of growth coincides with the distinct dryness and high temperatures of the summer months. Additionally, cold winters with temperatures below freezing as well as a hot summer with an extended dry period can result in crop failures. An example is given by the olive; long lasting periods of frost with temperatures of – 10 °C and below lead to poor harvests or even to crop failure (Steduto et al. 2012). Furthermore, various of the plants cultivated in Andalusia are very sensitive to fluctuations in temperature. As a consequence, especially in the driest parts of Andalusia, irrigation is a necessity to ensure good harvests for agricultural goods such as olives.

One of the challenges concerning irrigation farming is the cultivators' profit orientation. Frequently, cash crop farming is practiced in areas where climate conditions barely suite the natural needs of the cultivated crops during its periods of growth and hence, high yields can only be achieved by intensive irrigation. Especially in areas where irrigation is supplied by groundwater, the higher water demand for irrigation often results in an increased abstraction of groundwater (Custodio et al. 2016; Garrido 2011). In fact, the extraction of groundwater by deep wells has increased dramatically since the 1950s, leading to an uncontrolled overexploitation of groundwater bodies (Geiger 1970), triggered by private farmers as well as by large companies. Consequently, human-induced intensification of the already existing natural water scarcity is increasingly becoming a serious problem in large areas (Aldaya et al. 2009).

3.5.6 Conclusions

The comprehensive analysis of the state inventory “Inventario de Regadíos”, in combination with a literature review, enables new insights into Andalusian irrigation communities and reveals some of the challenges they face.

From this we conclude, that:

(i) An average Andalusian irrigation community is characterized by a property size of roughly 3 ha per farmer, which is fed by about 3,700 m3*ha-1 of irrigation water.

(ii) 41 % of the irrigation communities suffer water deficits concerning their respective crops, while nearly 60 % of the irrigation communities have an excess of water in regards to their irrigation demand for cultivation.

(iii) The high seasonal and spatial variability of precipitation in Andalusia means that, in many regions, it is necessary to irrigate crops to safeguard harvests and avoid crop loss.

(iv) The outstanding feature that distinguishes the Vega of Vélez Blanco from other irrigated areas is the tradition of auctioning irrigation water.

Acknowledgements

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3.6 A short history of the water and society in the region of Vélez Blanco, East Andalusia

Abstract

The network of irrigation canals and reservoirs in the Los Vélez region in Southern Spain has existed for centuries and is documented as tangible cultural heritage. But the region's 'water culture' also has an intangible aspect that involves water-related management, conflicts and jurisdiction. This paper traces the water-related history of the city and region of Vélez Blanco from the Muslim period through the medieval era and later centuries until today and embeds it in the development of legal history and the jurisdiction of water issues. We conclude with a reference to the 21st century and the value of historical and archival sources, as well as an appeal to found a museum and add the region to the list of UNESCO World Heritage sites.

4. Methods and Material

To answer the central research questions of this thesis, various methods were used to survey and analyze different data sets. This chapter outlines the data sets used and the methods applied.

4.1 Preparation and digitalization of archive material

Two data sets were collected from local archives by digitalization of analog documents. The specific procedure of data acquisition and processing is described in the following section.

Cadastral map material

To gain information about the land-use and parceling of the properties within the Vega of Vélez Blanco, modern and historical cadastral maps were analyzed. The digital cadastral map material provided by the Directorate General of Land Registry of Spain contains information about the size, usage, and location of cadastral parcels. Information about irrigation is also given in this data set (Gobierno de España 2018). For the delineation of the irrigated areas of the Vega of Vélez Blanco, cadastral parcels recorded as “irrigated” were detected and merged.

A set of hand-drawn historical maps from the 1930s are available at the Instituto de Estudios Almerienses in Almería (Fig. 1). They contain information about the location of springs, reservoirs (*balsas*), irrigation channels (*acequias*), and aqueducts in the irrigation network of the Vega of Vélez Blanco. To digitalize the map material, the plans were photographed with a reflex camera (Olympus E-410) and subsequently georeferenced in a geo-information system (ArcGIS 10.3) by using 5 - 29 ground control points, which are fixed points such as building structures or road junctions. In total, 19 maps were digitalized with overall low root-mean-square errors with a range of 1.4 - 14.5 (Appendix I). Subsequently, locations of springs, reservoirs, aqueducts, and courses of irrigation channels were also digitalized to compare the data set with the latest information about the technical components of the irrigation network.

Archive material on water auction records

To find information about the water usage within the Vega of Vélez Blanco, a rare data set of water auction records was digitalized. Account books, archived in the central office of the local irrigation community (*Alporchón*), document nearly all water sales from water auctions that took place between January 1929 and October 2012 (Fig. 1). The details recorded include the date of the water auction, the price the water was sold for (euro or pesetas), and information about the part of the irrigation network in which the water was sold. In terms of water auctioning, the irrigation network of the Vega of Vélez Blanco can be separated into five subsystems: Balsa Alara, Hilas de Turruquena, Hila de la Unión, Río de Argan and Hilas de Conceje. These data were digitalized by photography (Olympus E-410) in May 2015 and manually entered into an Excel spreadsheet (Microsoft Office 2010) to create a digital data set. In total, the records of 7,734 water sales were transmitted from the account books to the Excel spreadsheet. Further details can be found in section 5.3.

4.2 Processing of spatial data

To produce an inventory of the technical measures used for the water sharing within the Vega of Vélez Blanco, digital terrain information, orthophotos, and data collected by field surveys were combined in a GIS database. The methods and material used for the collection of the spatial information are described in the following sections.

Orthophotos

Orthophotos were used as base data to locate and map reservoirs (*balsas*) and the courses of irrigation channels within the Vega of Vélez Blanco. The digitalization was organized in processing units that were visually checked. The diameter of irrigation channels is only 15 to 20 cm, and they are often neglected or covered by vegetation; hence, it can be difficult to detect the channel structures in the satellite images. Data validation in the field was therefore indispensable. The data gained in his manner contributed to the GIS-based inventory of technical water management installations. Data digitalization was performed in ArcGIS 10.3 using orthophotos of a resolution of 0.25 × 0.5 cm as base data provided by the Gobierno de España (2016; Fig. 1).

Digital terrain information and field survey data

To validate and improve the results of the GIS-based detection of technical water management structures within the Vega of Vélez Blanco, field surveys of the irrigation network were carried out in May and June 2015 and July 2016. For real-time localization and digitalization of point, line, and polygon data, an iPad Mini 2 (cellular 32 GB – A-GPS & GLONASS) was used in combination with the application View Ranger. Within this application, regional topographical maps of the scale 1:25,000 were used as base data. The mapped objects were springs, reservoirs, sluice gates, aqueducts, water mills, and channel courses. During fieldwork in July 2016 and September 2017, results from digital mapping based on satellite images were checked on-site for ground truthing. For this purpose, the shape files were imported into View Ranger and validated by field mapping.

4.3 Statistical treatment

Standard descriptive statistical analyses were performed on water auction and climate data on monthly, seasonal, and annual bases. This included the calculation of maximum, minimum and mean values and the computation of the 0.25 quartile, 0.75 quartile, variance and standard deviation. Correlation analysis of water auction and climate data was used to investigate the significance of precipitation sums on variable scales for the determination of water-auction pricing. The software packages SPSS 19 and Microsoft Excel 2010 were used for the analysis. Further details are available in section 5.3.

Preparation of water-auction data

Since the water-auction data extracted from the archive data of the irrigation community of the Vega of Vélez Blanco cover the period from 1929 - 2012, it is necessary to convert all water prices recorded before the currency change in 1999 from pesetas to euro. The currency conversation was performed using the official conversion rate given by the European Central Bank (European Central Bank 2017). To improve the inter-annual comparability of the water-auction data, a historical set of annual inflation values for Spain, provided by de Motes (2013), were used for the inflation adjustment of the data set. Water prices were recalculated based on the given inflation value. The software package Excel 2010 was used for the calculations.

Climate data treatment

Daily precipitation measurements (1967 - 2006) recorded at the weather station in Vélez Blanco (37°41’N 2°05’W) and daily temperature data from the nearby station in María (37°42’N 2°09’W) were analyzed with standard statistical methods to characterize the local climate and for the correlation analyses on daily, monthly and annual scales (AEMET 2014). The temporal coverage of the data set is illustrated in Figure 1.

To determine the variability of the local climate in the region of Vélez Blanco, the calculation of the Standardized Precipitation Index (SPI) as developed by McKee et al. (1995) was applied on an annual and seasonal temporal scale. The index is widely used as an effective indicator for the quantification of rainfall deficits or surpluses that can be applied on several scales from months to years (McKee et al. 1995; Machado et al. 2011; Vicente-Serrano 2006; Ji and Peters 2003). The SPI values were classified as suggested by McKee et al. (1995).

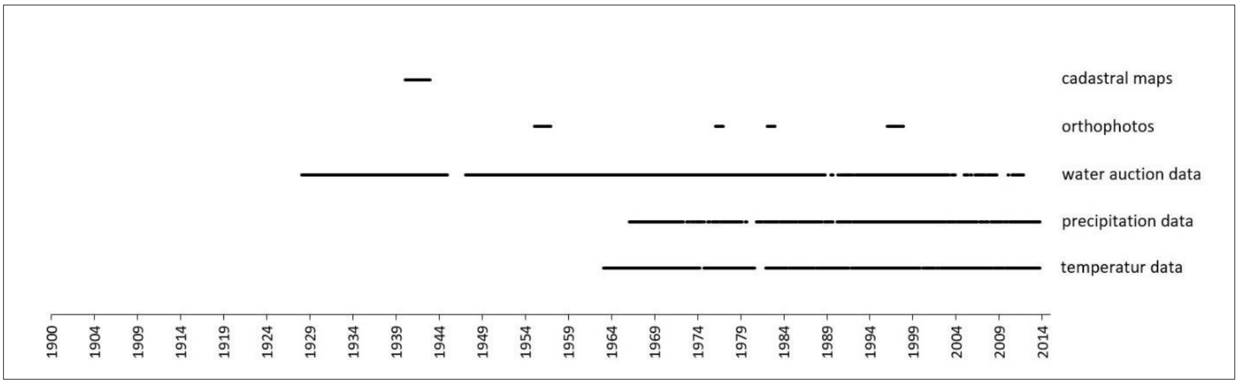

Fig. 1: Overview of the temporal coverage of data analyzed in the thesis.

4.4 Preparation and conduction of structured Interviews

A total of 30 interviews were conducted with randomly selected farmers who cultivate land in the Vega of Vélez Blanco. The interviews took place in spring 2016 and comprised 31 open, semi-open, and closed questions intended to elicit the farmers' subjective perspectives of the Vega´s current state and their individual methods of agricultural cultivation (Appendix IV & V). The software SPSS 19 and Microsoft Excel 2010 were used to analyze the collected data. Further details are available in section 5.3.

5. Results

The results that were used to answer the research questions of the thesis are presented in this chapter. A main focus of the following section is the unpublished results of the inventory of the water management facilities within the Vega of Vélez Blanco. Furthermore, the results of the analyses of the irrigation communities' organizational structures are outlined. The chapter is complemented by Isselhorst et al. (2018b), which includes local water-price and climate-data analyses.

5.1 Inventory of technical water management structures in the Vega of Vélez Blanco

A complex network of technical facilities is in operation to distribute irrigation water across the Vega of Vélez Blanco. This includes techniques used for the exploitation, distribution, temporal storage, and allocation of irrigation water. To provide an overview of the techniques, the main technical elements of the Vega are described below.

Tapped springs

Five major springs (Span. *fuente*) located upslope of the town predominate the water supply of the Vega. These tapped springs are named (from north to south): Fuente de Martilena, Fuente del Arco, Fuente de los Cinco Caños, Fuente de los Molinos and Fuentes de Hilas de Turruquena (see Fig. 1 A–F). Of minor importance, though still contributing to the irrigation water supply within the southern area of the Vega, is the Fuente del Río.

In former times, the spring water was also used for the domestic water supply within the town; today, domestic water is supplied by a deepwell situated in the mountains of the Sierra de María. Nevertheless, water intakes are distributed all over the town, enabling public water withdrawal, mainly as drinking water. These water intakes are locally called *caños* (pipes): Caños de la Plaza, Caños del Mesón, Caños de Caravaca and Caños de la Alameda (Tyrakowski 2001; Fig. 10).

Within the Vega, at least two *gallerias* can be found. This technique originates from the well-known qanat systems, in which a gently downsloping tunnel taps the upslope groundwater table and diverts the water to a captured spring (Beckers et al. 2013). Remains of such technical water-capture structures can be found at the Fuente de la Balsa de los Canales and the Fuente del Cortijo de Casanova in the lower part of the Vega of Vélez Blanco (Hermosilla Pla et al. 2004).

Fig. 1: Springs at the eastern slopes of the Sierra María. A & B: Fuente de Martilen; C & D: Fuente del Arco; E &F: Fuente de los Molinos (for their location, see Fig. 10).

Irrigation channels

From the tapped springs, the irrigation water is transported downhill by open gravity-flow channels and pipes (Roth et al. 2015; Isselhorst et al. 2018a). These irrigation channels, which distribute the water across the Vega, are locally called *Acequias*. Today these open channels are commonly made of concrete; until the 1950s, earthen channels were in use (Fig. 2). The channel network can be divided into two levels*:* main channels (Span. *acequia madre*) and distribution channels (Span. *acequia* *secundario*). The main channels are responsible only for the downhill transport of the irrigation water. They are connected to the main reservoirs managed by the local irrigation community. The distribution channels capture defined shares of irrigation water from the main channels and transport them to the agricultural fields of a certain parcel or to private reservoirs. Distribution channels are often in poor condition caused by a lack of maintenance. Hence, loss of irrigation water is a serious issue within the Vega. Overall, the network of irrigation channels extends about 130 km within an area of about 30 km² (Fig. 10).

Fig. 2: Irrigation channels in the Vega of Vélez Blanco. A: Modern concrete irrigation channel. B: Traditional earthern channel on an agricultural terrace within the Vega.

Sluice gates

The water distribution within the irrigation channel network of the Vega is managed by sluice gates (Span. *partidores*). In this technique, small-scale sluices block parts of the channel network to direct the irrigation water to its place of usage (Figs. 3 & 4). At several points in the network, sedimentation basins are installed to remove the sediment load by a reduction of discharge. These basins need to be maintained regularly.

Because of the high number of sluice gates, these structures are not illustrated within the map of the Vega of Vélez Blanco. Sluice gates are situated at least at every channel junction displayed within the map.

Fig. 3: Sluice gates and sedimentation basin in front of the inlet of the Balsa Alara reservoir (for the location, see Fig. 10).

Fig. 4: The diversion of irrigation water is managed by a simple sluice system. This type of allocation technique is commonly used all over the Vega.

Reservoirs

Within the Vega, more than 200 reservoirs of private or community ownership can be found. In Spain, these types of open reservoirs are called *balsas*. Today most of them are made of concrete; in former times, *balsas* were mainly stone walls built to impound the water. Originating in the 16th century, the Balsa del Marqués is an authentic example of the traditional construction of such reservoirs. It used to belong to the Magravate of Los Vélez (Fig. 5 A).

Irrigation is not practiced at night within the Vega. Instead, from 6 p.m. to 6 a.m., water flows from the upstream springs to refill the main reservoirs that belong to the local irrigation community. The stored water can then be used for irrigation purposes on the following day (6 a.m. - 6 p.m.). These reservoirs are maintained by members of the irrigation community (Roth et al. 2015; Isselhorst et al. 2018a). Smaller reservoirs are usually privately owned (Fig. 5 B). Examples of reservoirs maintained by the irrigation community include Balsa de Cenete, Balsa de Alara, Balsa de Argüit and Balsa de Leon (Fig. 10).

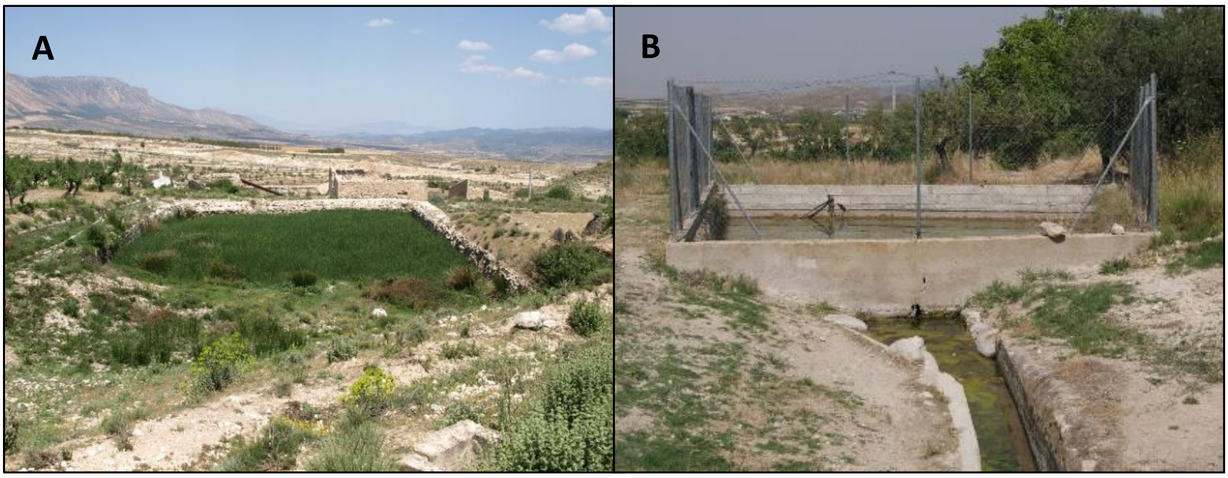

Fig. 5: Reservoirs in the Vega of Vélez Blanco. A: View over the Balsa de Marqués located at the Fuente de los Molinos. B: Private reservoir (*balsa*) owned by a farmer in the lower part of the Vega.

