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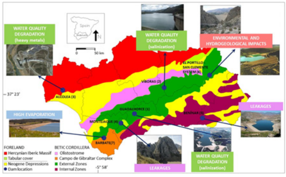
Graphical Abstract

Learning from hydrological and hydrogeological problems in civil engineering. Study of reservoirs in Andalusia, Spain

pp. xxx – xxx

Verónica Ruiz-Ortiz*, Santiago García-López, Mercedes Vélez-Nicolás, Ángel Sánchez-Bellón, Antonio Contreras de Villar, Francisco Contreras



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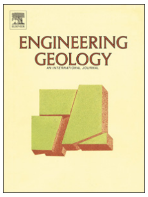

Highlights

Engineering Geology xxx (2020) xxx –xxx

Learning from hydrological and hydrogeological problems in civil engineering. Study of reservoirs in Andalusia, Spain

Verónica Ruiz-Ortiz[a,*], Santiago García-López[b], Mercedes Vélez-Nicolás[b], Ángel Sánchez-Bellón[b], Antonio Contreras de Villar[a], Francisco Contreras[a]

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- Eight case histories of Andalusian reservoirs with hydrological and hydrogeological problems are analyzed.
- Leakage, salinization, acidification, high evaporation losses and water transfer problems are identified
- More rigorous and multidisciplinary research would prevent detrimental economic, social and environmental impacts.
- How to learn from past mistakes to avoid failure in future hydraulic engineering projects.
- Incorporation of the joint use of surface-groundwater in hydrological planning and management are a necessity.

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Supplementary material 1

Supplementary video 1

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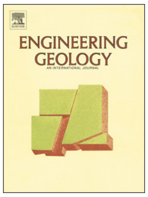

Learning from hydrological and hydrogeological problems in civil engineering. Study of reservoirs in Andalusia, Spain

Verónica Ruiz-Ortiz [a,*], Santiago García-López [b], Mercedes Vélez-Nicolás [b], Ángel Sánchez-Bellón [b], Antonio Contreras de Villar [a], Francisco Contreras [a]

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ABSTRACT

This study presents a novel review of seven case histories of Andalusian reservoirs (Southern Spain) affected by different hydrological and hydrogeological problems that have led to severe malfunctions. The failures reported are related to (i) water quality degradation due to salinization and acid mine drainage, (ii) leakage in karstified terrains, (iii) environmental and hydrogeological impacts associated with an inadequate water planning and (iv) large evaporative losses from the reservoir. Detailed information on the geological context, hydrological/hydrogeological origin of the problem, repercussions on infrastructure functioning and remedial measures applied or proposed has been gathered for each case. Results of on-site research carried out by the authors in some of the locations studied and a comparative analysis of similar case histories at international level are also included. The purpose of this work is to emphasize the need of learning from past mistakes and provide guidance for future dam construction works, especially in the Mediterranean region. It also highlights the role of geological and hydrogeological research in dam sitting and the consequences of inadequate terrain characterisation, biased hydrological planning and data misinterpretation or undervaluation. This review evidences the need of conducting comprehensive studies that do not only focus on the infrastructure itself, but also on non-constructive aspects (monitoring of geological features and hydrological variables) and relevant processes (e.g. leakage, salinization and contamination) that might compromise the efficient functioning of the infrastructure.

Contents

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1. Introduction

Achieving a sustainable and efficient management of water resources while ensuring the protection of freshwater environmental values is a mounting concern in developed societies. In Spain, water management must be adapted to the uneven time-space distribution of pluviometry and dams play a key role in planning schemes. In this country, the traditionally scarce knowledge about hydrogeological systems resulted in a widespread "dam culture" at a national scale and to the construction of numerous hydraulic infrastructures (more than 1200 large dams) aimed at achieving an extensive regulation of surface water resources (Ruiz et al., 2016). This management model has traditionally stirred up controversy among dam advocates, who regard them as engines of economic and social development despite their environmental costs (García-López et al., 2018), and their detractors (Sallam et al., 2018; Wu et al., 2019).

Dams are complex infrastructures built for different purposes such as meeting water and energy needs, or protection against floods. Their specific features are defined by the physical environment (especially by topographic and geological aspects), technical limitations, the expected functionality and by economic, social and environmental constraints. Although most of these hydraulic infrastructures worldwide fulfil their functions satisfactorily, different combinations of factors may potentially result in dam failure, damages and reduction of useful life. There are several examples of construction defects and other deficiencies that have threaten the integrity of people, ecosystems and of the infrastructures themselves (Alcrudo and Mulet, 2007; Prieto Calderón et al., 2017; Glotov et al., 2018; Ibanez and Hatzor, 2018). However, the most abundant cases are those of poor-functioning infrastructures owing to the geological and hydrological conditions. The main deficiencies in these large dams are related to water contamination/degradation (Jalali et al., 2019; Peng et al., 2020); leakage from the impoundment structure (Turkmen et al., 2002; De Waele, 2008; Dong et al., 2016; Shangxin et al., 2020); severe environmental and hydrogeological impacts on the natural system that compel to change the initial hydrological plans (Micklin, 2011), or the inability to store the resource due to high direct evaporation from the surface (Nguyen et al., 2020).

Although individualized studies on certain reservoirs and their issues have been carried out in recent decades, few provide a comprehensive review of case histories with different problems and the lessons to be learned from them. Sojka et al. (2017) provide a classification of the functioning and operation problems of several dams located in a province of Poland. The authors divide them into (i) technical (dam failure, water release elements failure, damage of reservoir embankments and failure of other structures like hydroplants), (ii) non-technical (loss of water resources, water quality degradation, sediment accumulation, vegetation growth and cyanobacterial blooms) or administrative (reservoir operation) depending on their origin. Habets et al. (2018) conduct a review on the cumulative impacts of small reservoirs on water resources from a quantitative point of view (seepage, evaporation etc). In addition, Flagg (1979), Sharma and Kumar (2013) and Talukdar and Dey (2019) report case histories of several dam failures and accidents motivated by a poor understanding of geology and the conclusions drawn from each of them.

Learning from a region's reservoir history and failures may provide valuable insights and tools for a more efficient planning and future dam development. For this reason, this study presents for the first time a comprehensive review of Andalusian reservoirs (Southern Spain) with a range of hydrological and hydrogeological problems that resulted in serious operating deficiencies. The 7 selected case studies include (i) reservoirs with serious problems of water quality degradation due to salinization (Guadalhorce (1) and Víboras (2) reservoirs) and mining-related contamination (Alcolea reservoir (3)), (ii) infrastructures with substantial water losses owing to leakage (Montejaque (4) and Benínar (5) reservoirs), iii) a water transfer project with such dramatic environmental impacts that compelled to modify the projected hydrological planning (El Portillo-San Clemente system (6)) and iv) excessive evaporation losses from the flooded surface of the reservoir (Barbate reservoir (7)). This paper, the first of its kind at national (Spain) and international level from a hydrological and hydrogeological perspective, has a twofold purpose. Firstly, to describe the causes and consequences of some of the most notorious dam failures in Andalusia by presenting the history of events through an exhaustive bibliographic compilation (including historical archives of difficult access) and graphic and visual material produced by the authors. Secondly, to provide lessons and guidance for future dam construction works by highlighting the role of geological and hydrogeological research in dam sitting and the consequences of inadequate hydrogeological investigation, planning or data misinterpretation, which may result in severe malfunctions.

2. Andalusian geological context

Andalusia, with an area of 87.270 km^2, is the southernmost region of the Iberian Peninsula. Most of its surface is occupied by the Betic Cordillera, which is the most western stretch of the Alpine orogen. This orogen was formed during the Tertiary period by the folding of allochthonous materials caused by the approach of the African plate towards the southern edge of the European plate. Numerous studies have dealt with the geological configuration of this area, among which it's worth to mention the great synthesis compiled by Vera (2004) (Fig. 1).

The foreland of the northern edge of the Betic Cordillera is the Iberian Massif, which is made up of three different structural domains (Southportuguese Zone, Ossa-Morena Zone and Centroiberic Zone) in this region and presents deformed igneous and metamorphic materials from the Precambrian and Paleozoic periods. In the eastern sector of the Iberian Massif outcrops a tabular cover of unfolded Meso-Cenozoic sediments. In the Southportuguese Zone, there is an underwater volcano-sedimentary complex that underwent hydrothermal alteration, giving rise to one of the most important deposits of polymetallic sulphides in the world. These mineral resources have been exploited from Roman times to the present day and forms the so-called Iberian Pyrite Belt (hereinafter IPB). The numerous mines located in this complex profoundly affect the quality of the run-off water and consequently, that of the planned Alcolea reservoir (3).

There is a foreland basin located between the Betic Cordillera and the Iberian Massif. The basin is associated with the main river valley in the region (River Guadalquivir), which was filled with postorogenic sediments from the surrounding reliefs during the Neogene and Quaternary. There are also other important intramountain depressions in the Betic Cordillera, such as that of Granada.

Within the Betic Cordillera, three large geological units can be differentiated; the External Zones, the Campo de Gibraltar Complex and the Internal Zones. These are made up of tectonic units that have undergone large displacements from their original sedimentation site to their current position.

