The role of groundwater in highly human-modified hydrosystems: A review of impacts and mitigation options in the Campo de Cartagena-Mar Menor coastal plain (SE Spain)

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Abstract. Hydrological processes and water resources are increasingly modified by anthropogenic actions, leading to multiple pressures on the environment and related ecosystems. A better understanding of the interactions between the anthroposphere and the hydrosphere is necessary to shape more sustainable societies. The pressure of human activities on the environment is especially high along the circum-Mediterranean area due to a combination of biophysical and economic factors. The Campo the Cartagena coastal plain together with the Mar Menor lagoon is one of the most exemplary areas in this aspect. This work analyzes this system at the basin level by providing a synthesis of the state of knowledge of each hydrological compartment and the links between them. We pay special attention to the important role that groundwater plays in the overall functioning of the

Jiménez-Martínez, J., García-Aróstegui, J.L., Hunink, J., Contreras, S., Baudron, P., Candela, L. (2016) The role of groundwater in highly human-modified hydrosystems: A review of impacts and mitigation options in the Campo de Cartagena-Mar Menor coastal plain (SE Spain). Environmental Reviews. doi: 10.1139/er-2015-0089

system, both as a promoting and/or mitigating agent. The principal identified impacts from human actions are: water imbalance (28% of consumed water resources are not renewable), aquifer-cross contamination (high areal density, ~1.2 wells per km^2), acid-mine drainage (mine wastes, accounting for ~175 hm^3 on land and ~25 hm^3 in the sea, accumulated mainly between 1957 and 1992), and lagoon euthrophication (NO_3^- up to 1 mg/L). A set of mitigation options and complementary management measures that should be implemented following an integrative and holistic approach are presented and discussed, supporting a more sustainable regional economy and the recovery of critical ecosystem services.

Keywords: water imbalance, aquifer-cross contamination, acid-mine drainage, eutrophication

1. Introduction

Hydrological systems and basin water resources are increasingly impacted by anthropogenic actions, leading to multiple stresses on ecosystems and jeopardizing the provision of a broad range of ecosystem services. These pressures and impacts are more evident in drylands where a third of the total worldwide population is concentrated and water is a scarce natural resource (*UNEP*, 2005). In some regions, as it occurs along the circum-Mediterranean countries (Israel, Spain, Italy or Greece), intensive economic development has been possible owing to the exploitation of groundwater resources. Although less visible, the impacts of human activities on the aquifers of those regions are usually more severe and persistent than in the other environmental compartments (*Gleeson et al.,* 2015). Because groundwater plays a critical role in shaping the human development in drylands, a better understanding of their status, functioning and links with the anthroposphere is required in order to reach higher states of economic sustainability. This study focuses on the Campo de Cartagena basin and the Mar Menor lagoon, included in the RAMSAR international convention, as a paradigmatic Mediterranean system in which human development and groundwater exploitation has been especially intensive in the last decades (*Custodio et al.,* 2016).

The Campo de Cartagena basin is a semi-arid region located in southeastern Spain, and is connected to the Mediterranean Sea primarily through a hypersaline coastal lagoon, the Mar Menor.

Land use in the basin is primarily dominated by rainfed and irrigated intensive agriculture. Water requirements for this activity are mainly met with groundwater pumped from aquifers, surface water resources from the inter-basin *Tajo-Segura Water Transfer* (since 1979) and more recently, with water from seawater desalination plants (*March et al.*, 2014) and brackish groundwater (*Aparicio et al.,* 2015). The population's water supply relies on an independent infrastructure (*Mancomunidad de Canales del Taibilla*), and on a relatively high-priced water transfer (*Garcia-Rubio et al.,* 2015). The domestic water demand is highly seasonal due to tourism.

Although in the past, the mining industry was the key source of income, currently, the main drivers of the regional economy are irrigated intensive agriculture and tourism. Intensive development of these activities has led to a complex mixture of environmental impacts on the local hydrological system. Water deficit, pollution and the consequent euthrophication of the Mar Menor lagoon are considered by far the primary concerns in the region (e.g., *Perez-Ruzafa et al.,* 1991; *Conesa and Jimenez-Carceles,* 2007; *Lloret et al.,* 2005). Tourism is partly responsible but is also suffering its consequences to some extent due to the blooming of jellyfish in the lagoon (*Perni and Martinez-Paz,* 2013).

Pressure on the hydrological cycle will intensify if global warming continues to rise and the Mediterranean region becomes dryer and warmer (e.g., *Giorgi and Lionello,* 2008). Regional Climate Models run for the Mediterranean region predict a long-term decrease in precipitation of about 15% for the end of the century (2070-2099) and of 8% in the near future (2020-2049) when compared to the 1950-2000 period (e.g., *Mariotti et al.,* 2008). This could deepen the existing gap between water demand and water availability and increase the competition for water among economic sectors (*Stefanova et al.,* 2015). For the case of Mar Menor coastal lagoon, the current multiple stressors are likely to be strengthened (*De Pascalis et al.,* 2012) and an increase in sea water temperature, could lead to an intensification of the eutrophication processes in the lagoon and the ecological disruption of the surface water body (*Lloret et al.,* 2008).