Spillways

Due to the infrequent heavy rainfall events that can occur under the local semi-arid climate conditions, it is necessary to provide a security system that protects the agricultural terraces from flash floods. This semi-natural protection system consists of spillway chutes (Span. *barrancos*). In case of flash floods coming from the mountains of the Sierra de María, large water masses are led into a large-scale spillway system that directs the water masses past the agricultural terraces and directly downhill to the valley into the receiving Río Claro. Hence, the hydrological strain is minimized. From north to south, these spillways are the Barranco de Martilena, Barranco de la Fuente and Barranco de la Canastera in the main part of the Vega (Figs. 6 & 10). The Los Molinos valley is incised by the Barranco de la Cruz del Pinar (Fig. 10).

Fig. 6: Spillway system (Barranco de la Canastera; for its location, see Fig. 10) to protect the agricultural terraces in the central part of the Vega of Vélez Blanco. The course of the main spillway system is highlighted by the dashed red line. The view is from the west.

Aqueducts

The aqueducts (Span. *aqueducto*) in the Vega of Vélez Blanco are used to transport the irrigation water across the *barrancos* in the upper part of the Vega and to transfer the irrigation water to the lower slopes of the Muela Grande, situated at the opposite side of the valley of the Río Claro (Figs. 7 & 10).

Fig. 7: Aqueduct bridging the riverbed of the Río Claro in the vicinity of the Cortijo Corneros (for its location, see Fig. 10).

Lavaderos

In the upper course of the Fuente del Arco is a *lavadero*. In former days, *lavaderos* were used for laundry, but today it is rarely used. Similar installations can also be found in neighboring villages such as María (Fig. 8).

Fig. 8: Traditional *lavadero* in the village of María.

Watermills

It is assumed that at least since Muslim times, watermills were operated within the Los Molinos valley. Today, remains of 32 mills (Span. *molino*) can be found in the valley; for example, Molino de Basque, Molino de la Noguera and Molino de Reloj (Tyrakowski 2001). The mills are always located along the course of the irrigation channels. Hence, before the water was used for its original purpose on the agricultural terraces in the lower parts of the Vega, the kinetic energy of the water running downhill impelled the mills (Figs. 9 & 10). Most of the mills were used for the production of olive oil; only a few were used for flour production. The reorganization of processes and technical progress in agricultural production during the 1960s led to the abandonment of the watermills within the valley (Tyrakowski 2001).

Fig. 9: Ruins of a former mill located below the Balsa de Marqués (for its location, see Fig. 10). The main technical elements of the water management are highlighted. The course of the irrigation water is highlighted by the blue dashed line.

Overview map of the water management facilities within the Vega of Vélez Blanco

The overview map is a key outcome of this thesis. It represents a new and more detailed cadastre of the technical elements of the water-diversion system within the Vega of Vélez Blanco. It unites scattered historical cadastral information about the main courses of irrigation channels (Span. *acequía*) with new survey data. The subdivision between main and secondary channels is not illustrated. Nevertheless, the map enables the tracing of water courses starting from tapped springs via water storage facilities to the individual places of irrigation. Since the irrigation-channel network consists exclusively of gravity-flow channels, topographic information is necessary to retrace the possible flow directions of the irrigation water. This information is given by the contour lines on the map. To illustrate the shape of the landscape, the main topographical elements are shown as well. These include courses of spillways (Span. *barranco*), elevated areas and peaks (e.g., Maimón Grande), and intermittent (Span. *rambla*) and perennial (Span. *río*) streams (e.g., Rambla de Chirivel and Río Claro).

Community-owned reservoirs (Span. *balsa*) and those of private origin are are not distinguished on the map. Usually the largest reservoirs are owned by the local irrigation community; private ones are usually much smaller.

Land plots within the Vega of Vélez Blanco that are regularly irrigated are highlighted in green. These areas are directly connected to the irrigation-channel network. They periodically receive shares of irrigation water from the locally practiced irrigation rotations. To the east, the area under irrigation also includes the riverbed of the Río Claro via aqueducts (Span. *acueducto*). At two locations, the irrigation water is transported by aqueducts from the lower hillside of the Maimón Grande eastwards to the counter slope of the Muela Grande. These locations are highlighted within the overview map by the corresponding symbols.

The usage of the land plots within the cultivated area is divided into two types of farming by the respective signature. The cultivation of olives and almonds is predominant in most parts of the Vega of Vélez Blanco. All other areas are mainly used for grain farming and horticulture, which includes the cultivation of vegetables and fruits.

The scheme displayed in the lower left corner of the map illustrates the connection between springs, main reservoirs, and destinations of irrigation water. It also gives information about the individual channel lengths. This diagram indicates that the Fuente des Martilena exclusively serves the northern-most part of the Vega of Vélez Blanco. The water supply in this area is independent from the rest of the Vega. Another exclusive water supply is provided by the Río de Argan. Here, the irrigation water is used only for the water supply of the central and lower part of the Los Molinos valley and the town of Vélez Rubio.

After traversing the town of Vélez Blanco, the irrigation water tapped at the Fuente del Arco and the Fuente de los Cinco Caños exclusively provides the water supply for the central part of the Vega of Vélez Blanco. Within the town, there are several points for public water withdrawal, highlighted on the map by the signature “Extracción de Agua”. The main reservoirs that store the irrigation water originating from these springs are the Balsa de Cenete, Balsa de Algüit, Balsa de Léon and the Balsa de Alara. The water is also transported across the Río Claro by aqueducts.

The irrigation water that can be transported the longest distance within the Vega of Vélez Blanco is that originating from the Fuente de los Molinos and the Fuentes de Hilas de Turruquena. The water captured at these springs is used not only for the irrigation water supply within the Vega of Vélez Blanco, but also for the water supply of Vélez Rubio. Every Saturday, from 6 a.m. to 6 p.m., all the water from the springs is transferred directly to the town of Vélez Rubio. The water shares received by Vélez Rubio are stored in cisterns. From there, the water is also used for domestic water supply within the town. The shares of water that are used for the irrigation water supply of the Vega of Vélez Blanco can be transferred north-eastwards along the footslopes of the Pinar del Ray to the central part of the Vega. At night, the irrigation water from the Fuente de los Molinos and Fuentes de Hilas de Turruquena is usually stored at the Balsa Alara.

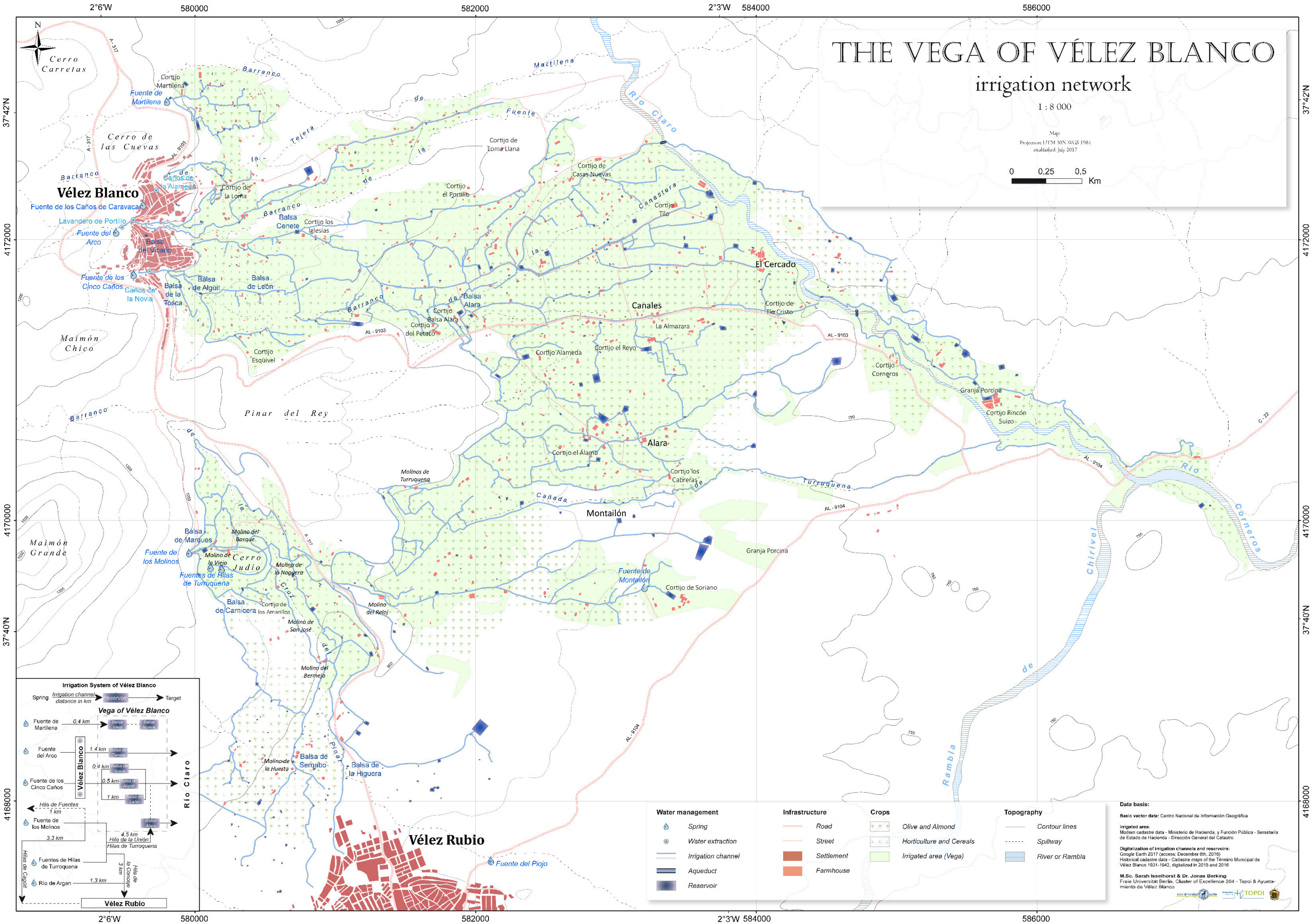

Fig. 10: Overview map of the water management facilities within the Vega of Vélez Blanco. *Left corner:* Simplified diagram of the main irrigation courses.

5.2 Organization of the irrigation community and water sharing

In general, every farmer owning irrigated land in the Vega of Vélez Blanco that is connected to the irrigation channel network described in section 5.1 has a legal right to become an active stakeholder in the local irrigation community. During the communities' annual general assembly, a committee is elected by the landowners to manage the water sharing among the stakeholders throughout the year (Ordenanzas de la Comunidad 1903). From this committee, the administrative positions illustrated in Figure 11 are filled. This includes the positions of President and Vice-President of the irrigation communities as well as the Treasurer and Secretary. Another crucial position is the Jury President, whose task is to settle disputes concerning the distribution of irrigation water and to enforce the water law. The responsibility for the monitoring and maintenance of the technical infrastructure of the canal network is given to the *Acequiero Mayor* (Ordenanzas de la Comunidad 1903; Ißelhorst et al. 2018c).

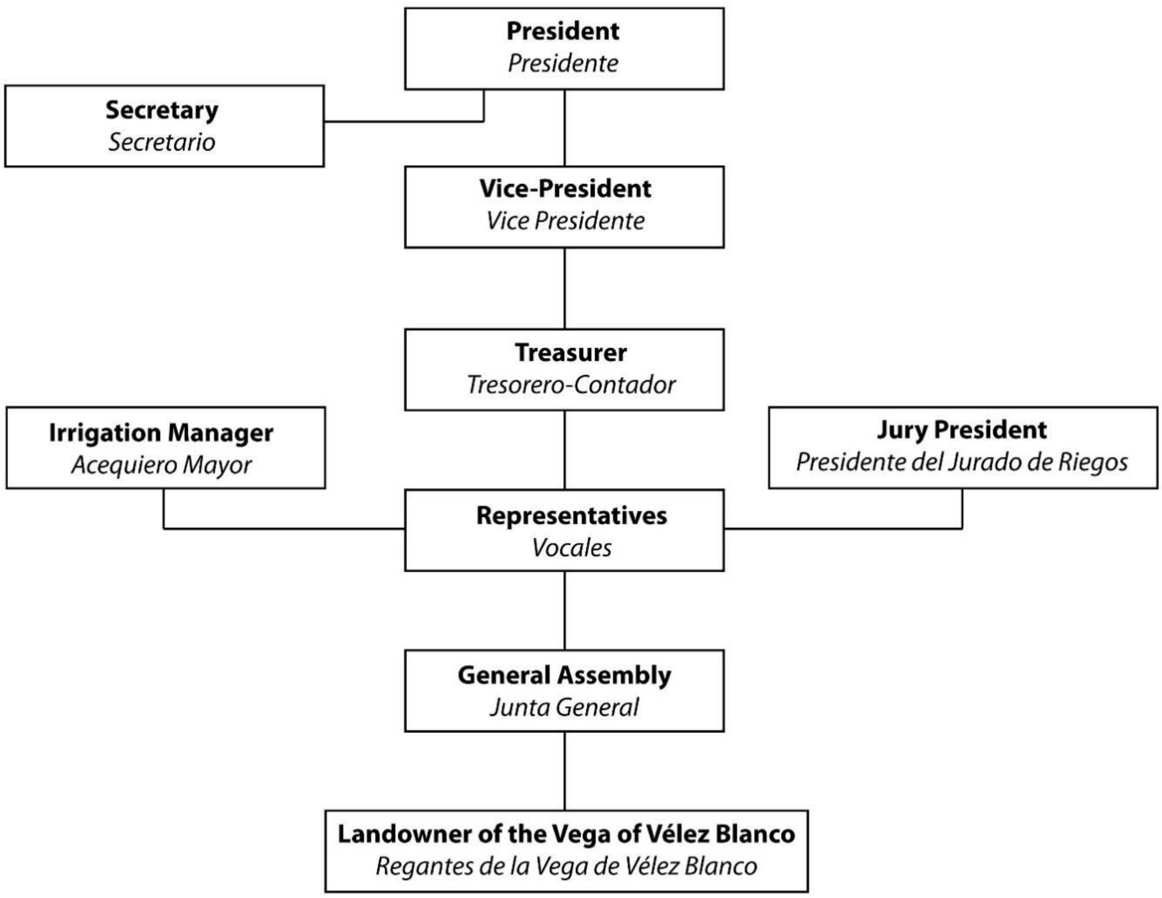

Fig. 11: Organization of the irrigation community of the Vega of Vélez Blanco (Ißelhorst et al. 2018 c).

In the Vega of Vélez Blanco, the responsibility for the water allocation and maintenance of technical infrastructure is clearly defined by territory and tasks (Fig. 12). While the maintenance and operation of the facilities for the management of spring water is assigned to the irrigation community, the task of distribution and storage of irrigation water is shared between the private water users and the representatives of the irrigation community. The irrigation water is mainly transported by concrete channels and aqueducts. The allocation is managed by sluice gates located at nearly all the junctions of the irrigation channels. In general, main channels are used to transport the irrigation water downhill from the springs only on central routes. These channels also feed the main reservoirs owned by the irrigation community. Main channels and community-owned reservoirs are maintained by the irrigation community. In contrast, channels that divert shares of water from the main channels and transport them to the irrigated agricultural terraces or privately owned reservoirs are maintained by individual private water users. This also applies for the individual irrigation technique practiced on the agricultural terraces. Within the Vega of Vélez Blanco, the predominant method of irrigation is traditional flood and furrow irrigation, although drip irrigation is also frequently practiced on the agricultural terraces. While receiving their assigned share of irrigation water, the private water users are responsible for the setting of sluice gates starting from the main channel to their individual land plot (further reading in sections 5.1 and 5.2).