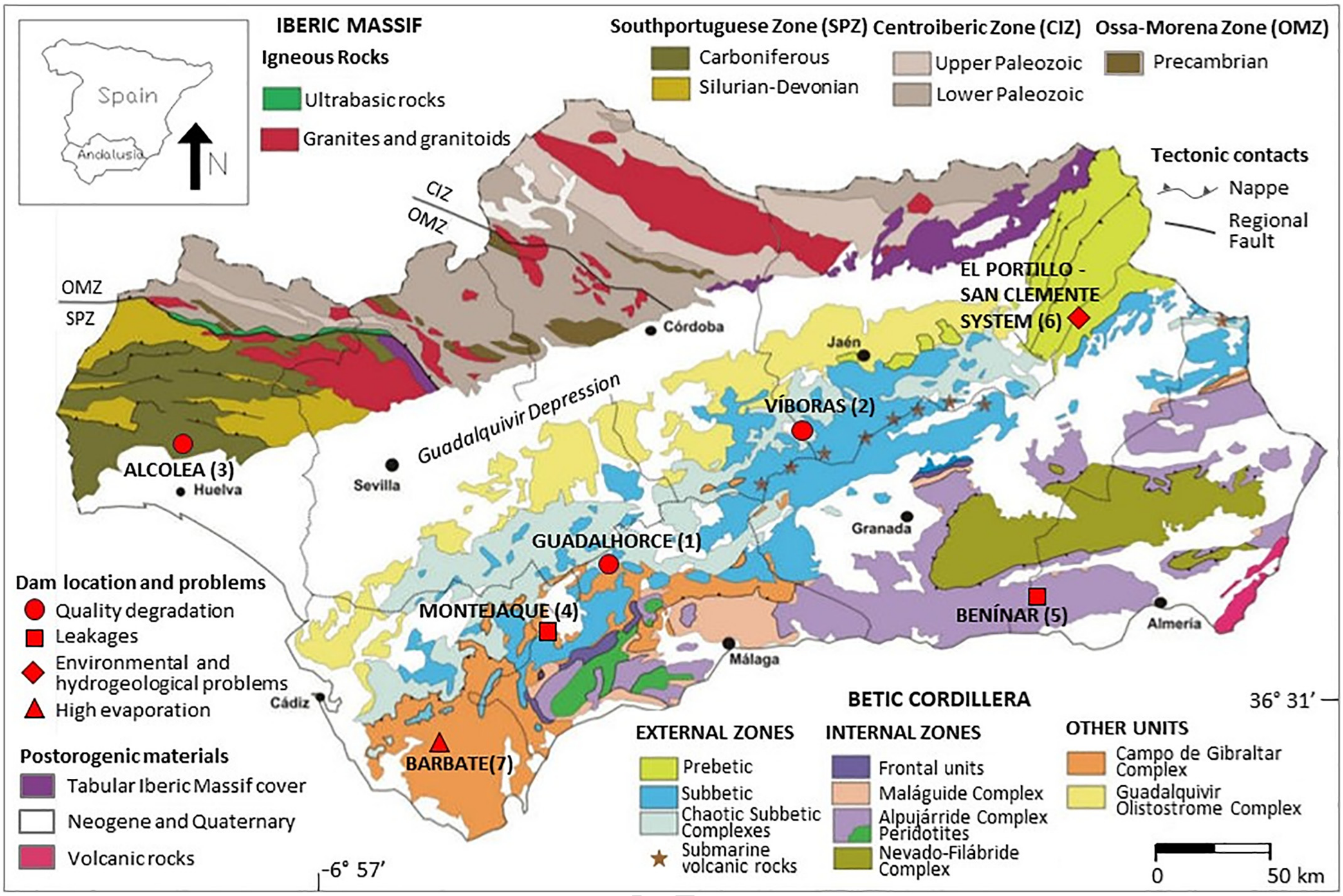

Fig. 1. Andalusian geological context (modified from Vera (2004)).

The External Zones emerge immediately to the south of the Guadalquivir Depression and are divided into two large domains: the Prebetic, which is moderately allochthonous and slightly deformed, and the Subbetic, which thrusts the Prebetic and is markedly allochthonous and intensely deformed. Carbonate rocks of Jurassic age are abundant in this domain and constitute important aquifers subject to karstification processes that sometimes seriously affect the local reservoirs; this is the case of the Montejaque reservoir (4) and El Portillo-San Clemente system (6). In very extensive sectors, the deformation has caused the loss of structural continuity, brecciation and the mixing of materials, giving rise to a unit known as the Subbetic Chaotic Complexes (SCC). This unit is basically made up of a clayey matrix that contains large blocks and olistolites of materials of different ages (Triassic to Miocene) and nature (gypsum and halite, dolomites, limestone, sandstone and sub-volcanic rocks). The dissolution of the soluble minerals (evaporites) of these materials degrades the quality of the run-off water (sometimes substantially) and are responsible for the quality problems of the reservoirs located above them, as is the case of Guadalhorce (1) and Víboras (2).

The Campo de Gibraltar Complex outcrops in the southwestern sector and is mainly made up of deep marine sediments (turbidites, clays and loams of Mesozoic and Neogene age) which have been heavily tectonized. They have flysch facies and were deposited in a groove originated during the Mesozoic, between the External and Internal Zones on oceanic crust that subsequently suffered subduction. In this domain, the Barbate reservoir (7) is located in a mature valley, what conditions its morphology.

Finally, the Internal Zones that emerge in the southernmost area, next to the Mediterranean Sea, is the most allochthonous and deformed geological unit of the mountain range and has also suffered Alpine metamorphism. The whole has an antiformal disposition with an altitude of more than 3.400 m and a very complex structure of superimposed nappes that produce repetitions vertically. The deformation of the Internal Zones even affects the deep continental crust and the upper mantle, giving rise to the outcrop of peridotite rocks. The domain is subdivided from bottom to top into three complexes: Nevado-Filábride (high-grade metamorphism), Alpujárride (medium-grade metamorphism) and Maláguide (low-grade metamorphism) plus a Frontal Unit in contact with the External Areas. The Benínar reservoir (5) is located within one of these complexes, concretely in the Alpujárride, which consists of a powerful Triassic-age limestone formation, with phyllites, quartzite and gypsum at its base and a complex tectonic structure of imbricated overthrusting belts in a compressive context.

With regard to the hydrography, the Andalusian region is structured into an extensive fluvial basin that crosses the territory from NE to SW (Guadalquivir river) and a set of minor basins that drain either towards the Mediterranean Sea or to the Atlantic Ocean. The basins draining towards the Mediterranean collect runoff from the southern slope of the Betic r and present pronounced reliefs. The 24% of the Andalusian area is occupied by permeable terrains of which the 60% correspond to detrital aquifers and 40% to calcareous ones. The latter type coincides with the reliefs of interior and coastal mountain ranges.

3. Summary of the details and problems of the studied reservoirs

This research work presents 7 cases of malfunctioning reservoirs from Andalusia (Southern Spain) (Fig. 1). The studied infrastructures are affected by different geological formations and processes. . Except for one, all the dams are state-owned. The age and typology of these infrastructures are diverse, including both embankment dams made of natural materials (earth fill and rock fill) and concrete dams that were built between 1920s and the present time. The dams included in this work are of considerable structural height, with values between 30 and 91.5 m from the crest to the foundation, and storage capacities between 19 and 274 hm^3. The main characteristics and type of problems of each case reservoir are detailed in Table 1.

4. Water quality degradation

4.1. Guadalhorce reservoir (Case 1)

The Guadalhorce dam is part of a multi-reservoir system constituted by three nearby dams that supply water to the city of Malaga: Conde de Guadalhorce, (74 hm^3) built in 1921 and enlarged in 1947, Guadalteba (150 hm^3) built in 1972 and Guadalhorce (135 hm^3) built in 1973. While the Guadalteba and Conde de Guadalhorce reservoirs lack significant water quality problems, Guadalhorce has undergone a severe salinization process that has made its water resources unusable for the intended purposes. The reason is that the tail-end of the reservoir receives hypersaline water from a set of springs that belong to one of the most important evaporite karst complexes in Spain, the aforementioned SCC, and more specifically, from the unit known as "Trias de Antequera" (Vera, 2004).

These materials have traditionally been considered as aquitards owing to the low permeability of the matrix, which is made of clay and fine sand, and contains blocks of various lithologies. However, the presence of conduits generated by dissolution processes within the evaporite blocks (gypsum and halite), which are strongly tectonized and very abundant locally, concentrates and speeds up the water flow, giving rise to a typically karstic behaviour. The lithological complexity of the CSC determines its hydrogeological heterogeneity, with groundwater pathways of different length and various scales from recharge areas to discharge zones (Andreo et al., 2016).

In the study area, numerous ponds, dissolution dolines, collapse structures, cavities and chasms have been identified (Fig. 2a). According to geological and hydrogeological evidences, Calaforra and Pulido-Bosch (1999), proposed the hypothesis on the existence of two halokinetic structures with subcircular morphology (diapirs) in both sides of the tail-end of the Guadalhorce reservoir. In this context, the above-mentioned set of hypersaline springs constitute the discharge pathways of the hydrogeological system. The conceptual model of the functioning of this sector considers distinct underground flows with different characteristics (Fig. 2b). Local flows are characterised by short pathways and are originated by infiltration of recent rainwater through the permeable materials around the springs. Intermediate flows are preferably developed along the karst network, are fed mainly through dolines and sinkholes and produce medium-mineralized water and sulfated calcium facies. These flows respond quickly to large recharge events. Finally, the deepest flows, have longer residence times and are originated in the areas most distant from the springs, producing water of higher mineralization and temperature with sodium chloride facies. These flows are responsible for the discharge of brines through springs even during droughts (Andreo et al., 2016). The application of environmental dating tracers (3H, 3He, 4He, CFC-12, SF6) and hydrochemical data has been recently proposed to corroborate this conceptual model (Gil-Márquez et al., 2020).

Of the springs associated to the "Trias de Antequera", Meliones spring (Fig. 2b) is the most important owing to its higher flow and salinity. The Meliones spring is located next to the Guadalhorce riverbed (345 m.a.s.l), below the maximum normal level and is usually covered by the water of the reservoir, what constitutes an important obstacle to its management and eradication (Carrasco Cantos, 2018). It has sodium-chloride type facies and the electrical conductivity reaches 200 mS/cm (four times greater than that of the sea) (Andreo et al., 2016). In fact, owing to these characteristics, the springs were traditionally exploited for the extraction of sodium chloride since ancient times. The amount of salt evacuated by the set of springs was estimated at 470 t/day on average for the period 1981–2003 (Durán-Valsero, 2007). This means a significant additional salt input (3.7 g/l) that is attributable to the saline discharge from the springs in that period.

The existence of the hypersaline springs was already known since the beginning of the construction of the Guadalhorce dam. Nonetheless, the resolution of the problem was postponed without implementing a corrective measure plan. Once the dam was built, these measures proved to be very difficult to apply. In light of the course of events, the project team did not properly assess the impact that this phenomenon would have on the operation and utility of the infrastructure.

Table 1
Summary of main characteristics, geological context and problems of the studied dams (own elaboration using information from: https://sig.mapama.gob.es/snczi/ and bibliographic research).

	GUADALHORCE (1)	**VIBORAS (2)**	**ALCOLEA (3)**	**MONTEJAQUE (4)**	**BENINAR (5)**	**EL PORTILLO-SAN CLEMENTE SYSTEM (6)**		**BARBATE (7)**
River	Guadalhorce	Víboras	Odiel	Guadares	Adra	Castril	Guardal	Barbate
Geologic context	SCC, External Zones (Betic Cordillera)	SCC, External Zones (Betic Cordillera)	IPB, Sud-portuguese Zone (Iberic Massif)	Subbetic, External Zones (Betic Cordillera)	Alpujárride Complex, Internal Zones (Betic Cordillera)	Prebetic, External Zones (Betic Cordillera)		Campo de Gibraltar Complex (Betic Cordillera)
End of works	1973	1997	Under construction	1924	1983	1999	1990	1992
Tipology	Embankment	Arch-Gravity	Gravity	Double curved arch	Embankment	Embankment		Embankment
Ownership	Public	Public	Public	Private	Public	Public		Public
Function	Water supply; hydroelectric	Water supply; irrigation	Irrigation, safety; environmental adaptation	Hydroelectric	Water supply; irrigation; safety	Irrigation; hydroelectric	Irrigation	Irrigation
Height from foundation (m)	75	48.5	61	83.75	87	83	91.5	30
Capacity (hm^3)	126	19	274	36	68	33.5	120	231
Runoff (hm^3/year)	59	57	31	25	45	115	31	125
Problem	Water quality degradation (salinization)	Water quality degradation (salinization)	Water quality degradation (heavy metals)	Leakage	Leakage	Environmental and hydrogeological impacts		High evaporation