The aforementioned pressures and impacts on the hydrological system in this basin have been widely studied and reported in many scientific papers and technical reports. However, few of them address the Campo de Cartagena basin and Mar Menor coastal lagoon in an integrated way (e.g., *Conesa and Jimenez-Carceles,* 2007). Therefore, the purpose of the current work is to synthesize pressures-impacts of different environmental domains in a holistic way through an extensive review and an overall discussion of their relationships, with special attention to the key role played by groundwater. Mitigation alternatives, including potential changes in land use and water management, are presented and discussed for each of the identified impacts. This case study represents a paradigmatic real case of a highly human-modified Mediterranean basin in which critical environmental and water, including groundwater, management challenges are emerging and should be properly afforded in order to increase its resilience against Global Change scenarios.

2. Campo de Cartagena area

The Campo de Cartagena basin is a flat region of 1236 km^2 located in southeastern Spain, with a gentle slope of around 1%. It is surrounded by small mountain ranges such as Sierra de las Victorias and Sierra Cartagena-La Unión on all borders except in the East, where it is open to the Mediterranean Sea. Between the plain and the Mediterranean Sea, a hypersaline lagoon, Mar Menor, extends (Figure 1). The region is characterized by a semi-arid climate, with 18º C mean annual temperature and 300 mm average annual precipitation, unevenly distributed into a few intensive events that is highly variable in space and time, although taking place mainly in spring and autumn. Potential evapotranspiration averages 1275 mm/year (*Sanchez et al.,* 1989).

Agriculture is the main land use in the region: rainfed covers 7350 ha (6% of the total basin), while 37600 ha (31%) is under intensive irrigation (average 2001-2010 according to local official statistics). The most representative rainfed crops are almond, winter cereals and olive, while the main irrigated crops are horticultural row crops (lettuce, broccoli, melon and others), and citrus trees (oranges and lemons). In plots dominated by row crops, rotation of autumn-winter (e.g., lettuce, artichoke) and spring-summer (e.g., melon) crops is a common practice. Drip is the primary irrigation method (90%) due to water scarcity and the requirement of water conservation (*Alcon et al.*, 2011). Non-cultivated soils have a low permeability, low organic carbon content and are poorly developed (*Garcia-Pintado et al.,* 2009).

The *Tajo-Segura Water Transfer* provides more than one third of the total water demand for irrigation. However, during the last decades, the unmet water demand for irrigated agriculture and tourism development led to the construction of several desalinization plants. From one side, seawater desalinization plants have their maximum production during summer and drought periods, to cover water demand peaks. However, the relatively high operational costs and quality issues limit its widespread use for irrigation (*Lapuente*, 2012; *Martin-Gorriz et al.*, 2014). Most of them are under their maximum desalination capacity (*March et al.,* 2014). On the other side, farmers have installed small desalination equipment to reduce the salinity of the low-quality pumped groundwater (brackish groundwater) and mix them with better quality surface water (i.e., *Tajo-Segura Water Transfer*) resources to get adequate water for irrigation. Finally, reclaimed water constitutes the last source of available water for meeting agricultural water demand.

2.1. Surface hydrology and groundwater relationship

There are no permanent watercourses (runoff mostly infiltrates in the streambeds of the drainage network), although the recent groundwater level rise indicates that several courses may behave partially and temporally as a watercourse (*Garcia-Pintado et al.,* 2007), which drain into the Mar Menor lagoon (*FIEA*, 2009) (Figure 1). The drainage network itself comes into operation only in episodes of intensive events (i.e., torrential rains).

The relationship between surface-groundwater hydrology begins with the establishment of the soil water balance (i.e., potential aquifer recharge). It has been studied by several authors, covering a wide range of scales. At plot scale, *Jimenez-Martinez et al.* (2009, 2010, 2012b) studied the impact of crops on the groundwater recharge patterns using various modelling approaches. They showed that although the agricultural practices are properly carried out by farmers (high irrigation efficiency), high recharge values and leaching of fertilizers and pesticides are produced after intense rainfall events. These simulation-based findings were also confirmed by *Baudron et al.* (2013a, 2014).

For the main irrigation district (intermediate scale), *Hunink et al.* (2015) evaluated the patterns of water consumption and groundwater reliance of agriculture in the area. A high spatio-temporal variability in the fraction of applied irrigation water that is met with groundwater was observed, ranging between 10 and 80% on average, but can be even higher during drought periods.