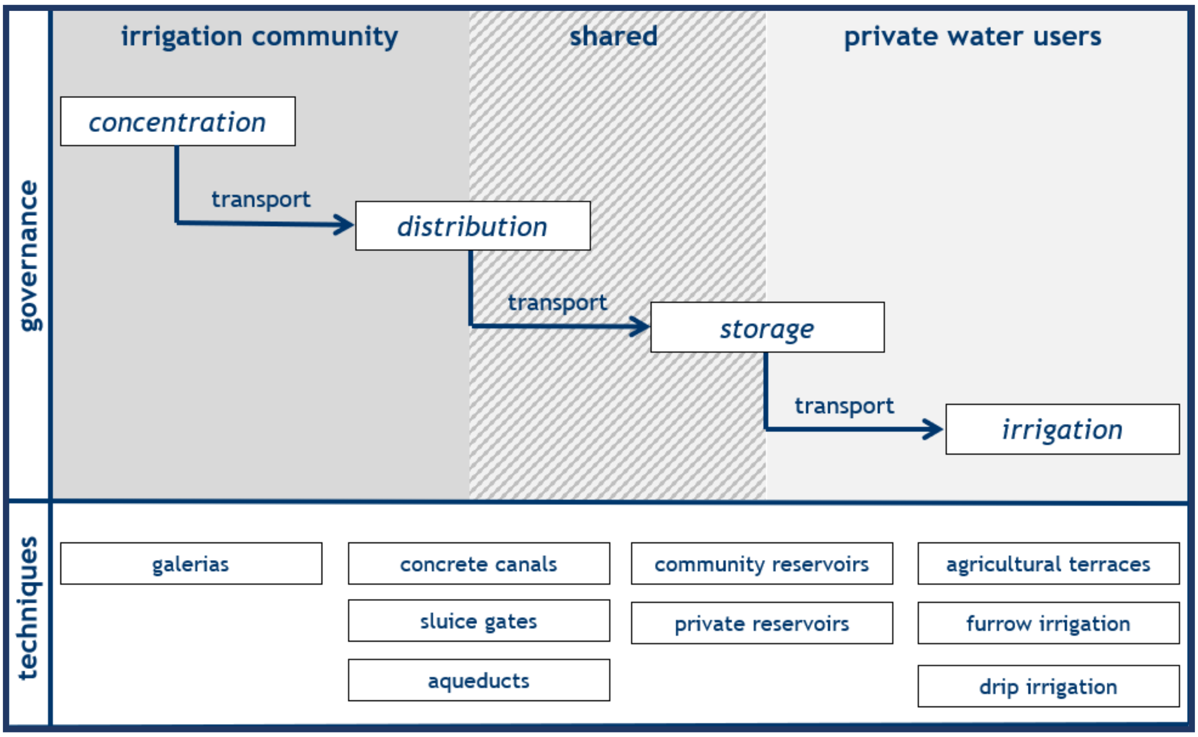

Fig. 12: Overview of the technical elements and their governance in the Vega of Vélez Blanco.

The water-sharing system in the Vega of Vélez Blanco can be divided into five subsystems: Balsa de Alara, Hila de la Unión, Hilas de Turruquena, Río de Argan, and Hila del Concejo (Navarro Sánchez 2007). Based on these subsystems, the irrigation water is distributed to the landowners by an organizational system of fixed rotations. The durations of the rotational cycles within the individual subsystems range from 20 to 282 days (Table 1). This means, for example, that an owner of irrigated land within the subsystem Balsa de Alara receives regular shares of water every only every 282 days. Within this rotational system, shares of irrigation water are mainly measured in time units (hours and minutes) with the exception of the subsystems Balsa de Alara and Hila de la Unión. Those subsystems are managed by units of volume (*arrobas* and *granos*; Navarro Sánchez 2007).

Table 1: Overview of the rotation duration and measurement unit within the main subsystems in the Vega of Vélez Blanco (Data: Navarro Sánchez 2007).

Subsystem	Duratuion of Rotation	Unit
Balsa de Alara	282 days	arrobas and granos
Hila de la Unión	20 days	arrobas and granos
Hilas de Turruquena	58 days	hours and minutes
Río de Argan	26 days	hours and minutes
Hila del Concejo	30 days	hours and minutes

Not only do these irrigation rotations provide landowners with shares of water on a regular basis, but they also benefit the irrigation community itself. The community receives a fixed amount of irrigation water that they sell during regular auctions in units of 12 hours of irrigation water. In these water auctions, landowners have the opportunity to purchase additional amounts of irrigation water for their cultivated land plots. Especially during dry periods, additional shares of irrigation water can be essential for the crop yield. The revenue from the water sales is used to cover the costs of the communities' administration and investments in the modernization and maintenance of the system's technical infrastructure.

Chapter 5.3: Sarah Isselhorst; Jonas Berking; Brigitta Schütt (2018): Rainfall distribution and its implications for irrigation practices and water pricing during the 20th century. A case study from Vélez Blanco, Andalusia (1967-2006). In: Agricultural Water Management. Volume 199. pp. 34-47. DOI: https://doi.org/10.1016/j.agwat.2017.11.018

5.3 Rainfall distribution and its implications for irrigation practices and water pricing during the 20th century. A case study from Vélez Blanco, Andalusia (1967-2006)

Abstract

This study uses data from water auctions, conducted by the traditional irrigation community of Vélez Blanco. Water prices are comprehensively compared and statically correlated with local precipitation data on different temporal scales; the data analyzed reach back to 1967. The rainfall distribution data used were of daily, seasonal and annual resolution and are assessed on their influence on the local water price formation. The results were validated with information about local agricultural practices and subjective perceptions of the *vega's* status, gained from interviews with local farmers. Results show that high correlation coefficients are achieved when water prices and precipitation data are correlated on a monthly scale. The highest correlation coefficients are achieved with a temporal offset of one month throughout the spring and summer season. Interestingly, neither short term water surplus, nor long term water deficit (consecutive drought years) are clearly reflected. Based on the given data-base, annual rainfall distribution has proven to be a significant factor that influences water price formation in the Vega of Vélez Blanco.

Chapter 6: Sarah Isselhorst; Jonas Berking; Brigitta Schütt (rejected 2019): Landscape development, Land Use and Water Management History in the Rio Guadalentín headwater area, SE Spain: A Review. *Submitted to: Physical Geography. Rejected: December 19th, 2019.*

6. Landscape development, Land Use and Water Management History in the Río Guadalentín headwater area, SE Spain: A Review

Abstract

Human activities gradually change natural landscapes into cultural ones. The appearance of today's Mediterranean cultural landscapes is characterized by terraced slopes, deforested and reforested areas as well as by extensive use of ground- and surface water resources for agricultural purposes. This paper reviews the Holocene landscape development and the development of human interventions that led to the shift from a natural to cultural landscape in the headwater area of the Guadalentín drainage basin in SE Spain. Most continuous data about human activities is available from the 8th century AD onwards. Information about the natural landscape development during the Late Glacial to Early- and Middle-Holocene are derived from geomorphological and the herein published radiocarbon ages. Additionally, original data from landscape historical studies conducted in the beginning of the 21st century AD are included.

6.1 Introduction

Numerous studies exist on the millennia-long development of Mediterranean landscapes at regional and local scales. Most of them relate to histories in which the colonization of these landscapes changed processes of a former 'natural' environment gradually into a coupled 'natural-cultural' landscape. Feedback cycles between cultural practices and natural processes of Mediterranean ecosystems also imply a high degree of resilience. The persistence and stability of structures and dynamics over time is attested by many studies (Blondel 2006; Grove and Rackham 2003; Berking et al. 2016).

In dry-subhumid to semi-arid SE Spain climate conditions, poor soil developments and often challenging water availabilities provoked intensive human interventions into the natural landscapes over the centuries to improve land use conditions (Berking et al. 2016; Bellin et al. 2013; Carrión et al. 2010; García-Ruiz 2010; Latorre et al. 2001). During the Holocene repeated changes in agricultural practices and settlement patterns, as well as processes of technical innovations and transfer of knowledge took place. They triggered transformations of the cultures, their adaption strategies to the environment and hereby their environments. In areas where agricultural production is not yet industrialized, terraced slopes cultivated with almond or olive orchards alternating with grain cultivation in high plains shape most of the region's landscapes. These types of agricultural goods are predominantly cultivated under rain fed farming conditions. Beyond, traditional irrigation agriculture is practiced in the so called huertas and vegas, water rich valley zones which are until today often administrated by traditional irrigation communities (Roth et al. 2015; Isselhorst et al. 2018a). Main products of the huertas and vegas are vegetables and fruits. Throughout history, especially technical solutions and various strategies of land use and water management on the Iberian Peninsula were strongly influenced by Roman and Muslim cultures (Brunhes 1902; Fröhling 1965; Glick 1970; Kress 1968; Ostrom 1990).

In this paper we focus on human induced landscape development in the headwater area of the Río Guadalentín. It is located in border region of the provinces of eastern Andalusia and western Murcia. Here, we carry out a literature review that deals with the main environmental processes. Furthermore, we analyze the triggers of forestation and deforestation, interventions into the natural hydrological regime, population development and evolution of agricultural production during historic time. The paper is based on the observation that with the onset of settlement activities, an increasing shift from natural to cultural landscapes took place. In order to test this assumption, we reviewed literature on landscape development and landscape history, mainly based on available publications and own scientific research, conducted in this region.

6.2 Study area

The Río Guadalentín is a major tributary of the Río Segura that is situated in south-east Spain. Its headwater area is located in the mountains of the Sierra de María (province of Almería, region of Andalusia), while most of the stream traverses the territory of the autonomous region of Murcia. In the Río Guadalentín basin annual amounts of precipitation show a gradient that ranges from more than 1,000 mm in the mountains of the Sierra de María to around 300 mm in the vicinity of the city of Murcia, where the Río Guadalentín disembogues into the Río Segura. Precipitation is characterized by a high seasonal and annual variability, while rainfall is most likely to occur in autumn (Isselhorst et al. 2018a). The rainfall peak in autumn is mainly caused by the Balearic low, a thermal depression of stationary character (Lautensach 1964). In contrast, the summer months are dominated by high temperatures and low amounts of precipitation (Isselhorst et al. 2018a). Over the year, the majority of summer-precipitation is characterized by intensities of less than 1 mm per event (Geiger 1970). Heavy rainfall events that generate high discharge volumes can occur throughout the whole year, but predominantly take place during autumn. In consequence, discharge of the Río Guadalentín has its seasonal peak during autumn, while spring shows a secondary maximum in runoff volumes. In contrast, winters are characterized by rather moderate discharge values, while lowest runoff is usually recorded during the hot and dry summer months (Capel 1968). Surface waters in the Guadalentín headwater area are regulated by two large dam structures situated close to the headwater area, the Embalse de Valdeinfierno and the Embalse de Puentes (Fig. 1). The main streams feeding the reservoir of the Valdeinfierno are the Río Caramel and the Rambla Mayor. 15 km downstream of the Embalse de Valdeinfierno and immediately upstream the town of Lorca, the reservoir Embalse de Puentes stores water of the Río Luchena and the Río Vélez. The drainage basin of the Río Guadalentín is at the embouchure into Río Segura. It totals 1864 km^2 (Fig. 1 b), while its headwater area located upstream the town of Lorca totals 1136 km^2. Due to the high frequency of flood events and their hazardous potential, the Río Guadalentín is known as one of the most turbulent rivers in the Mediterranean region (Gil Olcina 1968).

Fig. 1: Overview map of the headwater area of the Río Guadalentín drainage basin. A) Location of the study area (red) within the Iberian Peninsula (provincial boarders are displayed). The Segura basin is highlighted (light grey). B) Map of the Segura basin and its sub-catchments (basin limits are displayed). The location of the Río Guadalentín basin is marked in dark grey. The blue star marks the point where the Río Guadalentín disembogues into the Río Segura. C) Topographical overview map of the Guadalentín headwater area. Indicated are the locations of the local studies and radiocarbon sites compiled in this review paper. The location of the Vega of Vélez Blanco is highlighted in light green. The dashed red line marks the province boarders between Murcia and Almeria.

6.3 Materials and Methods

The review is based on regional studies on landscape and land use history as well as landscape development in the headwater area of the Río Guadalentín. It combines various base data such as age determinations of archaeological sources and radiocarbon dating of environmental archives, historical information (e.g. reports of catastrophes), climate records originating from published literature (e.g. climate reconstruction) and original data of radiocarbon datings which are not published yet. For this study in total 25 papers were reviewed, and 58 radiocarbon ages were gathered.

The compiled literature

For the review 25 scientific papers were analyzed (Tab. 1). The listing provides a brief overview of the text sources, sorted by topic and location. The spatial distribution of research locations is illustrated in figure 1. Most detailed information is given for the administrative area of Los Vélez and in particular the town of Vélez Blanco and its Vega.

Tab. 1: Overview of literature sources that are focused on the upper Guadalentín catchment area, sorted by topic field and location.

No.	Author	Title	Topic	Region
1	Araque Jiménez 2009	Refundición de Dominios y Repoblación Forestal en la Porción Andaluza de la Cuenca del Río Guadalentín	Forestation	Guadalentín Catchment
2	Segado Castro and Zamora Díaz 2016	Forest conflicts and public intervention. The case of the forests of María and Vélez Blanco (Almeria, Spain). 1879–1901	Forestation	Los Vélez
3	Araque Jiménez 2011	La Repoblación Forestal en los Montes de Los Vélez (Almería) Durante el Siglo XX	Forestation	Los Vélez
4	Alcocer Martínez, Araque Jiménez and Lentisco Puche 2011	La Crisis Forestal y la Refundición de Dominios, 1882-1900	Forestation	Los Vélez
5	Rodríguez Campos 2001	Der Naturpark Sierra de María-Los Vélez	Forestation	Sierra de María / Los Vélez
6	Roth 2011	La administración señorial de los montes, del siglo XVI a principios del XIX	Forestation	Sierra de María / Los Vélez
7	Gilman and Thornes 1985	Land-Use and Prehistory in South-East Spain	Forestation	Canales / Los Vélez
8	Benito et al. 2010	The impact of late Holocene climatic variability and land use change on the flood hydrology of the Guadalentín River, southeast Spain	Paleo-Environment	Upper Guadalentín Catchment
9	Benito et al. 2008	Palaeoflood and floodplain records from Spain: Evidence for long-term climate variability and environmental changes	Paleo-Environment	Upper Guadalentín Catchment

10	Baartman et al. 2011	Unravelling Late Pleistocene and Holocene landscape dynamics: The Upper Guadalentín Basin, SE Spain	Paleo-Environment	Upper Guadalentín Catchment
11	López and Muñoz 1997	Canales (Vélez Blanco-Almería), un enclave romano del Sureste entre la República y la Tardía Antigüedad	Archaeology	Canales / Los Vélez
12	López and Muñoz 1999	Poblamiento ibérico y romano en el sureste peninsular: la comarca de los Vélez (Almería)	Archaeology	Los Vélez
13	Isselhorst, Berking and Schütt 2018b	Irrigation Communities and agricultural water management in Andalusia - A special focus on the Vega of Vélez Blanco	Water Management	Vélez Blanco
14	Isselhorst, Berking and Schütt 2018 a	Rainfall distribution and its implications for irrigation practices and water pricing during the 20th century - A case study from Vélez Blanco, Andalusia (1967-2006)	Water Management	Vélez Blanco
15	Roth et al. 2015	A short history of the water and society in the region of Vélez Blanco, East Andalusia	Water Management	Vélez Blanco
16	Roth 2015	La cultura del agua en Vélez Blanco y su puesta en valor (1500-2015)	Water Management	Vélez Blanco
17	Navarro Sánchez 2007	El Alporchón de Vélez Blanco - Aproximación jurídica y etnográfica a una institución consuetudinaria einmemorial hidráulica velezana	Water Management	Vélez Blanco
18	Garrido 2009	Val de Infierno. Una presa bicentenaria (1806-2006)	Floods an Flood protection	Valdeinfierno
19	Gil Olcina 1968	El régimen del río Guadalentín	Floods & Flood protection	Upper Guadalentín Catchment
20	Capel 1968	Lorca, Capital Subregional	Floods & Flood protection	Lorca / Valdeinfierno / Puentes
21	Riedlinger 2006	Charakterisierung und Modellierung der interferierenden klimatischen, orographischen und anthropogenen Einflüsse auf die Landschaftsentwicklung des oberen Río Guadalentín (Spanien)	Holocene Climate and Landscape development	Upper Guadalentín Catchment
22	Schütt 2006	Rekonstruktion, Abbildung und Modellierung der holozänen Reliefentwicklung der Cañada Hermosa, Einzugsgebiet des Río Guadalentín (SE Iberische Halbinsel)	Landscape development	Upper Guadalentín Catchment

23	Schütt and Baumhauer 2000	Subrezente Morphodynamik im Bereich der Cañada Hermosa, SE Spanien.	Landscape development	Upper Guadalentín Catchment
24	Roth, Schütt and Baumhauer 2001	Los Vélez - Ein landeskundlicher Reiseführer in Südost-Spanien	General	Los Vélez
25	Lentisco Puche and Navarro López 2011	El Parque Natural Sierra de María los Vélez	General	Sierra de María / Los Vélez

The compiled radio-carbon ages

A number of 58 radiocarbon ages from the Río Guadalentín headwater area were compiled from the literature (Tab. 2). New insights into the historical landscape development of the region also are given by yet unpublished radiocarbon ages, mostly emphasizing slope processes due to early land cultivation; also, the PhD thesis of Riedlinger (2006) and the master-thesis of Thiemann (2001) contributed to this project.