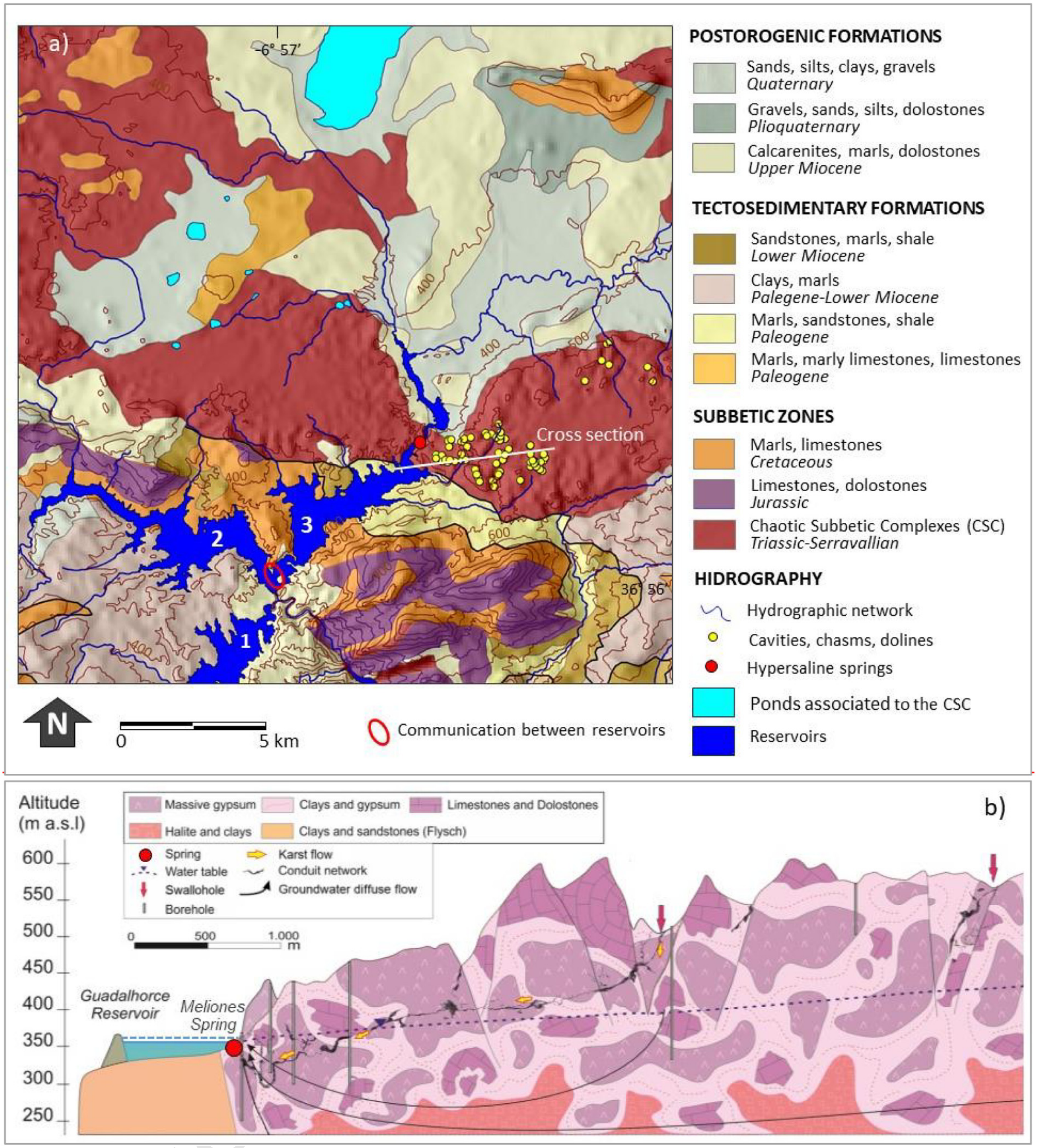

Fig. 2. a) Geological map of the multi-reservoir system that supply water to Malaga. The position of the interpretative cross section shown in b) is indicated (1: Conde de Guadalhorce reservoir, 2: Guadalteba reservoir, 3: Guadalhorce reservoir) (own elaboration using information from http://www.juntadeandalucia.es/medioambiente/site/rediam). b) Cross section and conceptual model of the hydrogeological functioning of the Trias de Antequera for the Meliones sector (modified from Andreo et al., 2016).

In fact, a major design fault was committed: the vessels of the Guadalteba and Guadalhorce dams, both adjacent and simultaneously built in the decade of the 60's, were communicated. Above certain level, due to topographic reasons, the saline waters of Guadalhorce overtopped the reliefs that separate both vessels and entered in Guadalteba. This situation worsened the problem, causing an impoverishment of the water quality in Guadalteba and compelling to the subsequent construction of a separation dyke (see Fig. 2a). Besides, this circumstance hindered the operation of the reservoirs and the obtention of water of adequate quality to supply the urban areas (Contreras et al., 2016). In fact, while the water level in the Guadalteba tended to decrease due to urban consumption (especially during drought periods), the level in the Guadalhorce reservoir increased because its resources couldn't be exploited. This situation forced, between 2003 and 2005, to evacuate through the river about 100 hm^3 of brackish water from the Guadalhorce reservoir to the sea. That large volume of water was released during rainy periods to reduce the negative environmental effects of brine on the riparian system. One year later, there was a severe drought that led to major restrictions on the supply of the city of Malaga. On the other hand, the regulation of the basin and the channelization of the Guadalhorce River mouth downstream the reservoir carried out in 2003 led to the degradation of the aquifer downstream the dam. This aggravated the supply problems in the metropolitan area (Nieto-López et al., 2020) and indirectly led to address the issue, as explained below.

Numerous attempts were made to solve the problem of salinization in the Guadalhorce reservoir. Troyano and Díaz (2006) and Carrasco Cantos (2018) give a detailed description of the measures adopted, which comprised the following: (i) 1985–1987: Pumping the water of Meliones to evaporation ponds located at a higher site, in the Cañaveralejo area. This initiative failed because the evaporation ponds had infiltration problems and part of the water returned to the reservoir. (ii) 1993: Collect the brine prior to its entry into the reservoir by isolating the discharge area with a sheet pile screen and pumping it to the sea through a pipeline (approximately 50 km long and 300 m elevation). The system could pump up to 75 l/s and came to reduce the salt inputs to 1/3 during dry periods, however, this measure was insufficient during very rainy periods when the discharge from the evaporitic karst increased significantly. This strategy was finally truncated by the collapse and subsidence of the immediate surroundings of the catchment and the breakage of the pipeline owing to landslides. This last event resulted in large spills of hypersaline water. (iii) 1998: Reduce the hypersaline discharge by waterproofing the dolines to prevent the entry of runoff. These works were not concluded due to environmental problems and only gave partial results because runoff tended to find new infiltration pathways into the karstic flow network, whose evolution and rate of change is very rapid. iv) 2004: Isolating Meliones by constructing one dam (20 m height) upstream and another downstream (30 m height) the spring. Then, the brine would be stored in the space between both dams and subsequently pumped to the sea through a pipeline. This scheme was finally rejected owing to the high cost and the uncertain results it may yield. (v) 2005: Finally, the solution adopted was the combined desalination of groundwater from a coastal aquifer and the brackish water from the reservoir in the Atabal water treatment plant, which is located 38 km SE from the Guadalhorce reservoir, in the city of Malaga. Water treatment at this facility, which is equipped with reverse osmosis technology, implied additional energy and economic costs (Andreo et al., 2016; Montalván et al., 2017; Carrasco Cantos, 2018).

4.2. Víboras reservoir (Case 2)

The Víboras dam (19 hm^3) is located in the province of Jaén (see Fig. 1) on the river of the same name, which is a tributary of the Guadalquivir River. This reservoir receives discharge from four karstic aquifers and from the runoff of the basin (57 hm^3/year). The intended functions of this infrastructure was urban supply and irrigation, however, severe quality problems were identified after the completion of the construction works.

Part of the reservoir vessel and most of its catchment area are located in the outcrops of the SCC, described above (see section 2), where the geological materials are mostly Triassic, contain mainly clays with gypsum (locally halite), and olistolites of limestones, subvolcanic rocks, marls and sandstones (Fig. 3). These evaporitic minerals (gypsum and halite) undergo dissolution processes when meteoric water and runoff leach the soil and infiltrate through the permeable layers of this formation, leading to an impoverishment in the quality of its water.

Although the Víboras reservoir was initially conceived as an independent management system, the poor quality of its resources forced the Administration to introduce significant changes in the initial planning (González-Ramón et al., 2002). Finally, Víboras reservoir was connected to a nearby system constituted by the Quiebrajano reservoir (which has minor leakage problems) and a set of aquifers, through a reversible conduction and two Water Treatment Plants (WTP) with osmosis desalination (Murillo and Navarro, 2008). Despite these measures and the investment made in the Quiebrajano-Víboras system, the optimal operation of the scheme has not yet been achieved (Lechuga et al., 2012). There are several studies that deal with this issue, such as the one by Murillo and Navarro (2008), who analyzed the system considering two simulation scenarios: In the first scenario, they assumed that both subsystems, Quiebrajano and Viboras, were independent, and in the second one, that they were connected. For the second scenario, 3 alternatives were considered; (i) A situation in which the Viboras reservoir was not operating, (ii) To carry out waterproofing works in the Quiebrajano reservoir and (iii) Discarding the operation of the Viboras reservoir and instead, pumping boreholes upstream. The conclusions of the study were indisputable; the poor quality and high costs associated with pumping to the WTP (what implied an elevation of about 190 m) and desalination meant that the construction of the Víboras reservoir would not have been advisable. However, there were other alternatives based on the extraction of groundwater from the upper basin (carbonate aquifers), which proved to be more advantageous and offered better results from a technical, economic and environmental point of view.

4.3. Alcolea reservoir (Case 3)

The future Alcolea reservoir (274 hm^3 of capacity) will be located on the Odiel River(province of Huelva, see Fig. 1). From a geological point of view, the projected dam is placed in the south-portuguese Zone of the Iberic Massif (see section 2) . Its most relevant feature is the predominance of thick and monotonous detrital series of flyschoid character that date from the Devonian and Carboniferous ages (Fig. 4). These series present a significant acidic and basic volcanism that originated the IPB a formation with one of the highest concentrations of massive sulphides in the Earth's crust (Almodóvar et al., 2019).

The problem of the future reservoir is that the water inputs from the local rivers have an extremely poor quality. The water resources from the River Odiel are acidic (pH = 3,4), with detected concentrations of toxic elements of 74.5 mg/L of Al, 19.6 mg/L of Zn, 12.8 mg/L of Fe, 3.2 µg/L of As, 195 µg/L of Cd, 33 µg/L of Cr, 662 µg/L of Ni and 493 µg/L of Pb (Olías et al., 2011). These metal concentrations were even higher during the hydrological year 2017/2018 (Olías et al., 2020). These extreme conditions derive from the intense mining activity historically carried out within the IPB area, especially in the 19th and 20th century . There are currently about 30 abandoned mines within the Odiel basin containing large quantities of waste with pyrite and other sulphides (Grande et al., 2018). Combined with the atmospheric oxygen, these sulphides produce acid leachates with large amounts of toxic metals that reach the Odiel River network, causing its degradation (Blanco et al., 2013). For instance, in 2017, a spill from a tailing pond resulted in the release of approximately 270,000 m^3 of extremely acidic waters to the Odiel River. Around 53 km of the Odiel River's main course, which was already contaminated by acid mine drainage (AMD), were affected (Fig. 4). The spill resulted in a significant degradation of the quality of the Odiel River (which was already extremely poor) and led to an in an increase of the dissolved concentrations of some metals (e.g. Fe and As) in the rive of up to 450 times the usual levels (Olías et al., 2019).