At the catchment scale, *Contreras et al.* (2014) assessed the spatial patterns and temporal dynamics of evapotranspiration and potential recharge of the region using a soil-water balance model. For the 2000-2010 period, *Contreras et al.* (2014) reported water accounting issues, based on the distributed *Spatial Processes in Hydrology* (SPHY) model, an open-source model/code that can be applied in different contexts and climates and includes remote sensing datasets (*Terink et al.*, 2015). SPHY computes the evapotranspiration based on a satellite-based vegetation index, saturation-excess runoff, percolation and potential recharge. Climate datasets were gathered from currently operational meteorological stations (17) in the basin. Figure 2 shows the mean annual precipitation isohyets, and the spatial patterns of mean annual evapotranspiration and potential recharge computed for the 2000-2012 period.

Other relevant fluxes for surface hydrology are conveyance and distribution losses: a local study (*CENTER*, 2000) estimated these at 7 and 10%, respectively. The impact of surface storage and channel roughness on the characteristic flash floods in the hydrologic network, has been studied by *Garcia-Pintado et al.* (2009). Obtained results confirmed the fact that transmission losses along the stream network are relatively high, producing surface runoff to the watershed outlets only during very intense rainfall events.

Finally, *Martinez-Alvarez et al.* (2008) estimated on about 16 hm^3/year of water loss by direct evaporation from approximately 4000 temporary irrigation reservoirs. Reservoirs are used by farmers as on-farm water storage systems to buffer periods of low water availability.

2.2. Groundwater hydrology

The area constitutes a Neogene and Quaternary sedimentary basin (East Betic Cordillera). The detrital sedimentary rocks are unconformably laid over three metamorphic complexes that constitute the Internal Zones of the cordillera (Figure 3), formed mainly by Triassic age metamorphic rocks (e.g., *Lopez-Garrido et al.,* 1997; *Garcia-Tortosa et al.,* 2000; *Manteca et al.,* 2004). The bedrock is fractured according to NE-SW to E-W normal faults developing several horst (e.g., Cabezo Gordo, Sucina) and graben, structures (e.g., *Robles-Arenas et al.,* 2006). The Neogene and Quaternary sedimentary rocks reach 2000 m thickness in the depocentres (i.e., grabens). The sedimentary infill has been divided into stratigraphic units according to lithostratigraphic and paleontologic criteria (Figure 3).

The observed stratigraphic variability and structural complexity of the area has important implications for the establishment of a conceptual hydrogeological model (*Jimenez-Martinez et al.,* 2012). The sedimentary infill of the basin is mainly composed of detrital, low-permeability sediments (marls) with interlayered high-permeability material (limestone, sands and conglomerates). Tortonian age sands and conglomerates, Messinian organic limestone and Pliocene sandstones constitute the aquifer materials. Quaternary sediments, also detrital, form the upper unconfined aquifer. Therefore, the hydrogeological system is constituted by three deep confined aquifers of Tortonian, Messinian and Pliocene age, and one Quaternary unconfined shallow aquifer (Figure 3). Finally, there is a fifth aquifer formed by carbonate rocks of Triassic-Permian age (locally present in the center, Cabezo Gordo, and in the West border of the basin, 'Los Victorias' aquifer).

Aquifers areal extensions have been plotted in Figure 3. The areal extent of the Tortonian aquifer unit below the Campo de Cartagena coastal plain is not well known. Although the unit is low lying to begin with, it pinches out to the center of the basin although can be locally found at greater depths (in contact with the basement). The Messinian aquifer is only present in the mid-North of Campo de Cartagena, while to the East, the unit is dipping under the Mediterranean Sea. Although no reliable information exists, aquifer presence has not been observed in the mid-South of the study area. This fact has historically been supported by the presence of faults acting as a structural boundary; however, recent work consider a lateral facies change as the best explanation (*Jimenez-Martinez et al.,* 2012). The Pliocene aquifer unit covers the entire area of Campo de Cartagena, except the western zone. At the north-eastern part, it is hydraulically disconnected from the rest of the unit and it is named 'Cabo Roig' aquifer. Finally, the Quaternary aquifer covers almost the entire Campo de Cartagena area. A horst (Cabezo Gordo) formed by marbles and limestone of Triassic basement crops out in the center of the basin. The hydraulic connection among aquifers and basement materials is unknown.

The natural recharge area of confined aquifers is constituted by a small fringe of the northern area where they outcrop, while the unconfined aquifer, besides precipitation, also recharge from irrigation return flows. Piezometric level is sub-parallel to the costal line (Figure 3) for all aquifers except the Tortonian. This natural pattern can be locally altered in zones with high-density of pumping wells. Natural submarine groundwater discharge from confined aquifers is not well known. Indeed, two situations are described: *i*) the Mar Menor boundary is conformed by faults which may act as a hydraulic barrier preventing seawater intrusion to the aquifers (*Rodriguez Estrella,* 2004); however, *ii*) further North, when limiting to the Mediterranean Sea, the presence of faults has not been detected, and aquifer offshore continuity is accepted (*Jimenez-Martinez et al.,* 2012; *Acosta et al.,* 2013). Groundwater discharge from the unconfined aquifer (Quaternary age) is to the Mar Menor lagoon and the Mediterranean Sea (*IGME*, 1991; *Garcia-Pintado et al.,* 2007; *Baudron et al.,* 2015). The hydraulic aquifers connection with the western (Los Victorias mountain range) and southern (Cartagena-La Unión mountain range) (*Robles-Arenas et al.,* 2006) borders is unknown.