Age-determinations published by Benito et al. (2010) delineate historical phases of high hydrological activities, defined as flood sequences of ordinary to catastrophic character at the confluence of the Rambla Mayor and the Río Caramel (Tab. 2, no. 19-31). The obtained ages are aligned with text sources about historical flood events. For the upper course of the Río Caramel, Braun (2015) sampled river-bank exposures close to an abandoned Roman settlement at the western footslope of the Sierra Gigante in the vicinity of the village Maria (López and Muñoz 1999). The radiocarbon data for this section of the Río Caramel confirm the findings of Benito et al. (2010), while it also emphasizes aggradation phases coinciding with the Roman settlement during Antiquity as well as for the early Holocene (Tab. 2, no. 32-39). Radiocarbon datings provided by Braun (2015) were conducted along the banks of the Río Caramel in order to reconstruct the area's settlement and land-use history.

Radiocarbon ages provided by Baartman et al. (2011) date several Late Pleistocene and Holocene phases of river terrace deposition at the lower course of the Vélez River west and northeast of the Puentes reservoir (Tab. 2, no. 40-43). Ages are also provided by a potential paleo-lake dating into the Late Pleistocene (Tab. 2, no. 40).

Riedlinger (2006) published a number of ten radiocarbon ages originating from three different outcrops in the vicinity of the village Maria. The oldest ages of the outcrop labeled Aufschluss 01 (Tab. 2, no. 48) dating to the Medieval period, while the outcrops Aufschluss 04 (Tab. 2, no. 44-47) and Aufschluss 05 (Tab. 2, no. 51-53) document Holocene hill-slope processes in the areas of the Barranco de la Canal and Barranco La Longaniza.

Radiocarbon ages published by Schütt and Baumhauer (2000) and Schütt (2006) for the Cañada Hermosa, a small graben structure close to the village of Zarcilla de Ramos, document processes of Holocene hill-slope erosion and colluvial formation. The samples originating from the foot-slope of the Sierra Gigante (Tab. 2, no. 1, 4-8) and the Sierra Maria (Tab. 2, no. 2,3) are comparable in age to those at the Cañada Hermosa. They also document discontinuous records of Holocene colluvium formation. In contrast, sediments extracted from the alluvial plain of the Río Lucena upstream its inflow into the Puentes reservoir date into the early Holocene and document aggradation and still-water phases.

The unpublished diploma thesis of Thiemann (2001) provides radiocarbon datings from fluvial deposits of the Río Luchena in the intramontaneous basin between Sierra Gigante (downstream the Valdeinfierno reservoir) and the hills upstream the Puentes reservoir (Sierra de Pericay). Data indicate sedimentation under low energy processes of the Río Luchena during the early Holocene with a sedimentation rate of 0.3 m*100 a^{-1} between 11010 – 10430 BP (datings in Aufschluss 3.3 and 3.2); while subsequently fluvial activities short term increased, corresponding to 5.8 m*100 a^{-1} in the onset of the 11th millennium BP (Aufschluss 3).

Radiocarbon datings from fluvial deposits of the Río Luchena in the intramontaneous basin between Sierra Gigante (downstream the Valdeinfierno reservoir) and the hills upstream the Puentes reservoir (Sierra de Pericay) indicate sedimentation under low energy processes of the Río Luchena during the early Holocene. While in the onset of the 11th millennium BP sedimentation rates in this basin were high and exceeded approximately 5 m*100 a^{-1} (Aufschluss 3), the strongly decreased until the end of the 11th millennium BP (roughly estimated less than 1 m*100 a^{-1}) (datings in Aufschluss 3.3 and 3.2).

Tab. 2: Set of radiocarbon datings from in the headwater area of the Guadalentín drainage basin with their according depositional context evaluated for this study. The corresponding histogram and probability distributions are compiled in figure 2 and 3.

Numbers acc. to Figure 1	Lab sample code	Sample location	easting X	northing Y	Depositional context	Calibrated age (yrs cal BP)	Depth (cm)	Name acc. Fig. 3	Source
1	KIA10933	Terrace infill in a valley at the eastern foot-slope of the Sierra Gigante	593000	4176500	valley infill in a first order tributary	166 ± 27	200	Schuett LaFuensanta	*
2	KIA9826	Terrace infill in a valley at the northern foot-slope of the Sierra María	587614	4186580	terrace deposits in a first order valley glacis	1911 ± 24	145	Schuett MariaPegera 1	*
3	KIA9827	Terrace infill in a valley at the northern foot-slope of the Sierra María	587614	4186580	terrace deposits in a first order valley glacis	6106 ± 37	230	Schuett MariaPegera 2	*
4	KIA9828	terrace infill in a valley at the eastern foot-slope of the Sierra Gigante	588637	4172742	terrace deposits in a first order valley glacis	211 ± 31	300	Schuett Xiquena 2	*
5	KIA9829	Valley infill at the eastern foot-slope of the Sierra Gigante	588637	4172742	terrace deposits in a first order valley glacis	210 ± 38	515	Schuett Xiquena 4	*

6	KIA9830	Terrace infill in a valley at the eastern foot-slope of the Sierra Gigante	588637	4172742	terrace deposits in a first order valley glacis	134 ± 24	132	Schuett Xiquena 1	*
7	KIA9831	Terrace infill in a valley at the eastern foot-slope of the Sierra Gigante	588637	4172742	terrace deposits in a first order valley glacis	4563 ± 59	340	Schuett Xiquena 5	*
8	KIA9832	terrace infill in a valley at the eastern foot-slope of the Sierra Gigante	588637	4172742	terrace deposits in a first order valley glacis	5260 ± 56	425	Schuett Xiquena 3	*
9	KIA10937	Río Lucena, alluvial plain	597252	4181575	flood sequences	10809 ± 76	600	Schuett RioLuchena 2	*
10	KIA10934	Río Lucena, alluvial plain	597252	4181575	flood sequences	10414 ± 48	390	Schuett RioLuchena 3	*
11	KIA10935	Río Lucena, alluvial plain	597252	4181575	flood sequences	10429 ±51	490	Schuett RioLuchena 4	*
12	KIA10936	Río Lucena, alluvial plain	597252	4181575	flood sequences	11007 ± 80	640	Schuett RioLuchena 5	*
13	KIA12860	Río Lucena, alluvial plain	595500	4182800	flood sequences	2151 ± 41	200	Schuett RioLuchena 1	*
14	KIA9833	Cañada Hermosa	604950	4183075	fan deposits	6216 ± 71	460	Schuett Cañada Hermosa 1	Schütt and Baumhauer (2000)
15	KIA9834	Cañada Hermosa graben structure outer zone	604950	4183075	fan deposits	9413 ± 293	580	Schuett Cañada Hermosa 2	Schütt and Baumhauer (2000)
16	KIA9835	Cañada Hermosa graben structure outer zone	604950	4183075	fan deposits	13269 ± 495	865	Schuett Cañada Hermosa 3	Schütt and Baumhauer (2000)
17	KIA12862	Cañada Hermosa graben structure outer zone	602232	4183877	alluvial deposits	2164 ± 30	430-440	Schuett Cañada Hermosa 4	*
18	KIA12861	Cañada Hermosa graben structure outer zone	602232	4183877	alluvial deposits	2182 ± 30	450-460	Schuett Cañada Hermosa 5	*
19	UZ-4597/ETH-24410	Río Caramel alluvial plain	587538	4186374	flood sequences	980 ± 45		Benito Caramel 1	Benito et al. (2010)
20	UZ-4598/ETH-24411	Río Caramel alluvial plain	587530	4186363	flood sequences	945 ± 45		Benito Caramel 2	Benito et al. (2010)
21	UZ-4599/ETH-24412	Río Caramel alluvial plain	587530	4186363	flood sequences	1020 ± 50		Benito Caramel 3	Benito et al. (2010)
22	UZ-4659/ETH-24681	Río Caramel alluvial plain	587452	4186470	flood sequences	190 ± 55		Benito Caramel 4	Benito et al. (2010)
23	UZ-4600/ETH-24413	Río Caramel alluvial plain	587530	4186363	flood sequences	340 ± 45		Benito Caramel 5	Benito et al. (2010)
24	UZ-4601/ETH-24414	Río Caramel alluvial plain	587530	4186363	flood sequences	205 ± 45		Benito Caramel 6	Benito et al. (2010)
25	UZ-4602/ETH-24415	Río Caramel alluvial plain	587530	4186363	flood sequences	120 ± 45		Benito Caramel 7	Benito et al. (2010)
26	UZ-4603/ETH-24416	Río Caramel alluvial plain	587452	4186470	flood sequences	1985 ± 50		Benito Caramel 8	Benito et al. (2010)
27	UZ-4660/ETH-24682	Río Caramel alluvial plain	587452	4186470	flood sequences	120 ± 55		Benito Caramel 9	Benito et al. (2010)
28	UZ-4994/ETH-27650	Rambla Mayor alluvial plain	587435	4186570	flood sequences	175 ± 45		Benito RamblaMayor 1	Benito et al. (2010)
29	UZ-4995/ETH-27651	Rambla Mayor alluvial plain	587435	4186570	flood sequences	190 ± 45		Benito RamblaMayor 2	Benito et al. (2010)
30	UZ-4996/ETH-27652	Rambla Mayor alluvial plain	587435	4186570	flood sequences	105 ± 45		Benito RamblaMayor 3	Benito et al. (2010)
32	A1	Río Caramel, alluvial plain	574749	4182398	flood sequences	595 ± 30	400	Braun 1	Braun (2015)
33	A2	Río Caramel, alluvial plain	574359	4182566	flood sequences	2000 ± 30	106	Braun 2	Braun (2015)
34	A3	Río Caramel, alluvial plain	573291	4182566	flood sequences	380 ± 35	180	Braun 3	Braun (2015)
35	A5	Río Caramel, alluvial plain	581416	4184668	flood sequences	9210 ± 60	670	Braun 4	Braun (2015)

36	A6.1	Río Caramel, alluvial plain	581486	4184668	flood sequences	405 ± 30	150	Braun 5	Braun (2015)
37	A6.2	Río Caramel, alluvial plain	581486	4184668	flood sequences	1540 ± 30	180	Braun 6	Braun (2015)
38	A7.1	Molino del Alcaide, middle reaches Rio caramel	582641	4183947	flood sequences	2200 ± 35	350	Braun 7	Braun (2015)
39	A7.2	Molino del Alcaide, middle reaches Rio caramel	582641	4183947	flood sequences	2365 ± 30	450	Braun 8	Braun (2015)
40	GrA-40516	Río Vélez alluvial plain	599302	4175917	potential paleo-lake formation	14190 ± 50	-	Baartman RioVelez 1	Baartman et al. (2011)
41	GrA-40684	Río Vélez alluvial plain	595434	4174761	river terrace deposition	11700 ± 60	325	Baartman RioVelez 2	Baartman et al. (2011)
42	GrN-25452	Río Vélez alluvial plain - North of Puentes	601486	4179444	river terrace deposition	1980 ± 60	350	Baartman Puentes 1	Baartman et al. (2011)
43	GrN-26176	Río Vélez alluvial plain - North of Puentes	601486	4179444	river terrace deposition	650 ± 35	150	Baartman Puentes 2	Baartman et al. (2011)
44	Aufschlus s 04	Barranco de la Canal	576005	4183340	alluvial deposits	2848 +8/-64	191	Riedlinger Barranco 1	Riedlinger (2006)
45	Aufschlus s 04	Barranco de la Canal	576005	4183340	agricultural terrace	7964 +16/-24	408	Riedlinger Barranco 2	Riedlinger (2006)
46	Aufschlus s 04	Barranco de la Canal	576005	4183340	agricultural terrace	10450 +51/-92	528	Riedlinger Barranco 3	Riedlinger (2006)
47	Aufschlus s 04	Barranco de la Canal	576005	4183340	agricultural terrace	14154 +184/-44	1110	Riedlinger Barranco 4	Riedlinger (2006)
48	Aufschlus s 01	Vélez Blanco - María	575985	4174046	agricultural terrace	512 +14/-11	76	Riedlinger Velez 1	Riedlinger (2006)
49	Aufschlus s 01	Vélez Blanco - María	575985	4174046	agricultural terrace	173 +41/-4	107	Riedlinger Velez 2	Riedlinger (2006)
50	Aufschlus s 01	Vélez Blanco - María	575985	4174046	agricultural terrace	50 +6/-4	131	Riedlinger Velez 3	Riedlinger (2006)
51	Aufschlus s 05	Agricultural Terrace - La Longaniza	571203	4178658	agricultural terrace	2753 +134/-47	168	Riedlinger Loganzia 1	Riedlinger (2006)
52	Aufschlus s 05	Agricultural Terrace - La Longaniza	571203	4178658	agricultural terrace	6769 +39/-36	295	Riedlinger Loganzia 2	Riedlinger (2006)
53	Aufschlus s 05	Agricultural Terrace - La Longaniza	571203	4178658	agricultural terrace	6882 +28/-34	324	Riedlinger Loganzia 3	Riedlinger (2006)
54	Aufschlus s 2	Río Luchena floodplain	595212	4182419	alluvial deposits	10810 ±80	1200	Thiemann RioLuchena 1	Thiemann (2001)
55	Aufschlus s 3.1	Río Luchena floodplain	597252	4181641	alluvial deposits	10415 ±50	1850	Thiemann RioLuchena 2	Thiemann (2001)
56	Aufschlus s 3.2	Río Luchena floodplain	597252	4181641	alluvial deposits	10430 ±50	1950	Thiemann RioLuchena 3	Thiemann (2001)
57	Aufschlus s 3.3	Río Luchena floodplain	597252	4181641	alluvial deposits	11010 ±80	2100	Thiemann RioLuchena 4	Thiemann (2001)
58	Aufschlus s 15	Río Luchena floodplain	579000	4181850	alluvial deposits	2100 ±30	200	Thiemann RioLuchena 5	Thiemann (2001)

* unpublished data from the DFG funded project Schu 949/4 “HisSVAA – Historical weathering and erosion processes in Spain”

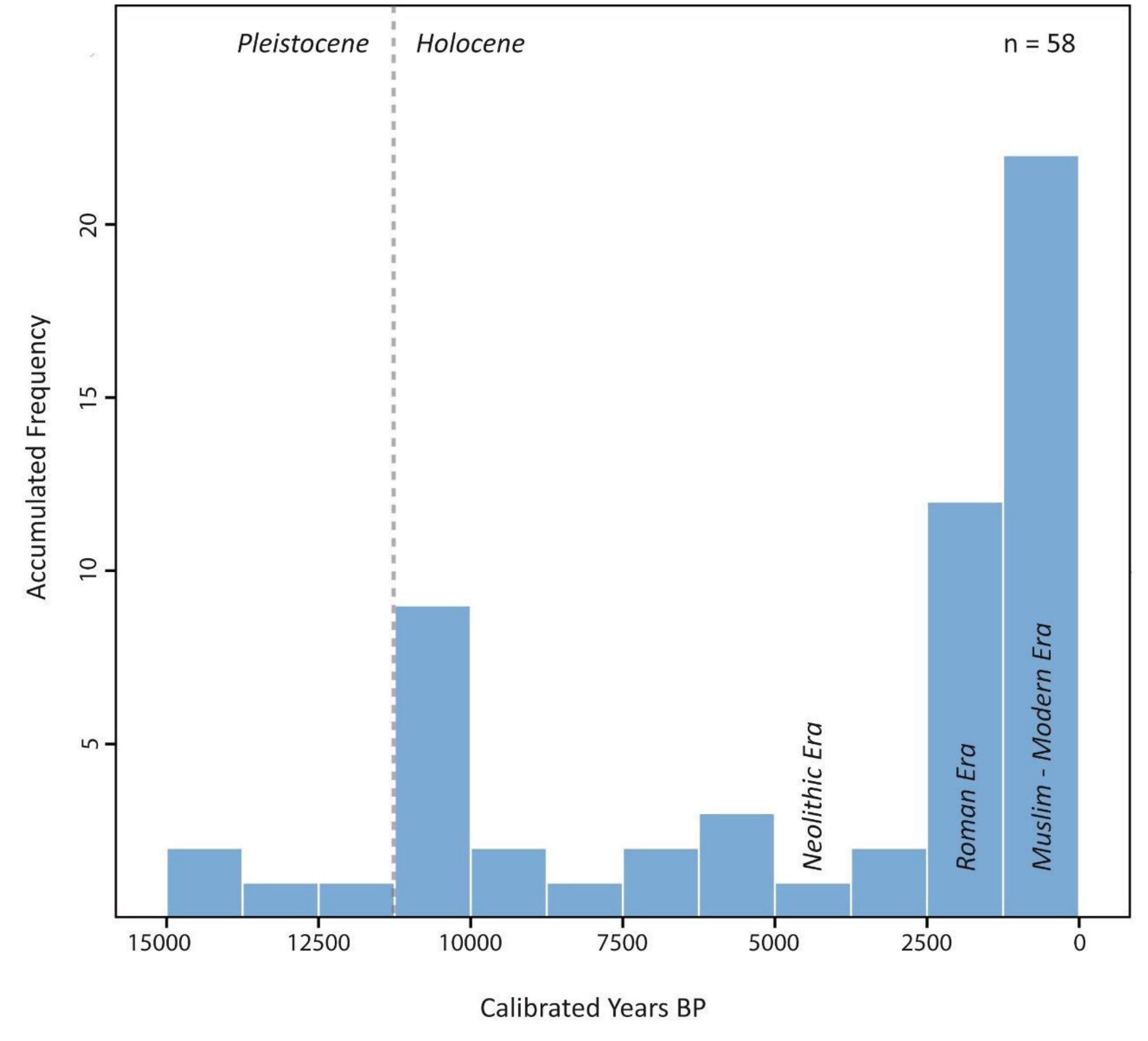

Fig. 2: Histogram showing the frequency distribution of the 58 Radiocarbon ages (cal. yrs BP) included in this study.