The objective of the Alcolea reservoir is to guarantee the supply to the city of Huelva, meet the demands of its industrial park and ensure the irrigation of 20,000 ha in the eastern area of the province. The administrative procedure of this project started in 1995. The dam achieved a favourable Environmental Impact Statement based on the forecast of the reduction of contamination by dilution and decantation, which has been questioned by the scientific community (Sarmiento et al., 2009; Olías et al., 2011). The construction of the infrastructure was adjudged in 2008. Later in 2010, the Secretary of State for Rural Environment and Water approved its Feasibility Study without the need of including any type of water treatment system, except for the construction of dykes on specific locations in order to remove contaminated sediments during the summer period. Despite the strong opposition from stakeholders (environmentalist groups, researchers and some politicians) the construction works of the Alcolea reservoir began in 2012. Owing to the acidic environment on which the dam is located, the combined use of concrete additives of hydrophobic properties, fly-ash (pozzolanic

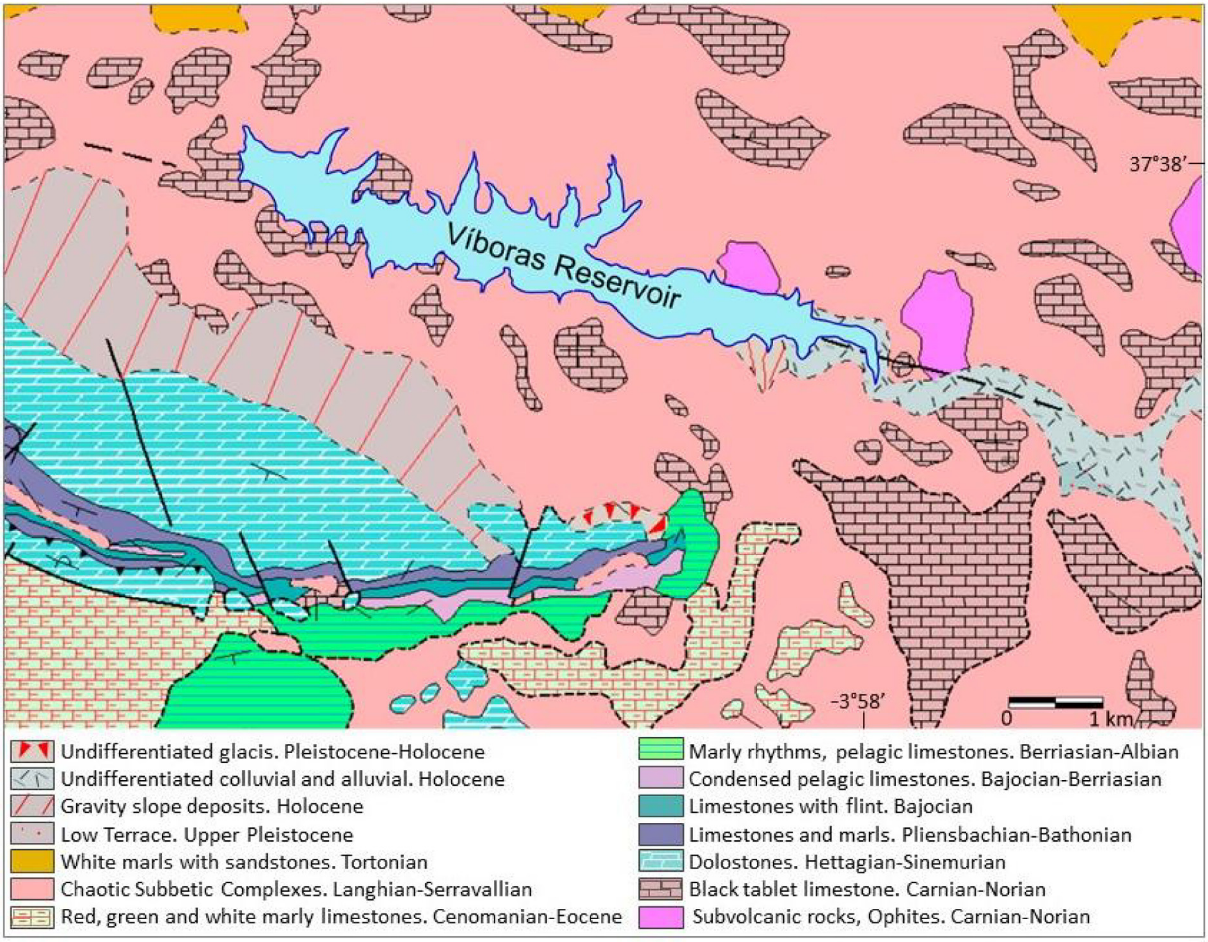

Fig. 3. Geological map of the Víboras reservoir (modified from: Continuous Digital Geological Map of Spain (GEODE, 2004).

additive) and microsilica is being necessary. Furthermore, during the construction and concrete watering works, these unfavourable environmental conditions made it impossible to use river water. The planned investment, including the auxiliary works, is approximately $160\cdot10^6$ €.

While the technicians that are currently working on this project argue that the contamination levels in the reservoir will decrease due to dilution and decantation processes, studies by various authors point out the opposite. Cánovas et al. (2016) simulated the foreseeable chemical evolution of the reservoir through the software PHREEQC. On the other hand, Cerón et al. (2014) took as a reference the nearby reservoir "El Sancho", which presents a maximum pH value of 4.67, high average sulphate levels (7937 mg/L), and high concentrations of Fe, Mn, Zn, Pb and Cu among others. These simulations predicted pH values up to 2.5, therefore, the water resources of the future reservoir would be unsuitable for the intended purposes. In line with this, passive or semi-passive treatments (Caraballo et al., 2011) based on the application of dispersed alkaline substrates (DAS) have been applied for more than a decade in the Odiel River basin producing positive, although absolutely insufficient results. Macías et al. (2017), proposed the implementation of 13 DAS treatment plants in specific areas with inputs of mining pollutants. The objective of these measures is to progressively recover of the Odiel River basin, in accordance with the provisions of the Water Framework Directive and the Hydrological Plan for the District of the Tinto, Odiel and Piedras rivers. As numerous researchers have shown (Olías et al., 2011; Cerón et al., 2014; Cánovas et al., 2016), the construction of the Alcolea reservoir before the implementation of the corresponding corrective measures in its basin is at least a questionable decision and augurs very negative outcomes. Besides, the potential results are difficult to predict, and in any case, in the very long term.

5. Leakage

5.1. Montejaque reservoir (Case 4)

The Montejaque reservoir (36 hm^3) is located in the province of Málaga (see Fig. 1). The dam was built for hydroelectric purposes and was a pioneer structure in its time (year 1924) due to its construction technique (double curved arch) and dimensions (height from foundation of 83.75 m). The dam sits on the canyon eroded by the Guadares River as it enters through the massif formed by the Jurassic limestones of the Libar mountain range (Fig. 5a). Owing to its narrow geometry and the resistance of the rock, the downstream boundary is suitable for a dam of this type from a technical point of view. Nevertheless, the rock formation that extends through the bottom of the impoundment presents a very high permeability as a result of fracturing and karstification processes, which are enhanced by (i) the high solubility of the rock; (ii) its structural arrangement; (iii) the abundant tectonic fractures and finally; (iv) the large amounts of rains (1500 mm/year) in this location (Durán-Valsero, 2007). The area displays numerous exokarst (karren fields, dolines, poljes, sinkholes, blind valleys, ponors, etc.) and endokarst features (caves, chasms, conduits, speleothems and other cave deposits, etc.) (Fig. 5b). In fact, prior to the construction of the dam, the Guadares River infiltrated completely through a ponor called "Hundidero", located at the end of the limestone blind valley (Lechuga et al., 2016). The infiltrated water fed a karstic aquifer that discharges through a spring in the cave known as "Cueva del Gato". The karstic network that comprises these features is known as the 'Hundidero-Gato' speleologic network.

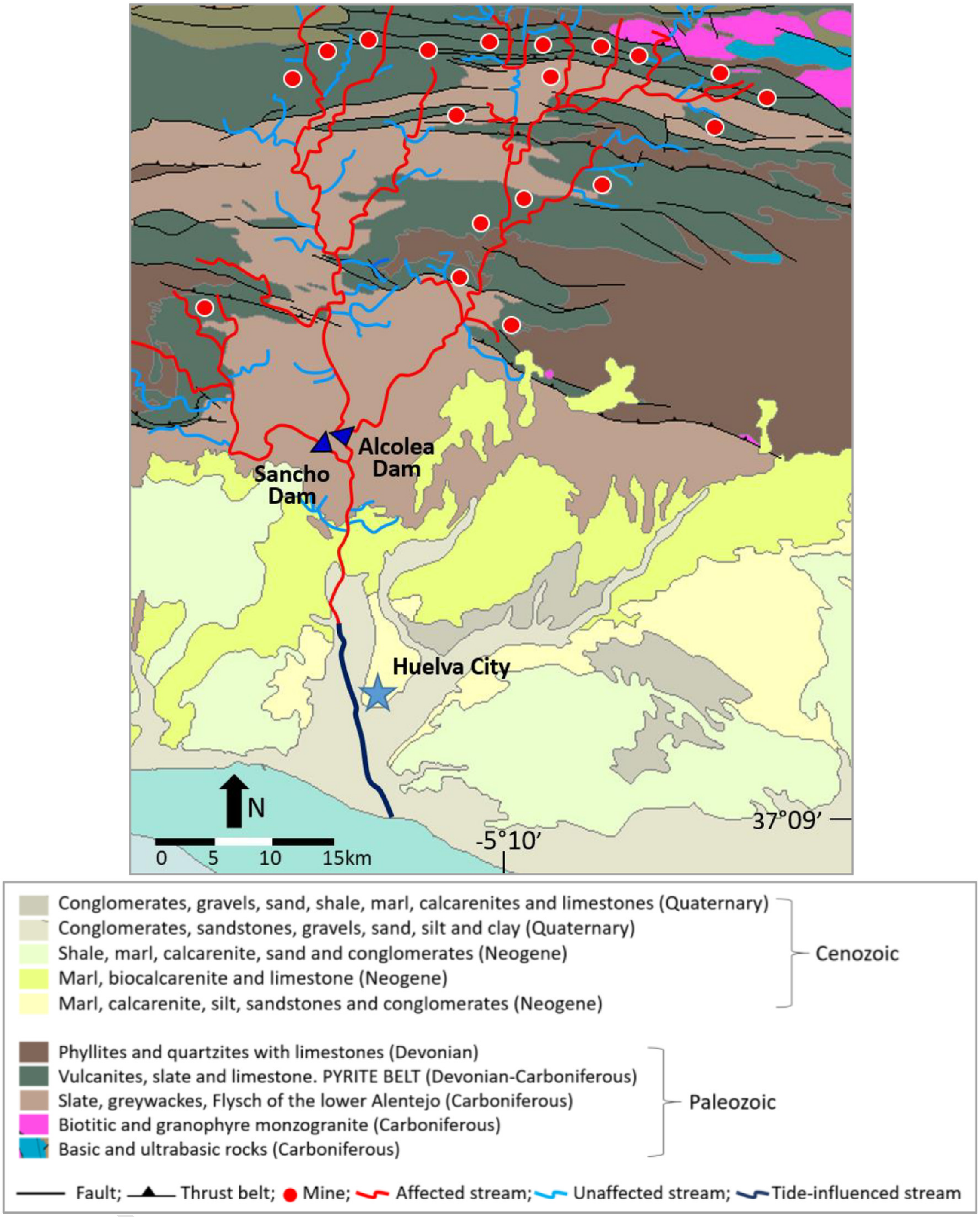

Fig. 4. Geological map of the Odiel river basin with the location of rivers affected by AMD, mines and dams (own elaboration using information from the Spanish Mining Geological Institute (http://info.igme.es/visorweb/) and Olías et al., 2011).