The confined aquifers were 'artesian' up to the early 20th century (e.g., *Dupuy de Lome et al.,* 1917). The increasing groundwater exploitation for agricultural purposes resulted in an inversion of the vertical hydraulic gradients, which was further mitigated with the *Tajo-Segura Water Transfer* in 1979 (*Garcia-Arostegui et al.*, 2012; *Baudron et al.,* 2014). The *Tajo-Segura Water Transfer* has led to an increase of groundwater recharge to the unconfined aquifer and subsequently in a groundwater level rise, leading to a drainage system design and construction which increased agrochemicals discharge into the Mar Menor lagoon (*IGME*, 1991; *Garcia-Pintado et al.,* 2007). The combination of the unconfined aquifer, polluted by agrochemicals due to the irrigation return flows (*Baudron et al.,* 2013a, 2014), and the great density of abandoned, leaky and poorly constructed wells, induce cross-formational groundwater flow and contaminant transport between the shallow, unconfined and the deep, confined aquifers (*Jimenez-Martinez et al.,* 2011; *Baudron et al.,* 2013a). To overcome contamination problems and satisfy water quality demand, the aforementioned small private desalination plants of brackish groundwater are also in operation.

3. Mar Menor coastal lagoon

The Mar Menor (135 km^2) is one of the largest and well-known coastal lagoons of the Mediterranean basin (*Perez-Ruzafa et al.,* 2011, 2013). It has a volume of 591 hm^3 with a mean depth of 4.5 m and a maximum depth close to 6.5 m (Figure 1). Water temperature at the bottom of the lagoon ranges from 30.2 in summer to 7.8 ºC in winter, in accordance with atmospheric temperature changes (*Baudron et al.,* 2015). The Mar Menor is separated from the Mediterranean Sea on its eastern side by a 22 km long, narrow, sandy bar system called La Manga (width between 100 and 1200 m). A significant number of the Mar Menor sand barrier sections can be particularly vulnerable to the effects of storm events, common in the Mediterranean coast, during spring and winter (*Sanchez-Badorrey and Jalon-Rojas*, 2015). The sand bar is scattered by four volcanic outcrops, along with three small volcanic islands in the lagoon (Figure 1 and 3).

This particular ecosystem has an important natural value, although it has been degraded in the last decades by the agricultural activities and the urbanization mainly in the perimeter of the lagoon. On the perimeter, salt marshes present numerous plant species adapted to salinity (e.g., *Martinez-Sanchez et al.*, 2006). Therefore, the lagoon and its salt marshes are an important place for migratory birds (e.g., *Fernandez et al.*, 2005). Fishing was practiced as an economic activity in the past, but the pollution of the lagoon in the last decades and the current standards of regulation have reduced its practice primarily to a sporting activity (e.g., *Marcos et al.*, 2015). Flora and fauna are bio-indicators of trophic changes and ecosystem deterioration in the Mar Menor lagoon. Due to its ecological importance, anthropogenic pressures, and the subsequent environmental impacts, several measures have been carried out in order to improve the protective status of the Mar Menor lagoon. In 2001 it was officially declared a vulnerable area by the 'Orden de 20 de diciembre de 2001'. This status imposes a rigorous treatment of urban wastewater, according to Directive 91/271/EEC. In addition, Mar Menor lagoon has been declared a Site of Community Importance (SCI), Special Protection Area (SPA), Specially Protected Area of Mediterranean Importance (SPAMI), and is included in the Wetland Protected Natural Area in the RAMSAR convention. Its main effluent, the Albujón *rambla* has also been declared a sensitive area by a Ministry of Environment Resolution (BOE No 180, 2011).

4. Campo de Cartagena anthropogenic impacts

4.1. Water imbalance

According to the Segura River Basin District Management Planning (*CHS*, 2014), water demand in the Segura River Basin exceeds available renewable water resources by about 35% (480 hm^3). Groundwater levels have been dropping steadily over the last decades (*Custodio* 2015; *Garcia-Arostegui et al.,* 2015; *Custodio et al.,* 2016), suggesting that part of this imbalance is met with non-renewable groundwater extraction. However, available data on extractions are not considered to be reliable. The *Tajo-Segura Water Transfer* became operational in 1979 to meet part of the unmet demand in the Campo de Cartagena area, and since then water demand coverage increased considerably. In spite of large investments in irrigation infrastructure, overall water demand remained more or less stable (*CHS*, 2014) over the last two decades (*Alcon et al.*, 2011; *Soto-Garcia et al.*, 2013). Indeed, higher irrigation efficiencies were balanced by the expansion of new irrigated areas (*Soto-Garcia et al.,* 2013) and touristic sector (*Zimmer*, 2010). The imbalance between renewable water availability and water demand already cause a wide range of pressures to the environment (*Conesa and Jimenez-Carceles*, 2007; *Carreño et al.*, 2008; *Senent-Aparicio et al.,* 2015) and pose a threat to the sustainability of the production systems in the Campo de Cartagena area.