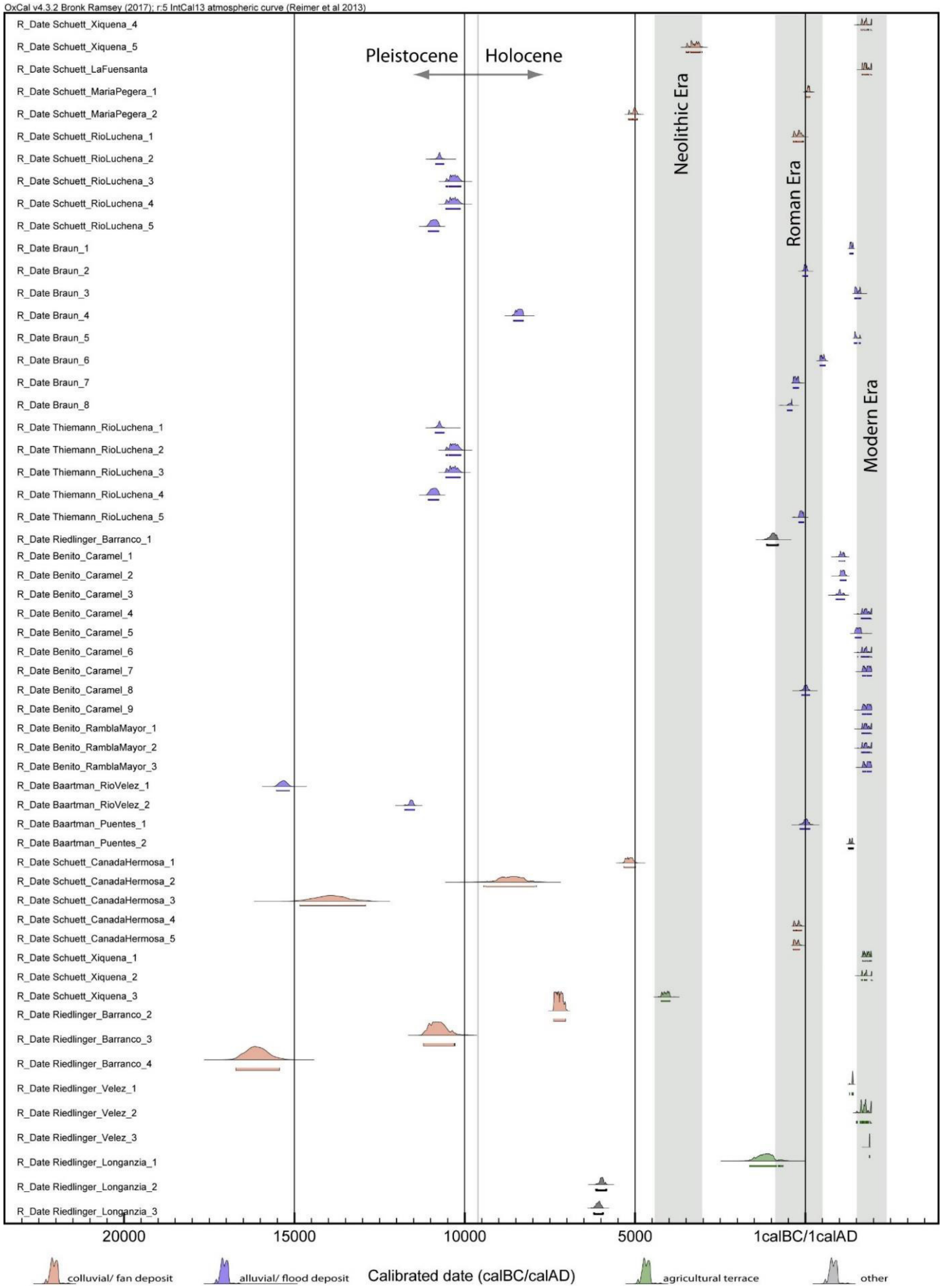

Fig. 3: Distribution of all evaluated radiocarbon ages evaluated for this study, according to table 2. The lower line indicates the colors for the respective depositional context. The main data was calibrated and designed in Oxcal version 4.3 and with the IntCal13 calibration curve.

6.4 Landscape development and settlement history of the Río Guadalentín headwater area

During the Last Glacial Maximum (LGM) (about 21-17 ka BP) (Williams et al. 1993) due to the barrier function of the Betic Cordillera regions situated at the Sierra Nevada's lee were dominated by a Cw climate (after Köppen-Geiger) with warm and dry winters (Font Tullot 1988; Schütt 2005). Snowlines ranged around 2.500 m a.s.l. in the Sierra Nevada (Lautensach 1964; Messerli 1967). During the Late Glacial period climate in the Río Guadalentin headwater area was characterized by more humid conditions than today. These altogether subhumid to dry-subhumid conditions were interrupted between 10.9 and 10.5 ka BP by a short arid phase (Fletcher et al. 2010; Bellin et al. 2013). The still water deposits in the middle reach of the Río Lucena described by Thiemann in his unpublished diploma-thesis (2001) confirm a perennial flow regime during early Holocene. Beyond, Baartman et al. (2011) dated floodwater deposits from the receiving Río Velez, which point to establishment of modern flow patterns shortly after LGM (Fig. 2 a & b). With the onset of the Holocene the regional climate gradually changed into more arid conditions (Schütt 2005). Pollen data from the Sierra de Gabór (100 km south of the upper Guadalentín catchment) and from Baza (50 km south-west of the catchment) also indicate a general trend of aridification for the region of south-eastern Spain since the mid-Holocene. Furthermore, the pollen data reveals a shift in vegetational occupation from pine to oak forests at 6-7 ka BP (Carrión et al. 2003; Carrión et al. 2007). Since the beginning of the Holocene, the southeastern lowland regions of the Iberian Peninsula are dominated by mostly stable steppe to semi-desert climate conditions (Schütt 2005; Schütt and Baumhauer 2000).

Pre- and early-historic era before 1.2 ka BP (before 8th cent. AD)

First evidence of a periodic human occupation in the headwater area of the Río Guadalentín occurred during the upper Paleolithic period and is provided by archaeological records from the Cueva de Ambrosio (easting: 579043, northing: 4188007 UTM coordinate system; Fig. 1). Latest excavations by López et al. (2015) show that settlement activities can be dated at least to 2 ka BP. During the Late Glacial period the cave was occupied by costal dwellers who used the mountainous area as hunting grounds during the summer (Roth 2001). Bone remains, discovered during archaeological excavations give information about the faunal state of the area during this period. Especially bones of ibex, deer, equids and rabbits were found in the Cueva de Ambrosio (López et al. 2015; Roth 2001). Pollen records from the Cueva de Ambrosio indicate warm and mild climate conditions during Late Glacial (Roth 2001). Villaverde et al. (1998) also conclude that human settlement strategies and economic activities were characterized by low mobility and a sufficient local supply with resources.

Neolithic and Chalcolithic period 6450 – 4950 BP (4500 – 3000 BC). Archaeological findings from the Cueva de Letreros (eating: 579716, northing: 4170223 UTM coordinate system) indicate that the area of the Guadalentín headwater area was settled during Neolithic and Chalcolithic periods. Detailed information about the occupation history in the county of Los Vélez is discussed by López and Muñoz (1999). For southeastern Spain, Bellin et al. (2013) conclude that during the Neolithic period settlement sites in valley bottoms were preferred due to their suitability for agricultural cultivation. While during the Neolithic period these settlements were still discontinuous, Bellin et al. (2013) describe for the Chalcolithic period an onset of permanent settlements in valley bottoms for southeastern Spain. Land use during the Neolithic period was dominated by initial dry farming endeavors and since the Chalcolithic period additionally by mining activities in the mountainous regions. It can be assumed that increased colluviation processes also triggered increased sediment load in the receiving streams. Above all, the invention of terracing in SE Spain has to be taken into account as a factor increasing the aggradation of downslope valley bottoms but also stabilizing the landscapes (Zapata et al. 2004).

Argaric and Post-Argaric era 4200 – 2850 BP (2250 – 900 BC). For the headwater area of the Río Guadalentín the Argaric and Post-Argaric era and the whole Bronze age is poorly covered in the literature (Harding and Fokkens 2013; Lentisco 2011; López et al. 2015; López and Muñoz 1999; Martínez García 2011). More information is available for the broader region of south-eastern Spain: Bellin et al. (2013) describe for the Argaric era an extensive practicing of dry farming with barley as main crop. During the Argaric and Post-Argaric era foothill regions were the preferred settlement sites due to favorable starting conditions for mining and good defense characteristics (Bellin et al. 2013). Carrión et al. (2010) describe the onset mountainous forest degradation in southeastern Spain for the end of the Argaric era. During the Post-Argaric era faming sites were abandoned on a large-scale and in consequence barley cultivation declined. Accordingly, for the Post-Agraric era a decrease in population is assumed (Bellin et al. 2013).

Roman era 2.9 ka – 1.5 ka BP (9th century BC – 5^th^ century AD). From the first millennium BC into the first centuries of the common-era, the upper Río Guadalentín basin experienced an increase of settlement and agricultural activities, emphasized by the appearance of Roman settlers in the Río Guadalentín basin around the 2nd century BC. First archaeological evidence about persistent human settlements is given for the Roman Period, although several Bronze-Age settlements sites are known, but not studied in detail (Lentisco 2011; López et al. 2015; López and Muñoz 1999; Martínez García 2011). Archaeological findings such as ceramic fragments and building structures confirm the existence of Roman settlements for several centuries. Based on linguistic derivations and superregional research results, it can be assumed that Roman settlers introduced water management facilities and technologies to the region for the utilization of water resources and for agricultural purpose (López Medina 1995; Roth and Schütt 2000). For example, in the lower part of the Vega of Vélez Blanco, the

Roman settlement at Canales offers a long chronology, covering the time period from the Late Republic (133-31 BC) to 6th century AD. It is assumed, that the location of the Canales settlement site was preferred due to the fertile farmland, the year-round availability of water and its proximity to the via Augusta (López and Muñoz 1997). López Medina (1995) indicate that Roman settlers in the region of the Río Guadelentín's headwater area practiced water management for human water supply as well as for irrigation agriculture. Etymological the toponym Canales possibly originates from Roman language; its Latin origin canalis-is implies the occurrence of a water pipe or canal (López and Muñoz 1997). Beyond these indications for the implementation of water management practices Carrión et al. (2010) presume a maximum of forest degradation in mountainous areas of southeastern Spain during the Roman era.

Visigothic and Byzanthic era 1.5 ka – 1.2 ka BP (5th – 8th cent. AD). For the Visigothic and Byzanthic era only little information on settlement activities is available for the Río Guadalentín headwater area. For south-eastern Spain it is generally known that agricultural production was dominated by cereal cultivation, while irrigation agriculture became increasingly propagated due to the development of hydraulic infrastructures (Bellin et al. 2013). Concerning landscape development, Silva et al. (2008) report high morphodynamics with subsequent river terrace formations in the area of Lorca during this period. They also describe a decrease of population during the Visigothic and Byzanthic eras coinciding with a reallocation of settlements towards mountainous locations (Bellin et al. 2013). For this period, pollen data indicate the onset of forest degradation and increasing agricultural production at 1.4 ka BP in the area of Siles (300 km north of the Guadalentín catchment; 1320 m a.s.l.). However, pollen data from the higher elevated area of Cañada de la Cruz (270 km north of the Guadalentín catchment; 1595 m a.s.l.) do not show this trend before 0.7 ka BP (Carrión 2002; Carrión et al. 2010).

Muslim period and Christian Reconquista 1.2 ka – 0.5 ka BP (8th – 15th cent. AD)

The Muslim period (8th century AD) was of coining importance for the implementation and development of water and landscape management practices all over the Iberian Peninsula settled by Muslims. Water management structures, partly probably already implemented by Roman settlers, were adopted and evolved by Muslim dwellers who settled the region of the upper Río Guadalentin in the 8th century AD. Their economic system was mainly based on irrigation agriculture (Benito et al. 2010). They adopted, improved and extended water management systems all over southern Spain. The Muslims also established jurisdiction and governmental structures in terms of land ownership and water-law and water-governance. Besides the proclamation of the Arab water law, they also installed so-called water tribunals in Spain, best known from Valencia (Glick 1970; Kress 1968), but also described for Velez Blanco (Roth et al. 2015). From that time on, scattered sources give evidence about a growth of population and coinciding an increase of pressure on the landscape.

In the headwater area of the Río Guadalentín during Muslim colonization the water management system of the region Los Vélez was fundamentally shaped, including the regulation of the joint usage of spring water between the two neighboring towns of Vélez Blanco and Vélez Rubio (Roth et al. 2015) (Fig.4). The Muslim settlers installed a water sharing system based on irrigation rotations and water auctions, administrated by an irrigation community that was staffed by local farmers (also see: Isselhorst et al. 2018a, Isselhorst et al. 2018b; Roth et al. 2015). During this time a water law was implemented by the settlers, regulating that irrigation rights and land ownership were inseparably bound to each other; Butzer et al. (1985) refer to this interrelation also as the Syrian system. This established water sharing system is practiced in the Vega of Vélez Blanco until today (Isselhorst et al. 2018a, Isselhorst et al. 2018b; Navarro Sánchez 2007; Roth et al. 2015). Also, the introduction of new water management technologies is known for this period. In the area of the upper Río Guadalentín at this time the technology of water extraction by qanat systems (locally called galerías or minas) were introduced by Muslime settlers (Roth and Schütt 2000). Today, remains of qanat systems can be found inter alia in the lower part of the Vega of Vélez Blanco as well as in the vicinity of María. Beyond that latest since the Muslim period the construction of aqueducts improved the transport and diversion of irrigation water. The implementation of aqueducts enabled a broader reach of irrigation water and with this an extend of agricultural land suitable for intensive cultivation. Altogether, the growth in population that is known for southeastern Spain during the Muslim period and Christian Reconquista required an extension of agricultural areas (Bellin et al. 2013). New farmland was opened up by deforestation and terraces were constructed to extend the cultivation of cereals and horticulture (e.g. olives, vegetables, vine and other fruits) (Bellin et al. 2013). As a consequence of the intensified human interventions into the landscape the regions overall water balance and landscape dynamics most likely experienced a significant shift. Decreasing inflow rates caused by water withdrawal for irrigation purpose reduce the dynamics of local rivers, turning perennial rivers into water bodies with periodic or even episodic runoff. E.g. the Río Claro, etymological a perennial river, transformed into a river with periodical water-flow (c.f. Tooth 2000).