Albeit at that time the previous experiences with similar cases were very scarce and knowledge about karst was poorly developed, before the construction of the dam, the judgement of renowned geologists and engineers about the construction of the infrastructure in this area was very negative (Sánchez and Herreros, 2002).Finally, the energy company that promoted the project assumed the risk and the works began, finishing in record time (less than 2 years). It was expected that an adequate treatment of the rock massif would correct its deficiencies, so waterproofing treatments were applied prior to the construction of the dyke. The treatments consisted of cement injections through perforations and sinkhole sealing. Once the dam was built, reservoir tests were conducted yielding very negative results. Sánchez and Herreros (2002) and Naranjo (2008) provide an interesting narrative about the subsequent operations undertaken over more than 15 years aimed at correcting the leakage problem. As the authors describe, tracer tests were conducted to define preferential flow paths and waterproofing works were carried out both from the surface and inner parts of the karst massif, taking advantage of the Hundidero-Gato speleologic network. The latter required the construction of an interior pathway approximately 5 km long whose completion was not exempt from risks

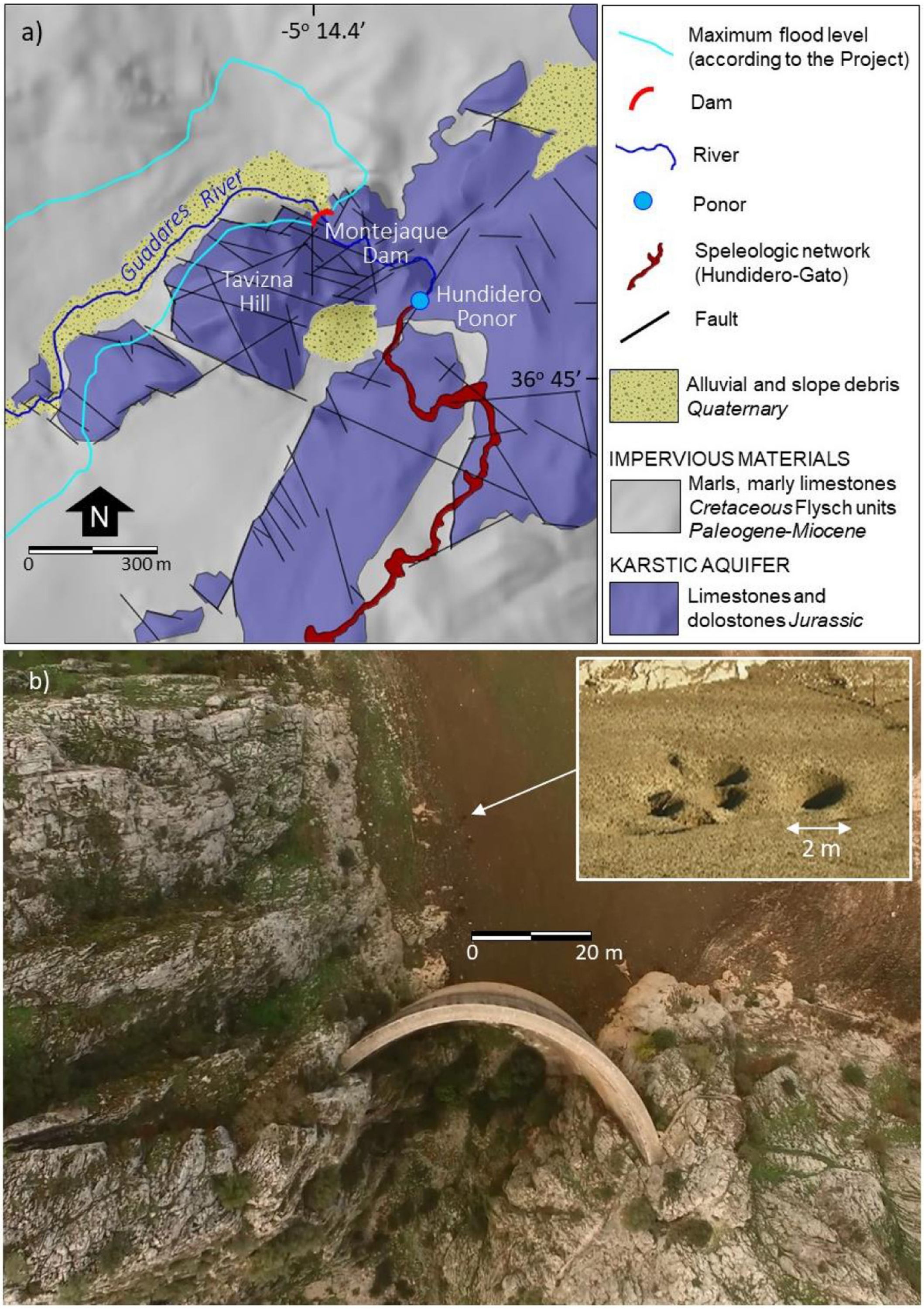

Fig. 5. a) Hydrogeological map of the Montejaque reservoir (own elaboration) b) Aerial vertical view of the Montejaque dam and detail of the suffosion dolines of the bottom of the reservoir (own elaboration).

and difficulties. Diverse materials were used to seal the conduits and cavities; concrete, asphalt and clay, giving similar results. When the reservoir was filled, water flowed through alternative flowpaths in a highly permeable medium, with a dense network of fractures and conduits widely distributed within the rock. It was also proposed to encase the bottom of the reservoir with an impervious layer, with gunite and even with an iron sheet cover to remediate the leakage problem. Nevertheless, these projects were not carried out owing to their high cost. As a result of the applied treatments the level of the reservoir rose during a flood (1930) reaching 30 m from the maximum (dam crest). Despite this the water drained quickly through the limestones. In subsequent floods the leakage problem kept progressing and counteracting the aforementioned treatments. Finally, coinciding with the Spanish Civil War (1936–1939), the works ceased and the dam was abandoned without ever performing the function for which it was built.

Since its construction, the infrastructure has only performed as a recharge element for the underlying aquifer. In a recent study, García-López et al. (2018) applied low cost terrestrial photogrammetry techniques to quantify the infiltration from the reservoir and therefore, the recharge of the aquifer. The authors installed time-lapse cameras over a period of 5 weeks to quantify the evolution of the level. Leaks of up to 4m^3/s were detected when the reservoir level was 665 a.s.l., nevertheless, when the reservoir had emptied to 25% of its capacity, leakage reduced to 0.35m^3/s (Video 1). These values are consistent with the average infiltrate on of 60 hm^3 per year estimated by Durán-Valsero (2007). This evidences a significant deterioration in the sealing of the reservoir, however, when the stored volume is reduced, this effect is counteracted by the prolonged deposition of fine fluvial materials that cover the bottom of the vessel.

5.2. Benínar reservoir (Case 5)

The Benínar dam is located in the middle course of the Adra River, (province of Almeria, see Fig. 1). The reservoir is placed on very complex geological structures that belong to the denominated "Alpujarride Complex" of the Internal Zone of the Betic Cordillera (see section 2). This complex is structured in tectonic nappes that produced vertical overlapping of units consisting of two lithological formations: a lower metapelitic formation of impervious nature (schists, phyllites, quartzites), and an upper carbonate formation (limestones and dolostones) with thickness up to 1000 m. Both the metapelitic formation and some of the carbonate levels presents high gypsum concentrations. As the numerous perforations and surveys conducted for the construction works (around 2500 linear meters drilled with 60 boreholes between 12 and 80 m deep) evidenced, under the recent materials (alluvial and colluvial) there are several units of the "Alpujarride Complex", which are affected by normal faults that sink and put in contact blocks of different geological nature. All this confers great geological complexity to the reservoir area.

The dam was built upstream of an abrupt canyon eroded by the river Adra in the carbonate formations of the lower nappe and floods several outcrops of carbonate that belong to different units and are intercaled with phyllites and locally, with gypsum (Fig. 6a). In the design of the infrastructure and in particular, of the impervious core, the contact with the large calcareous outcrop of the lower nappe was avoided. For this reason, the dam site was located further upstream than the first topographic closure proposals, and the core was built with a strong upstream inclination in order to reach the impervious materials of the closure. An interesting analysis of the design factors considered by the project team can be consulted in Álvarez et al. (1976). The mentioned document evidences that some geological problems were undervalued in the design stage: Firstly, the calcareous materials of the lower nappe, which play a major role in leakage, were catalogued as "chalcoesquists", whose permeability is significantly lower. This minimized the perception of the risk of leakage. These materials are of great thickness and highly heterogeneous and, despite having calcareous levels with greater presence of siliceous minerals, the permeability of the overall is high owing to intense fracturing of the medium. There are even levels affected by evident karstification processes. As indicated below, this formation constitutes the large regional aquifer that receives the aforementioned leakage and whose piezometric level is about 150 m below the dam foundation.