Contreras and Hunink (2015) analyzed the use and supply of water resources in the Campo de Cartagena area, applying a water accounting SEEAW methodology (*UN*, 2012). Most data used in this study were provided by the Segura Water Authority, other water-related entities and the Segura River Basin Management Plan (*CHS*, 2014). Table 1 summarizes the quantification of annual water use per sector and the corresponding water sources, including groundwater abstraction, desalinization, re-used wastewater, and external water from the inter-basin transfers. The Campo de Cartagena basin receives on average 87 hm^3/year of water from outside the basin, of which 79 hm^3/year (91%) is from *Tajo-Segura Water Transfer* mainly for irrigated agriculture, and 8 hm^3/year (9%) from the external *Taibilla* watershed for domestic (including tourism sector and households) and industrial use.

For the overall water balance assessment of the area, *Contreras et al.* (2014) used a hydrological model to simulate irrigation water applied and the soil-water balance. Estimates of groundwater exploitation were obtained from provided data on water transfer and water requirement. Finally, results have been summarized to assess surface-groundwater interaction at the basin scale in a water balance (period 2002-2011) diagram (see Figure 4). Besides the surface-groundwater relationships, this Sankey diagram shows separately accounted the main fluxes (in hm^3/year) in the irrigable area and rainfed-native lands of the basin. Mean annual precipitation for the analyzed period was 316 mm, while actual evapotranspiration from irrigable and non-irrigated areas was 448 mm and 210 mm, respectively. The diagram indicates that on average, less than half of the water lost by crop evapotranspiration comes from rainfed soil moisture and the rest comes from irrigation inputs. On an annual basis fraction of evapotranspiration met with irrigation varies between 35-70% during the simulation period (*Contreras et al.*, 2014). Based on the distributed modelling approach, infiltration from irrigable and non-irrigated areas was estimated to be on average 66 hm^3/year and 46 hm^3/year, respectively. Surface runoff to the Mar Menor lagoon was estimated to be around 8 hm^3/year, a value which is in agreement with that reported by *Garcia-Pintado et al.* (2007) and *Baudron et al.* (2015). According to *Jimenez-Martinez et al.* (2011), the diagram includes a rough-average estimate of the leaking water flux from the upper aquifer to the confined aquifers, i.e., a ~40% of the total incoming flow that reaches the Quaternary aquifer. It is assumed that the remaining fraction, i.e., 68 hm^3/year, discharges mainly into the Mar Menor lagoon, but also into the Mediterranean Sea (NE of the basin). This result is the same order of magnitude as those obtained from isotopic techniques (*Baudron et al.,* 2015).

To better understand the demand and supply imbalance at basin level, the following indicators were calculated from Table 1:

- *Water Consumption Index,* fraction of water consumption met with renewable and exploitable (re-use and desalinization) water resources (assuming transferred water is renewable water): $\frac{C-(G-L)}{C}100 = \frac{210-(104-46)}{210}100 = 72\%$, where C is the total consumption, G the groundwater extraction from confined aquifers, and L fraction leaking to confined aquifers.
- *External reliance*, fraction of water use met with external water resources from the inter-basin transfers: $\frac{WT}{WU}100 = \frac{87}{210}100 = 41\%$, where WT is the total water transfers, and WU the total water use.

- *Groundwater footprint,* area required to sustain groundwater use (*Gleeson et al.,* 2012): $\frac{G}{L-ER}A = \frac{104}{46-0}1236 = 2794\,\mathrm{km}^2$, where A is the basin size (km^2), G the groundwater abstraction, L fraction leaking to confined aquifers, and ER the environmental requirements (assumed 0 hm^3/year for confined aquifers).

The above indicators show that a significant part of water demand is currently met with non-sustainable groundwater resources through pumping as well as the high dependence of the basin on external resources. Moreover, the groundwater footprint is considerably greater than the total aquifers area (1238 km^2), stressing the extremely high pressure on the groundwater resources.

4.2. Aquifer cross-contamination

Characterizing the aquifer cross-contamination hazard of a multi-layered aquifer is a complex task that requires a thorough understanding of both the geological and artificial connections existing between aquifer layers. In the last decades, a number of studies described the hydrogeology of the Campo de Cartagena with relations to its aquifer potential and to natural aquifer cross-contamination (*IGME*, 1974, 1982, 1991; *IGME-IRYDA* 1979; *Jimenez-Martinez et al.,* 2011; *Rodriguez Estrella*, 2004). However, this topic has not yet been totally resolved yet due to the complexity of geological structures and the scarce number of boreholes featuring clear lithological and design data.