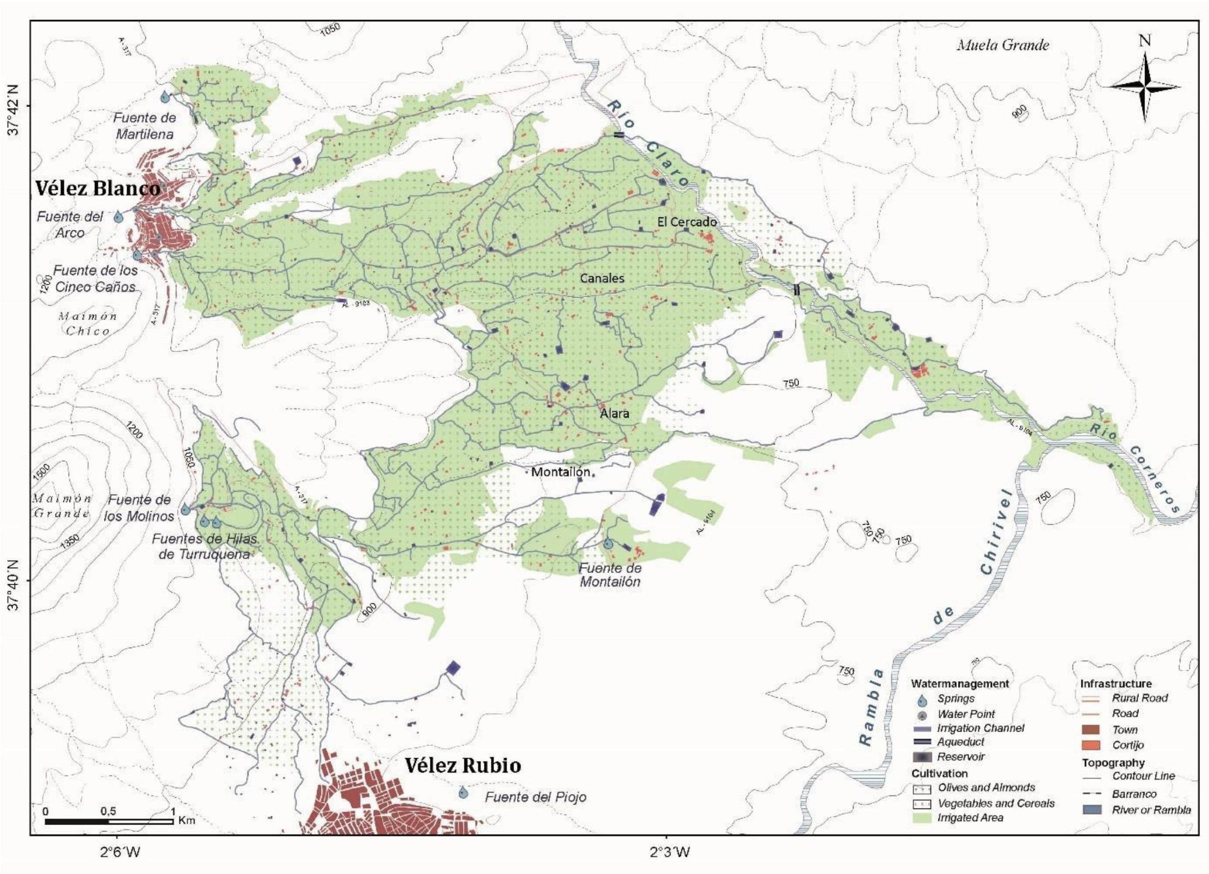

Fig. 4: Detailed map of the irrigation channel network within the Vega of Vélez Blanco. The area marked in green is connected to the irrigation network. The cultivated terraces within this area receive irrigation water out of the irrigation rotations of the traditional water sharing community of Vélez Blanco on a regular basis (more detail is given in: Isselhorst et al. 2018a, Isselhorst et al. 2018b; Navarro Sánchez 2007; Roth et al. 2015).

Modern Era 0.5 ka BP – present (15th – 20th cent. AD)

Forestation during the Modern Era

After the Christian Reconquista in 1492 AD, during the Repoblación, a large number of Christian settlers repopulated the former colonization territory of Al-Andalus, largely comprising the area of the todays' provinces of Andalusia and Murcia (see also: Glick 1979; Kress 1968). At that time, the Margravate of Los Vélez with a territorial dominion embracing an area of 70 km N-S-extension and 25 km E-W-extension (including inter alia the villages of Topares, Chirivel and Maria) with its seat located in the town of Vélez Blanco was formed (Roth et al. 2015). In consequence of demands on land holdings and increasing food requirements, new agricultural lands were opened in the Margravate of Los Vélez by massive deforestation (Segado Castro and Zamora Díaz 2016). The most intense clearing phase took place between 1550 and 1570 AD. However, due to the fact that the process of deforestation led to the destruction of the Margraves hunting grounds, Pedro Fajardo y Chacón (1478-1546 AD), Margrave of Los Vélez, established first protection measures to regulate the forest clearance (Rodríguez Campos 2001).

Another phase of massive deforestation occurred during the 18th century AD. At this time, wood was needed due to the boost in ship building along the major rivers and coasts of the Iberian Peninsula. This economic opportunity was taken by the Margrave of Los Vélez in order to maximize the revenues of the natural resource, leading to a severe deforestation in the woodlands of the Río Guadalentín headwater area (Rodríguez Campos 2001). The repeatedly documented flood sequences in the alluvial deposits of Río Caramel and Rambla Major (Benito et al. 2010) as well as the slope deposits in the foot zones of the Sierra Gigante (Tab. 2, consecutive number 1, 4-6) most likely reflect the reaction of the morphodynamics on upslope deforestation processes.

First quantitative information about the forest area in the Río Guadalentín headwater area date back to 1752 AD. Based on the regulations to conserve the mountain area of the Sierra de María (Ordenanzas para la conservación de la Marina; established January 31, 1748), a detailed inventory of the forests of the municipal territory of Vélez Blanco was carried out (Roth 2011). At that time, the forests around the town of Vélez Blanco had an extent of 20,000 ha, primary covered by holm oaks and pines (pinus nigra and pinus pinaster) (Gilman and Thornes 1985; Roth 2011). In the inventory a number of 243,577 pine trees and 313,499 holm oaks were registered for November 1752 AD (Roth 2011) (Fig. 5 d). Since the 16th century, the supremacy over the forests of the Margraviate of Los Vélez was assigned to the family Fajardo, which also granted the margraviate. This ownership was only abolished during the last quarter of the 19th century AD when the ownership of the woodlands was divided between the towns of Vélez Blanco, Vélez Rubio, María and the Ducal house (Segado Castro and Zamora Díaz 2016).

The first comprehensive study of the forested area in the Río Guadalentin headwater area was compiled by Domingo Olazábal in 1880 AD. He stated that the forests in the headwater area of the Guadalentín were in the late 19th century AD in a very poor condition. Beyond, he already emphasized the importance of the forests in terms of flood protection within the Río Guadalentín basin (Carricondo Martínez and Ortiz Martín 2011). At that time, a forest area of 8,566 ha (1880 – 1885 AD; c.f. Olazábal (1885)) was recorded in the headwater area of the Río Guadalentín. This number accounts for only 42.8% of the forested area recorded in 1752 AD (Fig. 5 d). As a consequence of this poor forest cover that was also observed in other areas during the second half of the 19th century AD, the División Hidrológico Forestal del Segura was founded in the late 19th century in order to coordinate the regional reforestation processes and to implement the construction of hydrological regulation structures (Carricondo Martínez and Ortiz Martín 2011). In 1880 AD, the region’s forests were for the first time included in the state-managed “Provincial Exploitation Plans” of the Forestry Administration (Segado

Castro and Zamora Díaz 2016). In 1898 AD an increase of the forest area was recorded in the area around the town of Vélez Blanco, now totaling an extend of 9,865 ha, representing a spatial increase of 15% from 1880 to 1898 AD (Olazábal 1898; c.f. Segado Castro and Zamora Díaz 2016). This corresponds to an area growth of more than 1,000 ha of wooded land in less than ten years. Within the following two decades further afforestation measures took place, causing an increase of woodlands by 1,000 ha in 1906 AD, 2,000 ha in 1907 AD and another 2,000 ha in 1917 AD (Araque Jiménez 2009, 2011) (Fig. 5 d). An even more intensive second phase of reforestation started in 1941 AD, predominantly aiming for a reduction of erosion processes in the headwater area of the Río Guadalentín and improving the flood protection for the whole Guadalentín basin (Araque Jiménez 2011). In order to achieve this, 5,291 ha of land were reforested in the Río Guadalentín's headwater area between 1941 – 1970 AD (Patrimonio Forestal del Estado 2009). In addition, at the end of the 1940s about 630 ha of forest area was redeveloped at the Sierra Larga and Dehesa de la Alfahuara while in the 1950s large areas within the drainage basins of the Rambla Mayor and Rambla Seca also were reforested, recreating 6,551 ha of woodland (Araque Jiménez 2011) (Fig. 5 d). The intensification of reforestation in the 1950s occurred with help of governmental support. Despite all efforts, the implemented measures fulfilled only a quarter of the initial planned extent of reforestation (Araque Jiménez 2011). The interrelationship of forest coverage and frequency of flood events is emphasized as well in figure 5 (a, c, d). It is shown that from the start of the 20th century, the onset of major reforestation projects corresponds to a noticeable decline of the occurrence of flood events. Meanwhile, the rainfall index interannually peaks during spring season.

During the 1990s, about a century after the first forest inventory, the forest cover for the modern region of Los Vélez (covering the area of María, Vélez Rubio and Vélez Blanco) clearly shows a recovery. In 1989 the regions forest cover totaled 15,380 ha and even extended to 18,072 ha in 1995 AD (Instituto Nacional de Estadistica 1989, 1999) (Fig. 5 d). With this, the recorded forest cover of 1995 AD equals about 90% of the former extend known from 1752 AD.

Population development during the **Modern Era**

At the End of the 16th century AD, after the Christian Reconquista, the small numbers of Christian settlers that arrived in the region did not compensate the high number of Muslim people that were expelled. Not until 18th century AD the demographic development within the headwater area of the Río Guadalentín slowly changed into a constant population growth and stabilized in the 19th century AD (Roth 2001). A significant break is recorded for 1648/49 AD when the pest raged in the region. A second, less devastating epidemic is noted for the year 1834 AD (Roth 2001). From the mid 19th to the mid 20th century AD the demographic development in the headwater area of the Río

Guadalentín was widely stable (Junta de Andalucia 2017). During this time, changes in population numbers are mainly affected by epidemics and a minor migration phase. A considerable decline of population within the towns all over the province of Almería occurred during the 1930s as a result of the Spanish civil war (1936 – 1939 AD) (Roth 2001) (Fig. 5 e). Subsequently, a much more rapid decrease in population has developed during the past 50 years: Due to a loss of economic potential, life in the rural areas was marked by high unemployment rates, providing only poor prospects for young people. As a consequence, especially young people migrated into the cities (Lentisco 2011). Within only three decades the rural population declined by nearly one third. Local consequences of this migration process include the neglecting of rural infrastructures and an aging of population (Lentisco 2011). This downward demographic development just recently got reduced by establishing regional promotion plans and subsidies to strengthen rural areas.

Land-use development during the **Modern Era**

The arrival of new settlers and the expulsion of the Muslim people resulted in the redistribution and exploitation of agricultural land, starting in the 15th century AD. In the 16th and 17th centuries AD animal husbandry became the most important economic revenue in the Río Guadalentín headwater area. The growing population caused an increasing pressure on agricultural land and forested areas. The establishment of new trading routes in the late 18th century AD and hereby the opening up of new markets caused an intensification of land use: former woodland was cut and mainly transformed into pastureland and dry farming fields for the cultivation of wheat and barley (Roth 2001).

The new – global - trading routes also brought the devastating phylloxera epidemic from North America to Europe, what is also documented for the Vega of Velez Blanco. Here at the end of the 19th century AD, the agricultural sector was affected by the destruction of viticulture due to phylloxera, documented in records about the abandonment of vineyards in the Vega since the 1880s AD. Until this time, viniculture was vitally important for the region (Roth 2001). Nowadays, a slow recovery of viniculture can be observed, but it is still of minor importance for the regional agricultural sector. Along with the onset of the mechanization of agricultural production during the 1960s, a shift in cultivation practices occurred. The introduction of new farming methods coming along with labour-intensive husbandry led to an intensification of agricultural production (Sanchez Guirao 2001). Another shift in cultivation products was initiated by the extensive state subsidization during the 1960s and 70s to cultivate almond orchards. This project aimed to support the rural economy by improving agricultural production in areas characterized by unprofitable natural and climatic conditions. The robustness and adaptability of almond trees were exploited to overcome poor soils and water shortage in order to enable a more efficient cultivation in rural areas. The plantation of almond trees was also utilized for protection against erosion (Carricondo Martínez and Ortiz Martín 2011). In the 1990s, cash crop farming was first introduced to the headwater area of the Río Guadalentín. At this time, large scale irrigation and intensive cultivation of lettuce and broccoli were established in Chirivel (Sanchez Guirao 2001). Today, this type of agricultural production is found all over the area.

Water Management since the **Modern Era**

The dam building projects for the Valdeinfierno and Puentes reservoirs were already initiated in 1576 AD under the regimen of Felipe II (1527-1598 AD). He proposed to regulate the runoff of the upper Guadalentín catchment to improve water availability, especially during the hot and dry summer months for the downstream towns and vicinities of Lorca and Murcia. In 1648 AD, initial trials to dam the water from the Guadalentín headwater area failed already during the early construction stage when the basic structures of the Puentes I were destroyed by a flood event (Capel 1968). It took more than two centuries until the initial plans were finally realized by Carlos III (1716-1788 AD). Constructions on both dams started in 1785 AD. At this time, the main purpose of the dams still was to improve the availability of irrigation water while flood protection was only of secondary importance (Garrido 2009). The first dam to be finished was the Puentes II in 1791 AD, which was destroyed by a catastrophic flood in 1802 AD. This flood also damaged the building structures of the unfinished Valdeinfierno dam and caused at least 608 dead people (Capel 1968; Garrido 2009). Construction works on the Valdeinfierno dam were finished in 1806 AD (Pictures 1, 2), but it took nearly another century until a new dam was build downstream at the Puentes reservoir, the Puentes III (1884). Lately, this building was improved in the 1990s by the construction of an additional dam wall, the Puentes IV (Garrido 2009) (Fig. 5 a; Picture 3).

Picture 1 (left): Embalse de Valdeinfierno. Today, the basin is completely silted and covered by a dense tamarisk scrubland and rarely stores water. Currently the reservoir is blocked by a sediment layer of a thickness of up to 30 m (Confederación Hidrográfica del Segura 2019).

Picture 2 (right): Arch Dam wall of the Valdeinfierno (completed in 1806 AD), situated in the upper end of the Río Luchena gorge.

Picture 3: View into the Embalse de Puentes from eastern direction with the dam Puentes IV (completed in 2000 AD).

During the 17th to 19th century AD, at least four periods of increased fluvial activity occurred as indicated by sedimentological records. Especially for the second half of the 19th century sedimentary records and radio carbon ages indicate an increasing flood frequency of extraordinary and catastrophic character, an observation that also correspond to records of historical floods and economic losses (Benito et al. 2010; Machado et al. 2011) (Fig. 5 a). With the finalization of the two reservoirs Valdeinfierno and Puentes a reduction in flood magnitude occurred latest since the late 19th century AD. Repeated siltation of both reservoirs points to the intensive soil erosion processes characterizing the morphodynamics Río Guadalentin headwater area. During the phase of the Little Ice Age (16th-19th century AD) more humid environmental conditions temporarily caused an increase of seasonal runoff (Benito et al. 2010).

With the reorganization of the water management units all over Spain during the first half of the 20th century AD, the drainage basin of the Río Guadalentín became part of the administrative division of the Confederación Hidrográfica del Segura (*CH Segura*). This state interference affected a large number of so-called irrigation communities within the Río Guadalentín basin, which were no longer able to operate as independent water users (Isselhorst et al. 2018b). An exception builds the irrigation community of Velez Blanco. Here, until today the organizational structures of the local irrigation network is only marginally affected by the nationwide reorganization of water management administration. The organizational structures in the Vega of Vélez Blanco overcame armed conflicts, political upheaval, economic crises as well as cultural evolution and still function in the same traditional way probably since the Muslim Period (Roth et al. 2015; Isselhorst et al. 2018b).

A characteristic feature of water sharing systems in the headwater area of the Río Guadalentín, known from the irrigation communities of the huerta of Lorca and the Vega of Vélez Blanco, is the auctioning of irrigation water among farmers. While water sales were abandoned in Lorca in 1960 AD, the irrigation community of Vélez Blanco still conducts water auctions until present (Capel 1968; Isselhorst et al. 2018b). The historical background, administrative organization and auctioning system of the irrigation community of Vélez Blanco is well documented (Isselhorst et al. 2018a, Isselhorst et al. 2018b; Navarro Sánchez 2007; Roth et al. 2015; Roth 2015). The work by Capel (1968) provides comprehensive information about the history of Lorca's water sharing system.