Secondly, the tectonics of the thrust sheet complicated the assignation of the lithological sections identified during the geotechnical drilling to their corresponding units. In fact, alternating stretches of phyllites (impermeable) and dolomites (permeable) were found in many boreholes, adding confusion to the geological model. Albeit the existence of large concentrations of gypsum in some sectors was detected, the possibility of development of preferential flows through dissolution conduits (circumstance that ultimately led to significant leaks) was not properly considered. In fact, in the upper part of the reservoir

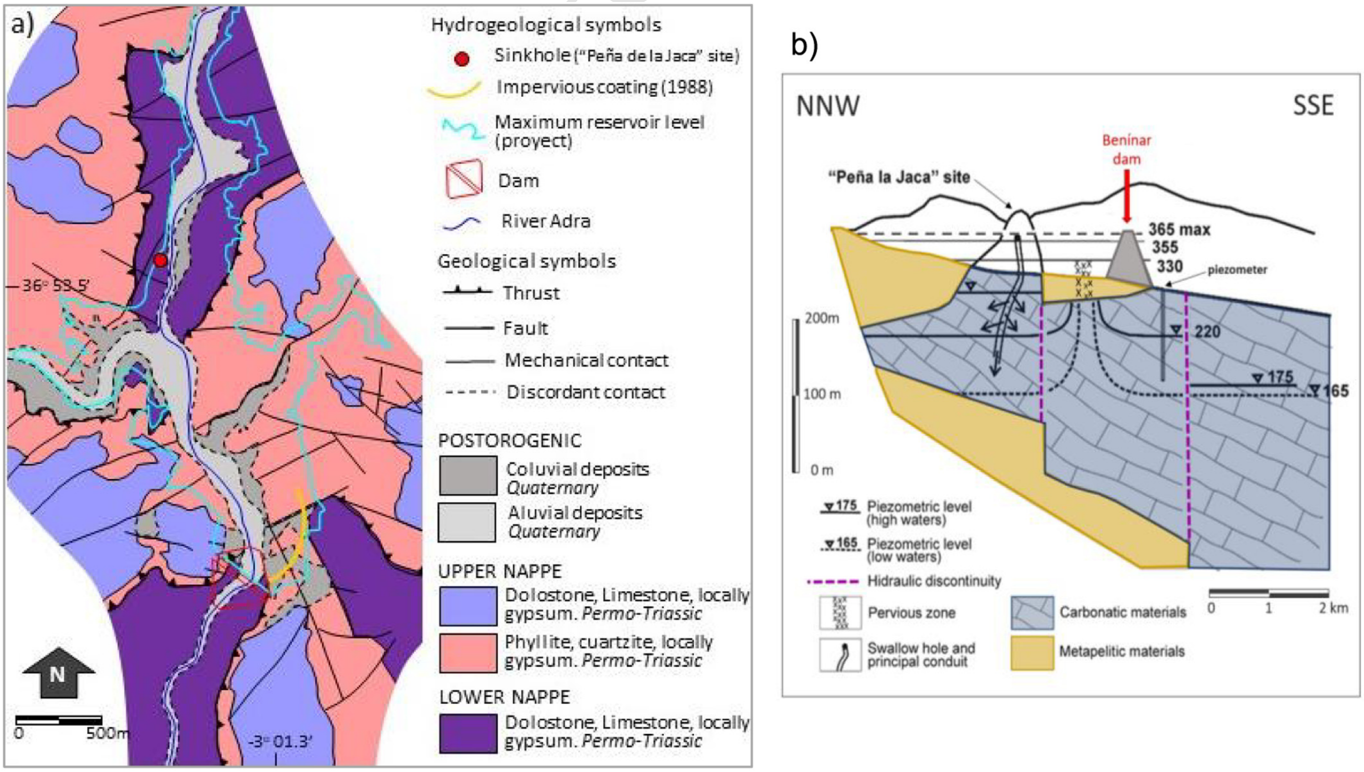

Fig. 6. a) Geological map of the Benínar reservoir (own elaboration); b) Conceptual model of compartmentalization of the recharge zone associated with the Benínar Dam (modified from García-López et al. (2009)).

vessel (known as Peña la Jaca site) there was a karstic sinkhole through which large volumes of water infiltrated, and whose existence was not detected until a significant flood event in the reservoir.

Downstream from the dam, there is a large carbonate aquifer that is crossed from N to S by the aforementioned canyon and received the river's seepage under natural regime. The aquifer is drained by a single spring (Fuentes de Marbella) located about 5 Km S from the dam, at the end of the limestone gorge. The spring is at an altitude of 165 m and had an average flow of 600 l/s under natural regime (García-López et al., 2009). Although the carbonate outcrops do not display intense karstification on the surface, several perforations have revealed the existence of cavities up to 5 m high. The abundant microfractures in the aquifer's dolomitic materials induce a behaviour that is closer to a high permeability diffuse flow than that of a karst formation, except for gypsum-rich sectors, where the behaviour is conduit flow type.

During the site preparation and excavation works, (several dolines) were already detected under recent materials (alluvial and colluvial). This circumstance compelled to perform filling and coating tasks with waterproof materials. Likewise, on the slope next to the left abutment (which lies on a large fractured carbonate outcrop that belongs to the lower nappe), it was necessary to apply a coat of the same impervious materials used in the dam core (phyllites) and the corresponding breakwater material (Fig. 6b), resulting in an important increase of the construction costs. The additional waterproofing treatments were concluded five years after the completion of the dam in 1988. Nevertheless the leakage problems, although reduced, persisted. Tritium and others tracing tests were carried out in 1989 by CEDEX (Centro de Estudios y Experimentación de Obras Públicas). Tritium was injected in several sites of the reservoir area and subsequently collected in a monitoring network that included the Fuentes de Marbella spring. The tracer concentration curve obtained at the spring put forward the hypothesis that part of the tracer had reached that site prior to sampling. In any case, flow speeds of several hectometres per day that were compatible with circulation through karst conduits were detected. These data were subsequently reinterpreted through the consideration of a dual mode of aquifer functioning, with preferential flow paths and diffuse flow. On the one hand, the preferential flow paths would rapidly connect the leakage zones with the spring. On the other hand a diffuse flow that widely distributes the tracer within a large volume of the calcareous aquifer would explain that the tritium concentration values in the spring were an order of magnitude higher than the natural concentration for several years after the tests were conducted, a large amount of rock affected by diffuse flow (García-López et al., 1994).

Shortly after, during a wet period (hydrological year 1989/90), it was possible to check the response of the reservoir to a large flood event. During the 12 months following that rainy period, the reservoir lost about 67 hm^3 owing to leakage towards the underlying aquifer. This volume lost exceeds the useful reservoir capacity (60 hm^3) and its four times greater than the volume of water supplied to users during that period. The comparison between the leakage flow and the reservoir level during that event allowed to identify three situations or scenarios: (i) When the reservoir level is below 330 m and the leakage flows range between 0.1 and 1.2 m^3/s, the relationship between both variables is quadratic. This can be interpreted as the progressive increase of the permeable flooded surface of the vessel as the reservoir level rise. (ii) Between 330 and 355 m and leakage flows of 1.2–2.3 m^3/s, there is a linear relationship between both variables. This suggests that the permeable surface remains constant while the reservoir level rises. The increase in the leakage flow is attributable to the rise of the hydraulic head. Therefore, in this range of levels, the impoundment would show a good watertightness. (iii) Finally, when the reservoir level reached 355 m, the flow peaked to 3.4 m^3/s and gradually decreased over the following 10 weeks until its stabilization at 2.3 m^3/s. During that period the reservoir level remained practically constant. This sharp increase in the leakage flow is related to the action of a karstic conduit associated with the gypsum formations at Peña la Jaca site. The flow decrease is interpreted as the gradual saturation of an underlying hydrogeological compartment. This compartment is partially connected with the rest of the aquifer through a hydraulic barrier of lower permeability and acts as storage blocks for large volumes of water (5–6 hm^3). During that period of extraordinary recharge, rises in the piezometric level of the aquifer that received the leakages were detected downstream from the dam. This evidenced the existence of at least another low-permeability hydraulic barrier and consequently, the presence of another compartment. Fig. 6b illustrates the interpretative conceptual model of the system's functioning deduced from reservoir leakage. With a delay of 4–6 months, the spring located downstream from the dam (Fuentes de Marbella) reached a flow of 2000 l/s that remained stable for months. A detailed study on the evolution of the reservoir, seepage and response of the underlying aquifer can be found in García-López et al. (2009).

Owing to the unsuccessful attempts to regulate the contributions of River Adra, the Public Administration conducted a set of surveys on the calcareous aquifer. The excellent response displayed by the aquifer led to the decision of begining its exploitation. Finally, it should be noted that, whereas the objective of defense against floods was achieved satisfactorily, the regulation purpose was not accomplished. This resulted in major modifications in the original water planning and the incorporation of groundwater bodies management (García-López et al., 2009).

6. Environmental and hydrogeological impacts

6.1. El Portillo-San Clemente system (Case 6)

El Portillo-San Clemente system is a two-reservoir system located in the north of the province of Granada (see Fig. 1). Both dams are situated about 13 km away in adjacent subbasins. The Integral Utilisation Plan of the Castril and Guardal rivers designed in the 1980s, considered the regulation of the two rivers. The optimal design storage capacity of El Portillo dam (Castril river) was limited to 33.5 hm^3 whereas the annual runoff of its basin was estimated at 115 hm^3/year approximately. On the other hand, the storage capacity of the San Clemente dam (Guardal river), 120 hm^3, significantly exceeded the runoff inputs of its basin, which were estimated at 31 hm^3. To address this issue, the Public Administration initially planned the construction of a 6 km tunnel aimed at transferring water resources from the Castril river to the San Clemente reservoir. The water transfer envisaged was about 54 hm^3/year, which would represent the 47% of the average flow of the Castril river. The tunnel would run through Sierra Seca. Sierra Seca is a large asymmetric anticline fold oriented N30E whose axis dips towards the north, where the most modern materials appear. The eastern flank dips towards the east (30–40°), giving rise to a thick stratigraphic succession of about 2000 m formed by limestones, dolomites and marls of Berriasian to Miocene age that is settled on Jurassic limestones. The western flank presents important inverse faults and a stratigraphic serie with subvertical disposition (Moral et al., 2005). The abundance of highly fracturated and karstified carbonate materials (limestones and dolostones) of Cretaceous age, , enable the existence of important aquifers within the area affected by the tunnel construction (Fig. 7a and b).

Another aspect that should have been considered is that the Castril river holds great landscape and ecological values, including diverse riparian ecosystems and numerous flora and fauna endemisms, which led to its declaration as Natural Park by the regional government in 1989.

The El Portillo and San Clemente dams were finished almost 20 years after the approval of the Integral Utilisation Plan of the Castril and Guardal rivers. Nevertheless, El Portillo dam met strong opposition from different groups of stakeholders, especially ecologists and conservationists, owing to the adverse effects of the infrastructure on the Castril river (Hervás-Gámez and Delgado-Ramos, 2019). In this regard, one of the most noticeable impacts of the reservoir on the river would