Structural and sedimentological data indicate the presence of very thick aquitard layers between aquifers. The geometry characterization rejected the existence of significant water fluxes through the thick aquitards-aquicludes (*Jimenez-Martinez et al.,* 2011). Furthermore, the presence of faults around the Cabezo Gordo outcrop (Triassic, Figure 1 and 3) may suggest a direct contact between the Neogene deposits and the basement rocks, and then a natural connection between aquifers. Nonetheless, the very low piezometric levels and the limited agricultural activity around this outcrop inhibit the hazard of contamination. Combining deep geology, geothermal, biological and archaeological (*Walker et al.,* 2011) data, *Garcia-Arostegui et al.* (2012) showed that the faults at the Cabezo Gordo outcrop appear as the most probable natural outlet for confined aquifers (Pliocene, Messinian and Triassic). The high groundwater temperature (> 35 ºC) measured in shallow tube-wells around Cabezo Gordo may suggest the uprising of deep groundwater (e.g., *IGME*, 1982), although this evidence requires further investigation to ensure that it is not a local anomalous geothermal gradient (e.g., *Baudron et al.,* 2014).

In addition to the aforementioned natural connections, boreholes may promote vertical connection between aquifer layers. This fact has been observed in numerous studies under different geological scenarios and exploitation frameworks (*Lacombe et al.,* 1995; *McMillan et al.,* 2014; *Tamea and Butera,* 2014). In a multi-layer aquifer, non-adequate or abandoned wells penetrating through geological strata, otherwise considered low-permeability (aquitard and aquiclude), can act as open conduits for pollutant migration. Currently, more than 2000 boreholes/wells exist in the Campo de Cartagena, having a high areal density (1.18 wells/km^2) that increases towards the coast. Therefore, aquifer cross-contamination is an issue of increasing concern in the Campo de Cartagena (*Jimenez-Martinez et al.,* 2011; *Baudron et al.,* 2013b and 2014).

Potentiometric data are required to understand the drivers of such inter-aquifer connections. Recently, a one-century reconstitution of the water table evolution has been proposed (e.g., *Garcia-Arostegui et al.,* 2012; *Baudron et al.,* 2014). It reveals an inversion of the vertical hydraulic gradient in 1950-60s, mainly in the coastal area, as a consequence of intense withdrawals (Figure 5). This inversion, along with the aforementioned high number of poorly constructed and abandoned wells, could be the primary cause of the aquifer cross-contamination. Regarding piezometric evidence, it is supported by different approaches. *Jimenez-Martinez et al.* (2011) included the use of geochemical and isotopic tools; specifically, nitrate was used as a tracer for evaluating the impact, and water mixing calculations. Results showed an increase of the impact of the unconfined aquifer on the confined aquifer along the groundwater flow direction toward the coast. Using high-sensitivity vertical temperature logging inside multi-layer boreholes, *Baudron et al.* (2014) also demonstrated the existence of downward inside-borehole vertical fluxes in steady-state regime (i.e., no pumping). From radiogenic and stable isotopes, *Baudron et al.* (2014) showed that the modern downward contamination can reach up to the Messinian aquifer, even deeper than the Pliocene as shown by *Jimenez-Martinez et al.,* (2011). Note that, lack of data regarding borehole designs (lithological columns and screen positions) makes difficult to adopt geochemical approaches using available databases, since uncertainty on groundwater sample origin (aquifer layer) still remains. A Random Forest method (*Baudron et al.,* 2013b) has recently been applied to identify the origin of water samples, and increase the quantity of reliably usable geochemical data. This study demonstrates a high degree of mixing, implying high groundwater sample origin (aquifer layer) uncertainty.

4.3. Acid mine drainage

Now derelict, the southern boundary of the Campo de Cartagena, Sierra de Cartagena-La Unión mountain range, was a very active mining district for Ag, Pb, Zn, Cu, Fe and Mn exploitation of the sulfide strata-bound ore deposits for more than three thousand years (*Manteca and Ovejero*, 1992). Nowadays, and since 1991 when a mining closure program was adopted, the area has remained abandoned (*Navarro et al.,* 2008).