Historical Climate since the Modern Era

The analysis of the historical climate in southeastern Spain by Machado et al. (2011) focuses on the past 500 years; they document an oscillation of wet and dry periods each with a duration of several decades. This is also discussed by Benito et al. (2010) observing an increased flood frequency during this period at the Río Caramel, also documented by several radio carbon ages (Tab. 2, Fig. 2). Furthermore, Machado et al. (2011) observed a fluctuating frequency of extreme rainfall events. Especially in the end of the Medieval warm period sediment records and historical sources indicate an increased flood frequency. In total, Machado et al. (2011) identify three types of intensive flood-generating climate phases, occurring repeatedly: (i) wet conditions (1600-1730 AD and 1860-1900 AD), (ii) wet to normal conditions (e.g. 1520-1570 AD; 1770-1800 AD; late 20th century AD) and (iii) dry climatic conditions characterized by ephemeral extreme precipitation events (e.g. 1507-1519 AD; 1752-1762AD).

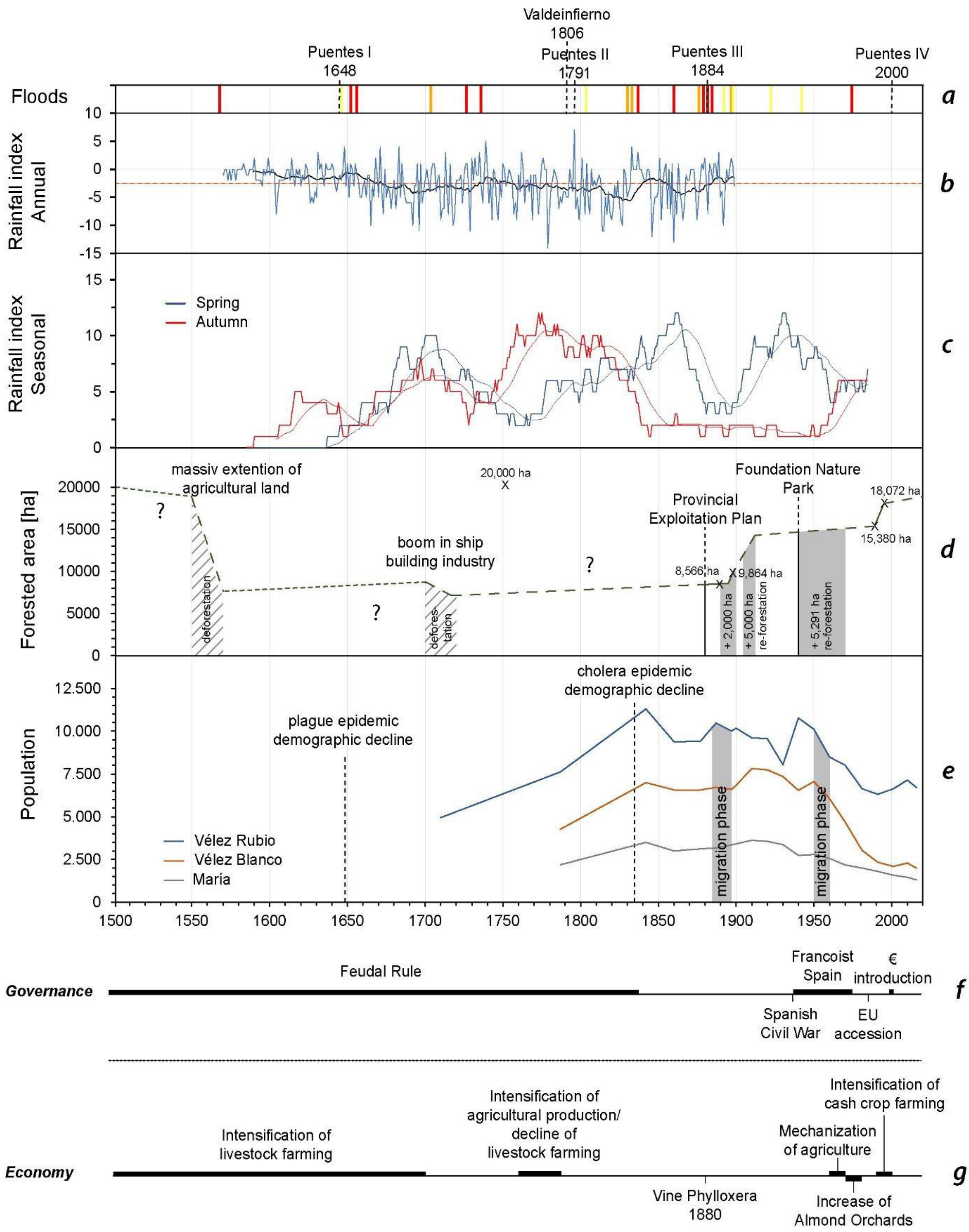

Fig. 5: Overview of the historical development of climate, land-use and settlement in the headwater area of the Guadalentín drainage basin. a) Documented flood events in the rivers headwater area (after Benito et al. (2010)). Floods of ordinary (yellow), extraordinary (orange) and catastrophic (red) character are displayed as well as construction dates of the Valdeinfierno and Puentes dam. b) Reconstruction of the annual rainfall index for the area of Murcia calculated by Rodrigo and Barriendos (2008). c) Seasonal division of the annual rainfall index for spring (blue) and summer (red), calculated by Rodrigo and Barriendos (2008) and Machado et al. (2011). d)

Development of forest cover between the 16th – 20th centuries AD in the area of Los Vélez (Alcocer Martínez et al. 2011; Araque Jiménez 2009, 2011; Segado Castro and Zamora Díaz 2016; Instituto Nacional de Estadistica 1989, 1999; Lentisco 2011; Olazábal 1885, 1898; Patrimonio Forestal del Estado 2009; Roth 2011). e) Population development in the towns of Vélez Rubio (blue), Vélez Blanco (red) and María (grey) since the 18th century AD. Epidemics and migration phases are highlighted (Junta de Andalucia 2017; Roth 2001). f) Overview of the prevailing Spanish government system and economic events since the 16th century AD. g) Important phases and events that influenced the economic development in the upper Guadalentín basin (Roth 2001; Roth et al. 2001; Roth et al. 2015).

6.5 Concluding remarks

Despite the diverse sources, information about the entire Holocene landscape development and settlement history of the upper Río Guadalentín headwater area remains patchy and discontinuous. This is to say that albeit numerous indicators pinpoint settlement activities throughout the Holocene. The first real evidence of ancient land colonization and major environmental impact is not verifiable until the Roman and especially the Muslim periods. It can be assumed that already during Moorish settlement agricultural practice considered practices to reduce land degradation such as terrace construction. However, there are no documents available that prove this general assumption for the area of the upper Río Guadalentín. Furthermore, only pollen data from the greater area was available to indicate the climate conditions and development of vegetation within the study area during the Holocene. Due to the diversity of landscapes in south-eastern Spain, assumptions from pollen data should not be directly transferred to the area of the upper Guadalentín catchment area. They can rather be seen as an indicator for climate conditions and vegetational status during this period of time.

Continuous written records are available since the 15th century AD. From that time on, data concerning human activities that allow conclusions on landscape and environmental impacts is broadly available. Phases of extensive deforestation for the purpose of farmland exploitation and subsequent implemented reforestation projects witness the cultural imprint on the regional landscapes. Especially the phase of deforestation in the second half of the 16th century AD is strongly connected to a growth of population. The population development peaked at the middle of the 19th century AD and kept stable for the subsequent century.

One of the main reasons that encouraged the regional and supra-regional interests to implement reforestation projects in the late 19th century AD was the increasing knowledge on the interrelation between deforestation processes and the occurrence of catastrophic flood and events and erosion dynamics. The importance of forest coverage for flood protection in the headwater area of the Río Guadalentín drainage basin was first discovered at the end of the 19th century AD (Carricondo Martínez and Ortiz Martín 2011). Locally, this point in time also marks a major leap in knowledge of human impact on landscape dynamics.

With the construction of the Valdeinfierno and Puentes dams in the late 18th century AD, the area experienced a major impact on the local hydrological-system and subsequent sediment-dynamics. Consequently, shifts in hydrological regimes and erosion and sedimentation processes occurred (Garrido 2009; Gil Olcina 1968). Today, the sediment filling of the Puentes and especially the Valdeinfierno reservoir is a witness of the misunderstanding of the prevailing hydrological dynamics, since at least the latter dam only functions as a sediment trap and not - as originally intended - as water reservoir (Picture 1 - 3).

The most characteristic human intervention that shapes the Mediterranean landscapes to this day is the broad usage of agricultural terraces. However, the introduction of terrace constructions can be dated back to the Bronze age for the headwater area of the Guadalentín basin (Gilman 1975). It is known that a massive expansion of agricultural land took place after the Christian Reconquista, reshaping the landscapes appearance from a natural to cultural landscape. Present and future challenges are the abandonment of farmland caused by migration of young people into the cities and the connected ageing of rural population and loss of traditional knowledge. Consequences are unmaintained terrace structures. The absence of maintenance enables the intensification of piping processes that increase the erosion potential of soils that are anyhow of thin and initial character (Schütt et al. 2011). Thus, especially heavy rainfall events will have an enhanced soil-erosive effect.

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7. Major Conclusions and Synthesis of the Research Results

7.1 Water management in the Vega of Vélez Blanco

In this thesis, different approaches were used to investigate and describe the technical structures, social organization, and hydrological conditions within the water-sharing system of the Vega of Vélez Blanco (Isselhorst et al. 2018a; Roth et al. 2015).

The study of Roth et al. (2015; section 3.5) summarizes the historical background of the irrigation community of the Vega of Vélez Blanco since the Muslim period. It describes the legal history concerning the local water management and provides an insight into the jurisdiction regarding water law. The results of the analysis of historical and archival sources indicate that the fundamental management structures of the local irrigation community have remained mainly unchanged since the Muslim period. The responsibility for the administration of the water-sharing system and maintenance of the technical facilities have remained with the self-organized local irrigation community.

The study of Isselhorst et al. (2018a) enables the Vega of Vélez Blanco to be classified within the broad system of irrigation communities in the autonomous region of Andalusia based on numerical, physical, and economic characteristics. By combining the numerical characteristics with the definitions by Butzer et al. (1985), the Vega of Vélez Blanco was classified as a meso-scale irrigation area. This classification also applies for the characteristics that define the average Andalusian irrigation community. It shows that the Vega of Vélez Blanco is a good example to study water management in southern Spain. On average, the Vega of Vélez Blanco shows a balanced relation between water consumption and water demand. However, this balance does not necessarily apply on the seasonal or inter-annual scale, as shown by Isselhorst et al. (2018b; section 5.3). Since the growth period of most plants cultivated within the Vega of Vélez Blanco coincides with the seasonal period of dryness and high temperatures, irrigation is often needed to safeguard harvests and avoid crop loss. Furthermore, the studies found the traditional auctioning of irrigation water to be a factor that distinguishes the Vega of Vélez Blanco from other irrigated areas.

The inventory of technical water management facilities (section 5.1), produced by the analyses of aerial photographs, cadastral maps, and field mapping, documents the high complexity of the irrigation network within the Vega of Vélez Blanco. The overview map is essential to understanding the local water-sharing system. It illustrates the complex channel network in detail and enables the traceability of the distribution of irrigation water within the Vega of Vélez Blanco. This improves the understanding of the water auctions by connecting individual subsystems to their physical territories.

7.2 Persistence of the water-sharing system of the Vega of Vélez Blanco

The information gathered about the water management system of the Vega of Vélez Blanco was used to support the correlation analysis of water price and climate data. The study of Isselhorst et al. (2018b; section 5.3) aimed to investigate and estimate the system's persistence against internal and external factors and their effect on the system stability.

The result of Isselhorst et al. (2018b) revealed a significant impact on irrigation water requirements of different rainfall patterns at various scales. It was concluded that the crops cultivated within the Vega of Vélez Blanco exhibit a delayed reaction to rainfall events. There is a one-month delay in the causal relationship between monthly precipitation sums and water auction prices. Overall, the reliability of the occurrence of precipitation events between the months of March and June was of great importance to the water requirements of cultivated plants during the annual dry period in the summer months. Ostrom (1990) defines the infrequent occurrence of precipitation as a major source of uncertainty that influences the stability of agricultural systems. As a consequence, perennial water supplies and irrigation strengthen the resilience of systems where irrigated agriculture is practiced. This finding indicates the importance of reliable fresh water supplies during the summer. However, interviews with local farmers revealed an appreciable seasonality in the discharge volume from the springs, with the annual dry season frequently characterized by noticeably lower discharge rates. This indicates seasonal fluctuations within the aquifer's water table (Isselhorst et al. 2018b). During recent years, the seasonal fluctuation has been intensified by unregulated water withdrawal by deep-well pumping in the catchment of the Orce-María aquifer. As a consequence, a lowering of the discharge during the summer has increased the system's vulnerability, as shares of water are mainly measured by time and not by volume (section 5.2).

One factor that has already led to the abandonment of water auctioning in other water management systems of the region (e.g., Lorca) during the past century is the social inequality that is a side-effect of this type of water sales (Capel 1968). In recent decades, the intensification of cash-crop farming and technical advancement has been widening the gap between small-scale agriculture, such as subsistence farming, and mid- to large-scale industrial agriculture. Especially during hot and dry summers, smallholder farmers who primarily practice subsistence farming are often not able to compete with large-scale farmers and their cash-crop production, resulting in a higher level of crop loss for smallholder farmers (Isselhorst et al. 2018b). At present, this trend is also recognizable within the Vega of Vélez Blanco, threatening the system's persistence.

As noted by Ostrom (1990), the existence of rules is a key factor in the robustness and sustainability of a water management system. The rules in a water-sharing system are usually customized for the particular natural environment and needs of the local population. Circumstances often differ, at least slightly, between individual irrigation communities. In the Vega of Vélez Blanco, changes within the political framework have affected the overall organization of the water management only marginally. As described by Isselhorst et al. (2018a; section 3.6), even today the irrigation community is an independent local authority that is only indirectly supervised by the central government of Spain. However, during the past century, several adaptions of the system can be recognized, including a loosening of legal structures. For example, water trade between neighboring landowners is mostly tolerated, whereas historically water rights were inseparably bound to a parcel of land (Syrian system; Butzer et al. 1985; Isselhorst et al 2018b). Still, the overall management structures and main tasks of the irrigation community remain unaffected. Hence, the individual design, adaptability, and continuity of the long-enduring water management system of the Vega of Vélez Blanco can be seen as a factor that characterizes the system's stability.

Based on the findings of the studies of Isselhorst et al. (2018a; 2018b; rejected 2019) and Roth et al. (2015), the effects of historical events and socio-economic developments can be ascertained. For instance, the analysis of the water-auction data revealed that in times of political disturbances, such as the Spanish Civil War (1936-1939), exceptionally water prices rose to exceptionally high levels, indicating a direct influence on the water-sharing system. However, the studies also revealed that it is difficult to assess the influence of certain events on the system's stability.

The synthesis of the research results suggests that the water management system of the Vega of Vélez Blanco reacts in the short-term to external factors such as variability in natural water availability and changes in the political framework. In contrast, the system's internal organizational structures and operation is characterized by long-term stability. This finding demonstrates the high resilience of the local water-sharing system. However, the results also revealed that the intensity of the impact of external factors on the system is difficult to assess.

7.3 Human-environment interactions

The reconstruction of the transformation process from a natural to a cultural landscape in the region of Vélez Blanco was outlined by Isselhorst et al. (rejected 2019; Chapter 6). It combined the results of Isselhorst et al. (2018a; 2018b; sections 3.6 & 5.3) and Roth et al. (2015; section 3.5) to identify interrelations between humans and the environment. It highlighted the significance of the implementation of water management on the landscape development.

The literature analyses showed that the first evidence for major human impact on the landscape development in the region of Vélez Blanco comes from the Roman and especially the Muslim period (Isselhorst et al. rejected 2019; Chapter 6). Gilman (1975) even estimates the local onset of terrace constructions during the Bronze age. However, continuous written records that allow conclusions on landscape development and interactions between humans and the environment are only available for the 15th century onwards; documentation for earlier times remains patchy. The studies showed that the most significant human intervention in the landscape of the study site has been the intensive usage of agricultural terraces. Terrace constructions were implemented to reduce land degradation, improve soil formation, and thus enable agricultural production. This is demonstrated by the impact of the local water management on the development of the local culture and economy. The advantage of a perennial water supply in an area of semi-arid climate with hot dry summers made the site of Vélez Blanco a favorable location for settlements, leading to increasing demand of food and water supply (Roth et al. 2015, Isselhorst et al. 2018a; 2018b). To meet the increased demand for nutrition, local forest areas were cleared for the extension of arable land. In the region of Vélez Blanco, the first extensive deforestation for the purpose of farmland exploitation that strongly contributed to the formation of today's cultural landscape took place during the 15th century and the second half of the 16th century. Both phases were strongly connected to a growth of population and the accompanying increase of food requirements (Isselhorst et al. rejected 2019). A causal relationship between the intensification of land clearance and increasing sediment dynamics was attested for the region by several authors (Benito 2010; Martínez and Ortiz Martín 2011). However, indications of an awareness of the impact of human intervention on the landscape were first attested locally in the late 19th century (Martínez and Ortiz Martín 2011). From that time, awareness greatly increased of the interrelations between deforestation, the occurrence of catastrophic flood events, and erosion dynamics, subsequently leading to the implementation of reforestation projects.