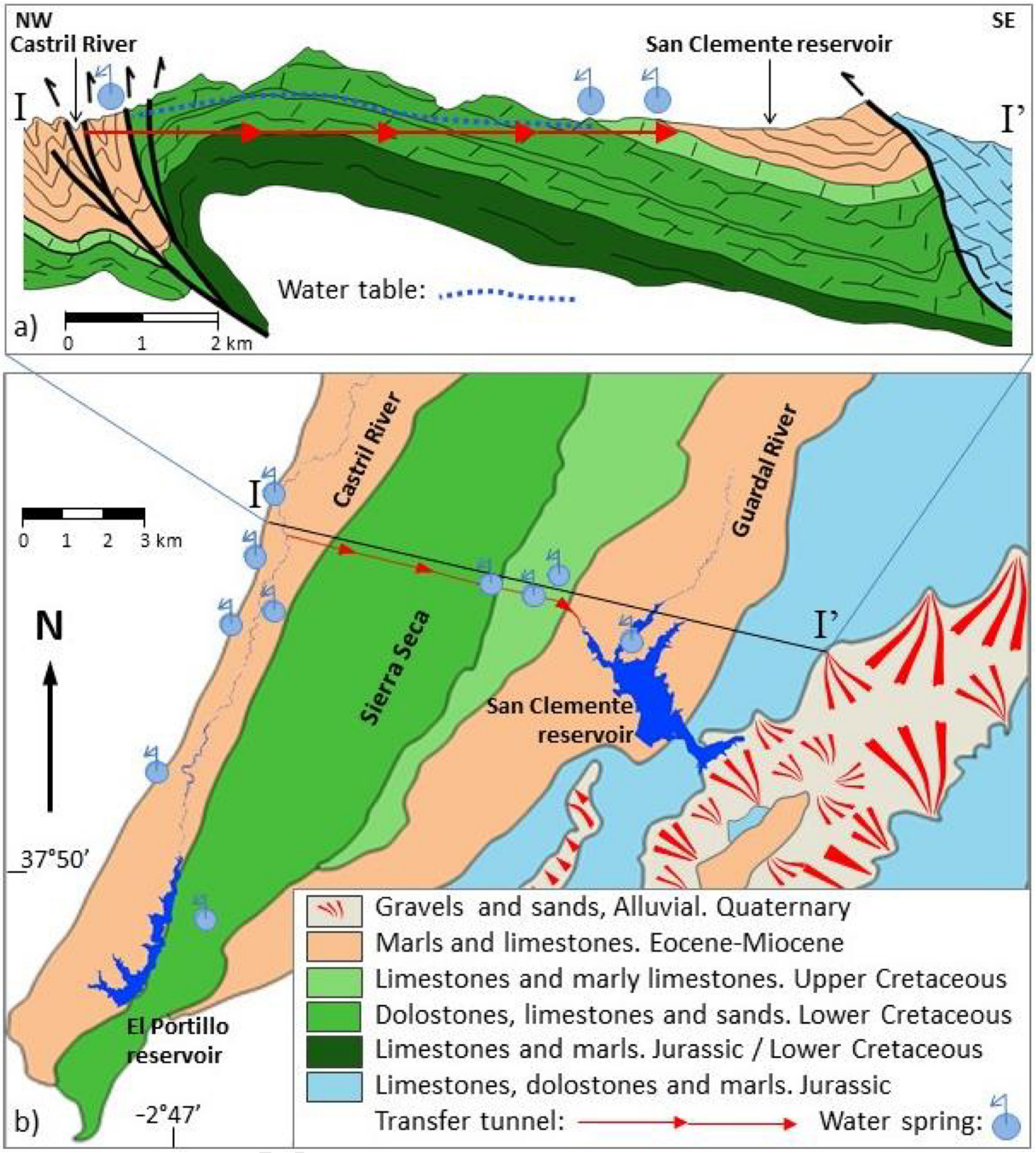

Fig. 7. a) Cross section of the area where the transfer between El Portillo and San Clemente was projected and b) geological map (own elaboration using information from: Continuous Digital Geological Map of Spain (GEODE, 2004)).

be the flooding of more than a half of the riverbed within the protected area. Likewise, the tunnel construction and water transfer plan met a widespread opposition that resulted in the cancellation of the project), decision that was also endorsed by expert reports. Aside from other considerations, the water transfer would have had significant impacts on the aquifers of Sierra Seca, as the tunnel was designed to run below the saturated area of some hydrogeological compartments, which could have facilitated their drainage . Consequently, the natural discharge of the aquifer (up to 500 l/s) would have been affected, drying up springs of great environmental value (temperature about 12 °C, low mineralization and high oxygen content) (Moral et al., 2005). In addition, the foreseeable decrease in the Castril river flow would have led to a water table drawdown in its small alluvial aquifer, with negative consequences for riparian communities (Cruz-Sanjulián, J.J. (coord)., 1992).

Once the transfer between the two basins was canceled, the very existence of the dams and in particular their dimensioning, size and functionality are clearly questioned. The conceived project disregarded the harmful consequences that the construction works would have for groundwater resources and the environment and was eventually affected by the recent paradigm shift in the management of water resources towards greater protection of the environment.

7. High Evaporation

7.1. Barbate reservoir (Case 7)

The Barbate reservoir is located in the Barbate river basin(province of Cadiz, see Fig. 1). This dam is the main infrastructure that supplies irrigation water and protects the crops of the area against floods. In this regard, it should be mentioned that agriculture and livestock farming are the main economic engines in the region. reservoirs). The Barbate reservoir has the largest storage capacity in the basin (228 hm^3) and is the only one that enables a multiannual regulation owing to its storage capacity, which is 2.65 times greater than the basin runoff (86 hm^3/year). This feature makes the reservoir a strategic element in water management, especially during wet years. However, significant volumes of the stored reserves are lost due to intense evaporative processes (the evaporated volume/supplied volume ratio is greater than 0.5) (Ruiz-Ortiz, 2019). These evaporated volumes are outputs from the system that could otherwise be exploited for human consumption and environmental uses. In this regard, it is noteworthy that the average annual evaporation reported in the Barbate reservoir (30 hm^3/year for the period 1999–2016) exceeds the volume pumped from all the aquifers in the basin (18.5 hm^3/year) (Junta de Andalucía, 2016). The cause of this phenomenon lies in the location of the dam itself. The infrastructure was built in 1992 in a smooth relief area (Fig. 8a) with less than 3% average slopes and terrain elevations between 20 and 80 m.a.s.l (Fig. 8b). The constructive singularities that this location conferred to the dam (dyke length 1360 m, dam height 25 m above the terrain, surface flooded of 2540 ha at maximum storage capacity) made it the most unfavourable case in Andalusia from the point of view of evaporation losses (Fig. 8c). Besides, the existence of strong and persistent winds (particularly easterly winds known as “Levante”) can substantially increase the daily evaporation, even doubling it.

Recently, Ruiz-Ortiz et al. (2019) analyzed in detail this hydrological problem and evaluated other water management alternatives in order to reduce the large evaporated volumes. This would also lead to the improvement of the current status of the basin's aquifers (Vélez-Nicolás et al., 2020), which are classified as in poor quantitative and chemical condition by the Administration. In their study, Ruiz-Ortiz et al. (2019) carried out analysis and modelling tasks based on Decision Support Systems (AQUATOOL-SIMGES) considering 5 potential strategies or scenarios: i) combined management of the reservoirs, ii) conjunctive use of surface water and groundwater, (iii) water transfer between reservoirs, iv) artificial recharge of aquifers, and v) a combination of the previous strategies that are compatible. In this work, the authors also compared the average evaporation associated with the current management strategy (30 hm^3/year from the period 1999–2016) with that obtained in each modelised scenario, obtaining a maximum resource gain of up to 8.5 hm^3/year during wet years (hydrological year 2004/2005) through the conjunctive use of surface water and groundwater and the transfer between reservoirs. In addition, some of the alternatives proposed (iii and iv) may contribute to improving the state of the groundwater bodies in the basin.

8. Discussion and Conclusions

The reservoir selected for this study are distributed throughout the Andalusian geography (Southern Spain), belong to different basins and geological contexts, and present distinct characteristics and construction types. Likewise, their hydrological and hydrogeological problems are of different nature. Although the cases presented here are representative of the region studied, they are also useful for other geographical contexts, especially in the Mediterranean area, and may contribute to a better assessment of potential problems in future projects.

The first problem analyzed in this paper is related to water quality degradation by salinization. Several cases of reservoir salinization have been documented worldwide (Miyamoto et al., 2007; Buachidze and Tevzadze, 2006). Saline water management is a challenge owing to

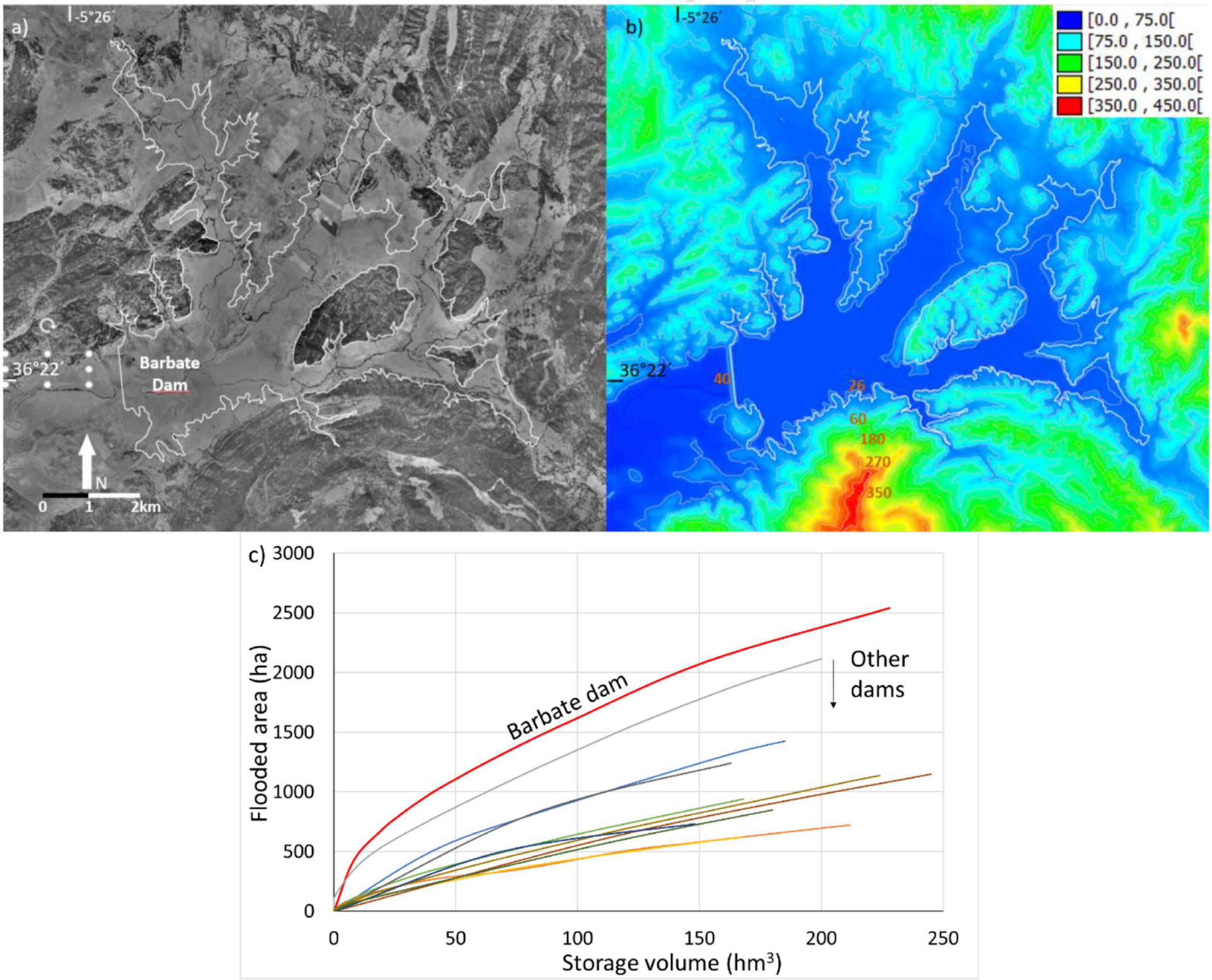

Fig. 8. a) Official aerial ortophotography from the 1980´s decade, prior to dam construction. The limits of the projected reservoir are indicated (modified from: http://centrodedescargas.cnig.es/CentroDescargas/catalogo.do?Serie=FPNOA). b) Topographic map of the Barbate reservoir area (own elaboration). c) Graph showing area/volume curves for reservoirs between 150 and 250 hm^3 of Andalusia. (own elaboration).