Underlying the southern part of the Campo de Cartagena basin and the Mediterranean Sea, the mining district constitutes a complex hardrock aquifer defined by five groundwater units of limited size formed along fracture zones outcropping over approximately 100 km^2. The local hydrology has been highly modified by more than 3000 open mine shafts, thousands of kilometers of underground workings, and from an unknown number of adits. While recharge is originated by precipitation, discharge is produced by intense evaporation from shafts, open-pit lakes, springs, seepages from adits and surface drainage to the Mediterranean Sea and to Campo de Cartagena. Pumping from wells also takes place in this sector. Local groundwater flow is controlled by underground mining (adits), joints and faults; hydraulic interconnection between blocks is extremely low in spite of the high shaft density in the area (Figure 6), and differences in water level greater than 100 meters are observed even in closely-spaced shafts (60 m). Inferred groundwater flow direction follows the N130E fault system and the underground workings trend. The hydrochemical facies, due to water interaction with silicate, carbonate and sulfides (pyrite, marcasite, galena, chalcopyrite and pyrotine) bearing deposits, are: SO_4^{2-} as the main anion, while Mg^{2+}, Na+ and Ca^{2+} as cations (*Robles-Arenas et al.,* 2006*; Robles-Arenas and Candela*, 2010).

Disregarding the surrounding hydrology and ecosystem, mineral production was the only objective of mining activities, leading to important environmental stresses (*Conesa and Schulin*, 2010;

Gonzalez-Fernandez et al., 2011a) and affecting the area in diverse ways. A post-mining evaluation of land-use changes identified 2351 mine waste dump accumulations from open-pits (12 in total), adits, waste-rocks metallurgical processes, and flotation (sludge) tailing dams (*Garcia*, 2004; *Robles-Arenas et al.,* 2006). They occupy an area of 9 km^2 and an approximate volume of 175 hm^3 on land and 25 hm^3 in the sea, mainly in the Portman Bay area (*Martinez-Sanchez et al.,* 2008; *Manteca et al.,* 2014). The chemical composition shows that mine and metallurgical wastes still have significant Pb, Zn, Fe, Mn, Cu, Cd and Ni concentrations. Surface-water and groundwater pollution by heavy metals and acid-mine drainage, caused by the oxidation and hydrolysis of metal sulfides, occur. Except for springs and rainwater, most of water samples exhibit neutral-acidic pH (e.g., shafts), while the two open-pit lakes have a pH between 2.5 and 3.0.

Rainfall, runoff originated during extreme events, and wind activity allow the transport of particles and dissolved contaminants from the eroded mining and metallurgical wastes to the Campo de Cartagena plain, the hypersaline lagoon of Mar Menor, and the Mediterranean Sea (*Tsakovski et al.,* 2012; *Marin-Guirao et al.,* 2007). Sediments in the stream beds (Beal and Ponce *ramblas*) are by nature composite samples with colloids and particulate formations with high presence of Pb (39000 ppm), Zn (2000 ppm) and Cd. The top-soil in the flood plain of wadis is extremely polluted, presenting high eco-toxicity (*Bes et al.,* 2014). The mean concentration for heavy metals is: Pb_{tot} 4000 ppm, Zn_{tot} 4600 ppm, Cd_{tot} 4.5 ppm and Cu_{tot} 50 ppm (*Navarro et al.,* 2008; *Robles-Arenas et al.,* 2006; *Gonzalez-Fernandez et al.,* 2011b, *Martinez-Martinez et al.* 2013). Evaporation of acid waters during dry periods triggers the precipitation of soluble salts. The efflorescent salts, secondary metal-sulfate minerals that form from weathering, are highly soluble salts that build up in waste-pile surfaces. During high-intensity rain storms salts readily dissolve and metals and metalloids are jointly mobilized with an appreciable amount of suspended solids by runoff (*Robles-Arenas and Candela*, 2010). The constant easterly wind, called ‘Levante’, creates dust storms, promoting soil erosion, and also transports fine particles of airborne sulphate and heavy metal concentrations from tailing dams to the surrounding areas (*Moreno Brotons et al.,* 2010). The result is an enrichment of dissolved solids in rainfall (*Alcolea et al.,* 2015) and its further deposition.

5. Mar Menor lagoon: contamination and eutrophication

The Mar Menor lagoon, on the eastern border of the study region, has been converted into a huge sink of nutrients and heavy metals derived of all anthropic activities previously presented (Figure 7). Anthropogenic pressure on the lagoon comes from multiple sources and occurs at different spatio-temporal scales (*Perez-Ruzafa et al.,* 2007), which can be grouped according to quantitative (hydrology) and qualitative (quality and pollution) aspects, with complex interrelationships/interlinks between them. Numerous works that characterize the ecosystem have been developed in order to improve the understanding of these processes. Anthropogenic pressure is linked to: *i*) hydrological changes, *ii*) mining activities, *iii*) agrochemicals, and *iv*) contaminants of emerging concern.

5.1. Impacts from hydrological changes

Hydrological changes in the lagoon have been mainly conditioned by resorts development for tourism, which has led to urban growth and associated spills, filling of reclaimed land, opening and dredging of channels in La Manga litoral barrier (sand bar), construction of marinas and artificial beaches, among others. Such actions have affected water fluxes and ecosystems at different levels.