Based on a case study of the Vega of Vélez Blanco, the findings of this doctoral thesis contribute to the outlining of the historical development of water management in southern Spain. The different approaches to the analysis of the water management structures and their historical development enabled a detailed description of human-environment dependencies and interactions within the Vega of Vélez Blanco. Furthermore, the resilience and overall persistence of the local water-sharing system is demonstrated by the water auctions that have been carried out in the Vega of Vélez Blanco from the Muslim period to this day.

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Appendix I: RMSE Historical Cadastral Maps

Table Appendix I: RMSE Historical Cadastral Maps

Map No.	No. of GCPs	RMS Error
82	29	4,5
077a	29	5,2
077b	16	3,8
079a	5	3,2
079b	10	4,4
078a	17	9,2
080a	12	3,3
080b	16	4,5
81	7	14,5
25	13	8,2
24	14	4,0
23	14	3,9
19	19	6,6
18a	8	1,4
18	18	4,7
27a	9	5,9
27b	20	2,0
27c	21	2,6
26	21	11,1

Appendix II: Cross correlation of monthly based precipitation sums and mean water prices

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The Table was removed for license reasons. The original Publication will be available at: https://doi.org/10.1016/j.agwat.2017.11.018

Appendix III: Seasonal based cross correlation of precipitation sums and mean water prices

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Appendix IV: Questionnaire for the Interviews in the Vega of Vélez Blanco

Datos generales

1) Datos personales

Edad ___ años Sexo ☐ h ☐ m

Miembros de la unidad familiar___ (entrevistado incl.)

☐ no sabe, no contesta

2) ¿Desde cuándo tiene Usted/ su familia campos de cultivo en la vega de Vélez Blanco?

Desde hace: menos de 5 años ☐ menos de 25 años ☐ más de 25 años ☐

☐ no sabe, no contesta

Cultivo/ economía

3) ¿Cuánta superficie cultiva?

☐ ½ ha o menos, ☐ entre ½ ha y 1 ha, ☐ más de 1 ha (1 ha = 10 000 m²)

☐ no sabe, no contesta

4) ¿Qué cultiva principalmente? (múltiples respuestas permitidos)

☐ Aceitunas ☐ Almendras ☐ Fruta: ______________________

☐ Hortalizas__________________ ☐ Cereales____________________

☐ Otros______________________

☐ no sabe, no contesta

5) ¿Cuántas variedades cultiva Usted?

Variedades por año _____ o por temporada_____

☐ no sabe, no contesta

6) ¿De qué depende, qué variedades se siembran/ se cultivan/ se preparan?

(Por favor, indique la relevancia con 3=muy relevante, 2=regular, 1= insignificante o utilice sus propias palabras)

Precio (Situación de la economía general) ____

Clima (de la temporada pasada)____

Mano de obra ____

Otro (Texto libre)____

☐ no sabe, no contesta

Comentarios:____

7) ¿Cuándo deciden qué variedades cultivan en la siguiente temporada?

Mes : __________ ☐ no procede

¿Cuáles son los criterios para la elección de la variedad de cultivo?

☐ no sabe, no contesta

8) Cuántas veces ha cambiado Usted el cultivo principal a lo largo de los últimos 10 años? (por ejemplo cambio de cultivo de trigo a cultivo de hortalizas)

___________ veces

¿Cuáles han sido las razones?

☐ no sabe, no contesta

9) ¿Utiliza Usted abono?

☐ siempre ☐ con frecuencia ☐ periódicamente ☐ raramente ☐ nunca

☐ no sabe, no contesta

En caso de sí, ¿utiliza?

☐ abono orgánico o o ☐ abono químico?

10) ¿Con qué frecuencia sufre malas cosechas?

☐ cada año ☐ varias veces a lo largo de 5 años

☐ una vez o menos a lo largo de 5 veces ☐ nunca

☐ no sabe, no contesta

¿Cuál es la razón principal para la mala cosecha?

11) ¿Para quién/ qué mercado produce Usted?

Múltiples respuestas posibles:

☐ Uso propio ☐ Compradores regionales ☐ Compradores extraregionales

☐ no sabe, no contesta

12) ¿Es Usted agricultor a título principal? ☐ Si ☐No

☐ no sabe, no contesta

Irrigación / Comunidad de regantes

13) ¿Forma Usted parte de la Comunidad de regantes de Vélez Blanco?

☐ si ☐ no ☐ lo fui

☐ no sabe, no contesta

14) ¿A qué „fuente de agua" pertenece?

☐ Balsa Alara ☐ Hilas de Turruquena ☐ Río de Argan ☐ Hila de la Unión
☐ Hilas de Conceje ☐ otros: ________________________

☐ no sabe, no contesta

15) ¿En qué parte de la Vega están sus campos de cultivo ubicados?

☐ Parte superior, cerca de Vélez Blanco ☐ Parte central
☐ Parte inferior, cerca del Río Claro

☐ no sabe, no contesta

16) ¿Con qué frecuencia asiste a las subastas de agua?

☐ Una vez al año o menos ☐ entre 2 y 5 veces al año ☐ más de 5 veces ☐ nunca
☐ no sabe, no contesta

¿Con qué frecuencia consigue comprar agua en las subastas (a lo largo de un año)?

☐ siempre ☐ con frecuencia ☐ de vez en cuando ☐ pocas veces ☐ nunca

☐ no sabe, no contesta

17) ¿Cuál ha sido el precio más alto que Usted ha pagado por el agua en la subasta)

_________ (¿€ o Pts.?) ______Indicar horas

☐ no sabe, no contesta

18) ¿Le parecen demasiado alto los precios del agua?

☐ Si ☐ No

☐ no sabe, no contesta

En caso de sí, ¿cuál es la razón según Usted?

____

____

____

19) ¿Necesita cada año el agua adicional de las subastas?

☐ Si ☐ No

☐ no sabe, no contesta

20) ¿Qué cantidad y con qué frecuencia le pertenece agua para regar sus tierras, independientemente de las subastas? (Cantidad en horas y minutos)

____

____

____

☐ no sabe, no contesta

21) ¿Cómo valora el funcionamiento de la Comunidad de Regantes?

☐ Bien ☐ Regular ☐ Mal

☐ no sabe, no contesta

Comentarios:

____

____

____

22) ¿Cómo de satisfecho es Usted con el sistema de la Comunidad de Regantes? ☐ satisfecho ☐ neutro ☐ insatisfecho

☐ no sabe, no contesta

Comentarios; ¿cuáles son los problemas?:

____

____

____

Agua /Infraestructura

23) ¿Con qué frecuencia revisa/ restaura Usted las acequias de su tierra?

☐ varias veces al año ☐ aproximadamente una vez al año
☐ cada 5 años o menos ☐ nunca

☐ no sabe, no contesta

24) Cuando tiene agua, ¿lo riega todo directamente o almacena una parte del agua en una balsa privada?

☐ Riego inmediato ☐ Almacenamiento en balsa

☐ no sabe, no contesta

25) ¿Con qué frecuencia revisan/ restauran sus bancales?

☐ varias veces al año ☐ aproximadamente una vez al año
☐ cada 5 años o menos ☐ nunca

☐ no sabe, no contesta

26) ¿Cultiva también en secano?

☐ Si ☐ No

En caso de sí, ¿cómo se distribuye la superficie entre secano y regadío?

_____% Secano

_____% Regadío perteneciente al sistema de regadío de Vélez Blanco

_____% Regadío independiente del sistema de regadío de Vélez Blanco

☐ no sabe, no contesta

27) Existen estudios que demuestran que se puede conseguir una mayor cosecha si los árboles no se riegan. ¿Qué opina Usted de éso?

____
____
____
____
____
____
____

☐ no sabe, no contesta

28) ¿De qué grado su tipo de cultivo es tradicional o moderno (automatizado)?

☐ Muy tradicional ☐ en gran parte tradicional ☐ equilibrado entre tradicional y moderno
☐ más bien moderno ☐ muy moderno

☐ no sabe, no contesta

¿Le gustaría cambiarlo?

____

____

____

____

____

29) ¿A lo largo de los últimos 10 años, ha Usted realizado alguna modernización en sus campos de cultivo? (p. Ej. Instalación de un sistema de riego por goteo o construcción de una nueva balsa)

☐ Si ☐ No ☐ no sabe, no contesta

En caso de sí, ¿cuáles?

____

____

30) ¿Que opina Usted de los pozos profundos?

____

____

____

____

____

☐ no sabe, no contesta

31) ¿Piensa Usted que el clima está cambiando?

☐ Si, para mejor ☐ Si, para peor. ☐ No, en absoluto.

☐ no sabe, no contesta

Muchas gracias.

Appendix V: Additional results of the expert interviews

To gather information about agricultural practices within the Vega of Vélez Blanco, local farmers were interviewed. The interviews were conducted with 27 male and 3 female farmers who cultivate agricultural land within the Vega. The average age of the interviewees was 58 and ranged from 38 to 83. Half of the interviewees are full-time farmers; for the others, farming provides only a supplementary income. The average household size of a family who practice farming is about 4 persons. Of the farmers surveyed, 97% stated that their family has held the land for more than 25 years; only 3% of the landowners purchased their land plot during the past 25 years. Ninety percent of the farmers hold more than 1 ha of arable land. With only one exception, all farmers cultivate olive groves (Fig. 1). Hence, olives are the main agricultural good cultivated within the Vega of Vélez Blanco. Behind olives rank various vegetables such as potatoes, pepper, and broccoli (Fig. 2 b). One third of the vegetable cultivation is for subsistence farming; the remainder is sold at regional and supraregional markets. The same applies to the cultivation of fruits. The main fruits cultivated are apricots, plums, and pears (Fig. 2 a). At least half of the farmers also stated that they maintain almond groves. Of rather minor importance is the cultivation of grain and other goods such as vine or alfalfa (Fig. 2 c & d). The survey also shows that 95% of the farmers within the Vega of Vélez Blanco usually cultivate at least five different agricultural goods on their farmland. The decision about which ones to cultivate is mainly influenced by the average market price of the agricultural product and by the local climate conditions. Nevertheless, traditional practices are also a key deciding-factor for a quarter of the questioned farmers. The survey also shows that about 50% of the farmers suffer from harvest failures on a regular basis usually once every five years. The interviewees stated that the main reason for the crop losses is water scarcity. This includes the general lack of precipitation as well as shortage of irrigation water. Further details are available in section 5.4.

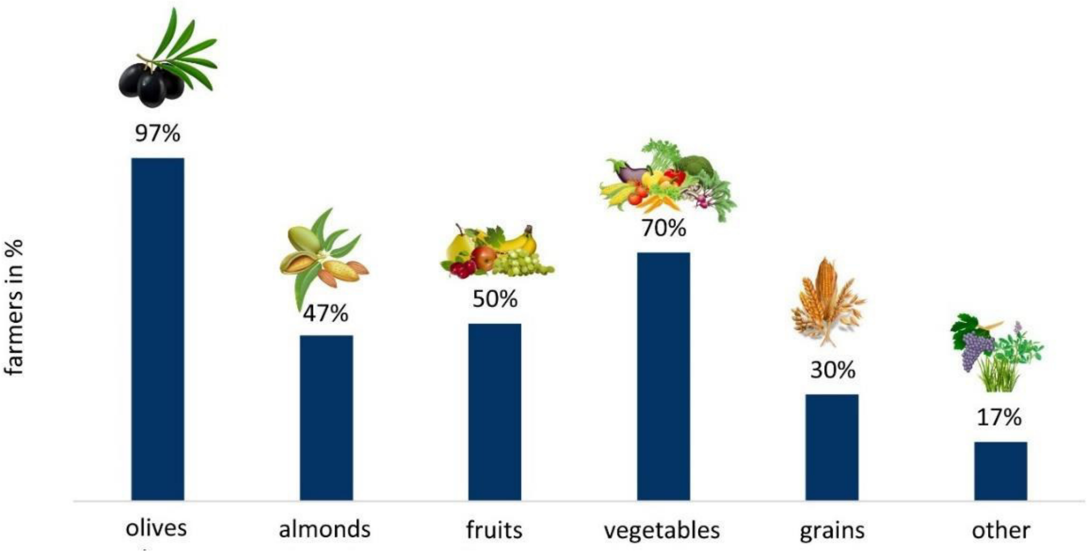

Fig. 1: Chart of the percentage of agricultural products on overall farming in the Vega of Vélez Blanco. Information was conducted by a survey of 30 local farmers.

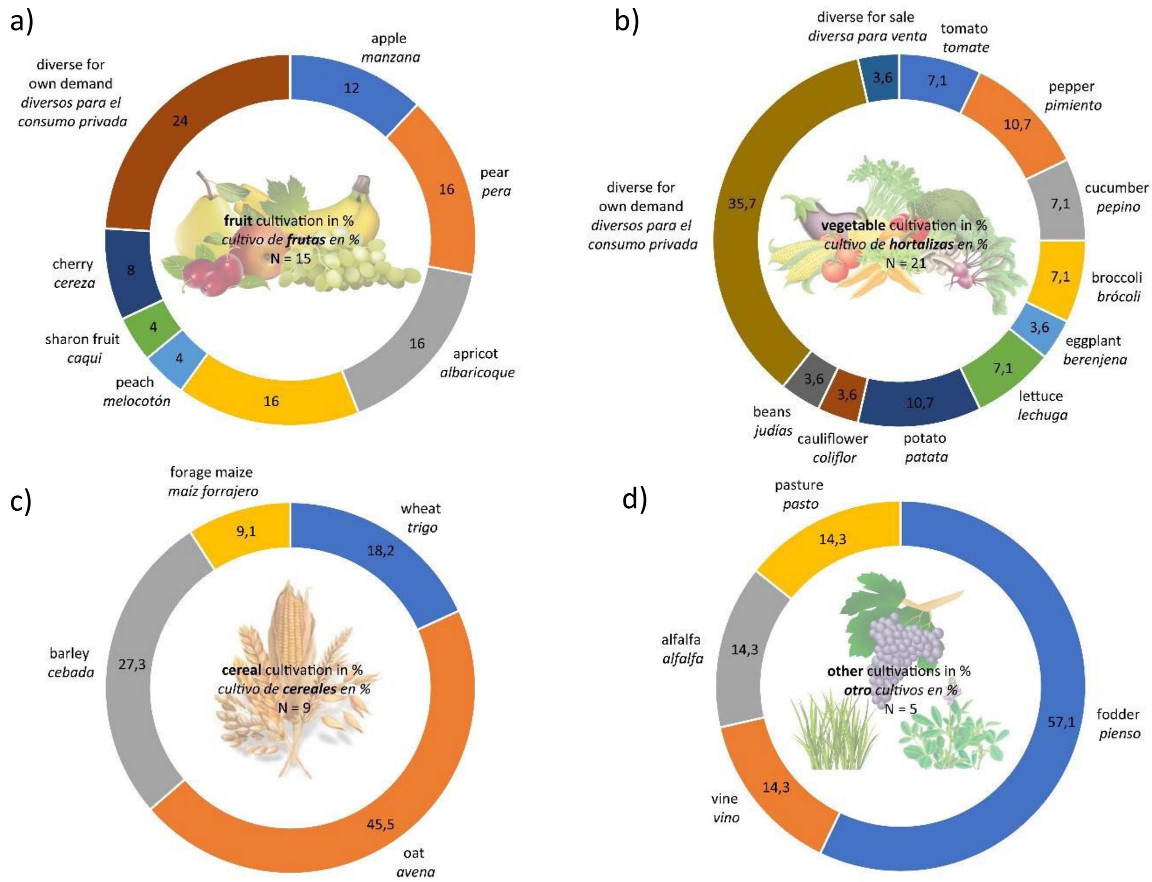

Fig. 2: Overview and subdivision of cultivated goods within the Vega of Vélez Blanco based on main product groups. a) Fruit cultivation: Percentage of products among 15 farmers. b) Vegetable cultivation: Percentage of products among 21 farmers. c) Cereal cultivation: Percentage of Products among 9 farmers. d) Other cultivations: Percentage among 5 farmers.

Appendix VI: Affidavit

Affidavit/Eidesstattliche Erklärung

Hiermit erkläre ich, Sarah Katharina Ißelhorst, dass ich die Dissertation *Historical Water Management in SE-Spain – with a focus on traditional irrigation strategies in NE Andalusia* selbstständig angefertigt und keine anderen als die von mir angegebenen Quellen und Hilfsmittel verwendet habe.

Ich erkläre weiterhin, dass die Dissertation in dieser oder anderer Form in keinem früheren Promotionsverfahren, sondern erstmalig am Fachbereich Geowissenschaften der Freien Universität Berlin eingereicht habe.

Schenefeld, den 10.12.2019