energy consumption, capital and operational costs, and environmental impacts. In fact, in some cases, no practical solutions to the salinization process have been found so far. An example is Upper Gotvand dam (Iran), where halite dissolution led to the accumulation of 66.5 million tons of dissolved salt in the reservoir (Jalali et al., 2019). However, desalination appears as a promising technology, especially reserve osmosis (RO) (Anis et al., 2019). This technology, which is the most commonly used and accounts for 69% of all desalination plants globally, is especially advantageous for brackish and saline groundwater in water-stressed countries. Likewise, the Mediterranean coast of the Iberian Peninsula has a long desalination tradition, with around 30 desalination plants of medium–high capacity (20,000–125,000 m3/day) built in the last 25 years, and 100 small brackish desalination plants, most of them using RO techniques. Although the solution adopted in Guadalhorce (1) and Víboras (2) reservoirs was desalination through RO techniques, the underlying problems were not related to the suitability of the desalination technology but to the location of the dam itself, (in the SCC domain) and the high costs that water pumping and treatment implied. These case histories evidence that, in order to reach an efficient solution to salinization, it is essential to deepen the current knowledge of the SCC hydrogeology. With respect to the Guadalhorce reservoir, prior to the construction of the infrastructure, it would have been necessary to (i) quantify infiltration, (ii) define the recharge areas and flow direction and velocity using artificial tracers, (iii) delimitate/identify subsidence associated with the dissolution of evaporites and the areas raised owing to diapirism through the analysis of radar images and (iv) to characterize the hypersaline spring's functioning in terms of hydrodynamics, hydrochemistry and isotopy.

In the case of Viboras reservoir the results obtained bring into question the construction of the structure itself, moreover if we consider the existence of calcareous aquifers of good quality in the area. It would have been convenient to reconsider the water scheme by including groundwater and improving the quantitative and qualitative control of aquifers in headwater areas. Likewise, it would have been necessary to have a sound knowledge of the aquifer's impervious limits, as well as having rigorously monitored the piezometric levels and regulated the springs to achieve a better exploitation of the resources.

On the other hand, AMD is a major quality issue that affects different types of water bodies at international scale, e.g.; the Keswick reservoir (California) receives metal-laden AMD from the abandoned mines of Iron Mountain, which presents the most acidic waters described so far (−3.6 pH). Iron Mountain discharges have been treated with costly acid neutralization plants, water diversions and through capping of selected areas (USGS, 2016), achieving a considerable reduction of metal loading. The Aha reservoir (Guiyang, China), was affected by the activity of about 220 small coal mines located in its catchment, resulting in Fe and Mn concentrations that significantly exceeded the drinking water standards. Although 2 water treatment plants were built to purify the inlet water of the reservoir, the SO_4^{-2} concentration reaches very high levels (Feng et al., 2011). In Spain, many reservoirs have also been impacted by mining; in the province of Huelva up to 23 reservoirs affected by the IPB present acidic waters and high concentrations of metals and sulphates (Santisteban et al., 2015). Natural attenuation mechanisms are often insufficient and source control measures based on excluding air from pyrite sources (e.g. flooding/sealing mines, microencapsulation or above-ground covers) are not feasible in many locations (Johnson and Hallberg, 2005). However, the application of passive remediation methods based on dispersed alkaline substrates (DAS) have yielded promising results in pilot studies in mines of the IPB, significantly reducing the pH and removing large concentrations of Fe, Zn, Cu, As and Cd (Rötting et al., 2008). Coupled application of natural Fe-oxidizing lagoons with limestone-DAS treatments have also produced good results in the same area, with relative removal of 100% Fe, Al, Cu, Pb, and As and 6% of Zn (Macías et al., 2012). After more than 10 years testing DAS in the IPB (Huelva, Spain), Macías et al. (2017) propose the implementation of 13 DAS treatment plants, strategy that could improve up to 128 km of streams and reduce the acid inputs into Alcolea reservoir (3). In relation to the future Alcolea reservoir, it seems daring to postpone the challenging task of recovering the environmental quality of the basin, moreover if we consider the negative predictions by the scientific community and the disastrous results yielded by previous experiences such as that in the nearby reservoir "El Sancho". This case clearly illustrates the fact that political-social issues are being prioritized over technical aspects (geological characteristics of the location, water chemistry etc.) and manifests the urgent need to take into consideration the proposals from the scientific community.

The second type of problem reported in this paper is ineffective water storage owing to the lack of watertightness in the vessel produced in karst terrains. The main measures implemented in these cases are impermeable blankets, cut-off walls and massive impermeation groutings with different materials (concrete, asphalt and clay). Nevertheless, in most cases these measures do not yield satisfactory results (Romanov et al., 2003; Ghobadi et al., 2005; Uromeihy and Barzegari, 2007; Gutiérrez et al., 2015; Milanović, 2018) owing to the rapid evolution of karstic systems and the development of collapse structures and dissolution features that may range from minute voids to large openings and caverns (Ciantia et al., 2015; Nam et al., 2020), making it necessary to define alternatives for the exploitation of resources (e.g.groundwater) like in the case of Beninar (5). Karstic systems pose major challenges for many engineering projects. Sometimes after many years of implementing corrective measures and large investments that significantly exceed the initial budget, the infrastructure has been abandoned like Montejaque reservoir (4). On the other hand, there are also examples of dam sites that had to be abandoned before construction, saving large economic investments and even preventing from possible catastrophic failures if the infrastructures had been built (Johnson, 2008). Cases of project relocation have also been documented in literature, such as Cedar Ridge dam (Texas) (Johnson and Wilkerson, 2013). In any case, having a thorough knowledge of the local geomorphology, hydrology and underlying geology is a priority for an adequate development and management of hydraulic works in karst areas.

In addition to the purely engineering aspects, hydraulic infrastructure projects must comply with the increasingly stringent requirements imposed by regulatory frameworks and meet the criteria of economic development, social equity and environmental sustainability. The third deficiency analyzed has been the impossibility of transferring resources between reservoirs owing to great environmental and hydrogeological impacts (El Portillo-San Clemente system (6)). In this case, both dams were originally conceived under the premise of being exploited jointly, by transferring 54 hm^3/year from El Portillo to the San Clemente reservoir through a tunnel that would have crossed important aquifer systems in the area, inducing their discharge and consequently, drying up the springs. In addition, the reduction in the Castril River flow would have severely damaged riparian communities and altered the physical-chemical properties of water. In this case, it is evident the need to deepen the knowledge on the geomorphological and hydrogeological characteristics of Sierra Seca, as well as the development of resource management plans and decision-making tools. As in this project, many other examples of large hydraulic schemes had to be canceled by virtue of their possible environmental repercussions. In Australia, the megaproject of Traveston Crossing dam was halted by the Federal Government in 2009. If constructed, the dam would have flooded more than 3000 ha of land and would have required the diversion of 4% of annual flow of the river Mary (Wasimi, 2010). Another gargantuan project that was abandoned is the Siberian water transfer scheme "Sibaral" (Micklin, 2011). If carried out, the scheme would have reduced the average annual discharge of two rivers by 32%, required the creation of a 25,000 km^2 reservoir on the West Siberian Plain and flooded forests, farmland, and swamps.

Finally, the last type of dam failure reported in this paper is related to very high evaporative loss from reservoir surface. Several cases of dams with high evaporation have been documented (Gökbulak and Özhan, 2006; Martínez-Granados et al., 2011; Zhao and Gao, 2019). To minimize evaporation from reservoirs a range of chemical, physical and biological methods have been developed. Chemical methods consist of the application of monolayers (usually long chain alcohols) that produce a diffusion barrier on the water surface, however, its application and maintenance is strongly affected by wind. Physical methods, which include continuous or modular floating covers, shadecloths, windbreaks, photovoltaic panel covers or bubble injections, can save up to 70–95% of water in reservoirs (Youssef and Khodzinskaya, 2019). Recent experimental studies and simulations have yielded promising and economically efficient results in countries like China (Han et al., 2019), Iran (Azami et al., 2017; Hashemi Monfared et al., 2019), Brazil (Rodrigues et al., 2020) and Spain (Martinez-Alvarez et al., 2010). Finally, biological methods comprise tree “shelterbelts” (only effective for small-sized reservoirs), palm frond shading covers or the use of floating aquatic plants, approach that requires previous studies as plants may affect water quality and biological communities (Youssef and Khodzinskaya, 2019). The aforementioned remedial measures seem difficult to apply in the case of Barbate (7) due to its dimensions, climatic conditions (strong and persistent winds) and the high cost they would entail. Prior to the construction of the dam, it would have been advisable to analyse potential alternative dam sites in the upper basin, where the orography is more abrupt. Once the dam was built, Ruiz-Ortiz et al. (2019) proposed to modify the reservoir's management by incorporating groundwater resources and keeping the reservoir at the lowest level in order to reduce evaporation. We can conclude that, although the phenomenon of evaporation in reservoirs has been widely documented, it is not usually considered as a design factor that restricts the location of reservoirs. In order to choose suitable dam sites in warm climates, it is not only fundamental to analyse the topographic and geological characteristics of the dam, but also the morphology of the vessel in terms of flooded surface/volume stored ratio.

The following general conclusions can be drawn from the case histories analyzed: In all the cases presented, the cause of the problem was already detected during the preliminary studies to the construction of the infrastructure, even though the technical solutions were (or will be) postponed until the completion of the construction works. Among the factors that have led to the malfunction of these infrastructures, the following can be mentioned: i) the nature of the geological environment, which is not fully understood and still requires further research; ii) the traditional biased vision of water resource managament, in which the Administration efforts were exclusively focused on the regulation of surface water for a long time. This conception was detrimental to the joint use of surface/groundwater and made other alternatives that proved to be technically and economically more adequate to be overlooked; (iii) the extraordinary complexity of the technical-administrative process associated with dam construction and the long periods required for their execution and operation, which give rise to legislation changes (such as environmental restrictions) that might affect the projects; iv) the interests of pressure groups that could even promote actions against the opinion of experts; v) the Spanish financing policy on this type of investment, which sometimes implies disguised forms of subsidy that are contrary to the Water Framework Directive and requires substantial investment from the State while users only benefit from them.

Given all these factors, it seems evident the need to conduct comprehensive studies on the construction projects that do not focus exclusively on the infrastructure itself. Monitoring the geological features comprising a possible geohazard or relevant processes is of vital importance to ensure the overall safety and reliability of dams and reservoirs (Sigtryggsdóttir and Snæbjörnsson, 2019). In addition, it is also imperative to rigorously consider other aspects such as the hydrogeology of the area, the foreseeable effects on the hydrogeological systems and on the local population, natural environment and biota.

For this reason, the present work highlights the need to learn from past mistakes in order to successfully face future water planning works and challenges, especially by the Administration. To achieve this, it is convenient to conduct systematic research on the functioning of the reservoirs and their deficiencies, as well as the incorporation of the joint use of surface-groundwater in hydrological planning and management.

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Uncited references

Garcia de Jalon et al., 2019
Murilo and Rubio, 2009

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Appendix A. Supplementary data

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