Several inlets connect the lagoon with the Mediterranean Sea (Las Encañizadas, El Estacio and Marchamalo artificial channels, see Figure 7). The main water exchange occurs through the artificial El Estacio channel, which was widened and dredged in 1972 to make it navigable. The opening of artificial channels increased the water renovation rate, decreased water salinity (from 50-53 to 40-45 psu), and softened extreme temperatures. New colonizing species could then access the lagoon in a 'Mediterraneanisation' process (*Perez-Ruzafa et al.,* 1987, 1991, 2005, 2009). It has important consequences for tourism, but, on the other hand, helps to regulate and maintain the food web water quality.

Several studies have been recently conducted to understand the hydrodynamics and water balance of the Mar Menor lagoon (*Baudron et al.,* 2015; *Cabezas,* 2009; *De Pascalis et al.,* 2012; *Gilabert,* 2009; *Martinez-Alvarez et al.,* 2011). All of them agree in the need to improve the present biological and chemical monitoring system. Water surface inflows to the lagoon does not counterbalance the high evaporation rates due to the low values of precipitation, which may occur during storm events, so a net inflow from the Mediterranean Sea has been estimated to be 130 hm^3/year (*Cabezas,* 2009). From 2003 to 2006, the mean daily water exchange with the Mediterranean Sea was estimated to be 1.77 hm^3/day, considering water, heat and salt balances (*Martinez-Alvarez et al.,* 2011). The hypersaline lagoon is therefore euhaline. Renewal time rate ranges from 0.66 to 1.2 year (*Cabezas,* 2009; *Martinez-Alvarez et al.,* 2011; *Perez-Ruzafa et al.,* 2005; *Umgiesser et al.,* 2014). Water circulation can be very dynamic and is mainly controlled by wind and atmospheric pressure. Despite a weak stratification in the early morning, the water column can be considered homogeneous along depth (*Baudron et al.,* 2015; *De Pascalis et al.,* 2012). Recently, an estimate of submarine groundwater discharge from the Quaternary aquifer to the lagoon was performed combining radon, radium and hydrodynamic modeling (*Baudron et al.,* 2015). Based on these results, saline recirculation through the sediment was evidenced as the main process governing total groundwater discharge, while the influence of groundwater inputs from the Albujón *rambla* (Figure 1 and 7) on the spatial distribution of physico-chemical and geochemical tracers along the coast could be assessed.

Additionally, the Mar Menor lagoon is considered to be one of the most threatened Spanish coastal areas by the potential rise of the Mean Sea Level (*Losada et al.,* 2014). Results from climate change simulations projected to 2100 under A2 scenario and combined with hydrodynamic models may suggest an increase of annual mean temperature of the water by 3.28 ºC and a decrease of salinity by 1.53 psu (*De Pascalis et al.,* 2012). On the other hand, the potential sea level rise could modify the hydrological functioning of the system: changing for example the base level of the *ramblas* and the erosion rates; changing the current groundwater discharge regime, and the pollutants and nutrients discharge as consequence.

5.2. Impacts from mining activities

The oldest anthropogenic pressure on the Mar Menor lagoon is linked to the above-described mining in the Sierra de Cartagena-La Unión (Figure 7). As mentioned above, numerous studies exist on the impact of mining wastes on the surrounding streams and wetlands to the Mar Menor lagoon, and the role they play in retaining metal contaminants (*Alvarez-Rogel et al.,* 2004, 2007, 2006; *Gonzalez-*

Alcaraz et al., 2011, 2013; *Jimenez-Carceles and Alvarez-Rogel,* 2008; *Jimenez-Carceles et al.,* 2008, 2006). However, studies for quantifying the presence of metals in the lagoon are scarce. In the marine environment, metals appear as dissolved, particulate, and complexed forms, distributed between different environmental compartments, such as water, suspended solids, sediments and biota. Lagoon waters do not present significant amounts of dissolved metals due to the basic pH and high salinity (*Lloret et al.,* 2005), although concentration abruptly increase during storm episodes, when water becomes toxic mainly in areas close to the outlets of the southern streams (*Albaladejo et al.,* 2009; *Marin-Guirao et al.,* 2007). High amounts of metals and metalloids (Zn≥Pb>Mn>>As>>Cu>Cd) have been detected in sediments (*Albaladejo et al.,* 2009; *Conesa and Jimenez-Carceles,* 2007; *Maria-Cervantes et al.,* 2009), with maximum values (mg/kg dry weight [dw]) of 7.1 for Zn, 6.9 for Pb, 5 for Mn, 501 for As, 74 for Cu and 9.1 for Cd (*Maria-Cervantes et al.,* 2009). Removing these pollutants from the sediments is a complex task due to the elevated quantities and the possible additional environmental impacts on the lagoon ecosystem (*Conesa and Jimenez-Carceles,* 2007).

Bioavailability of metals in three macrophytes plants has been studied, demonstrating the existence of high levels of Pb and Zn (*Sanchiz et al.,* 2000, 2001). Metals concentrations in biofilms reflect their high bioavailability in the organisms that live in the lagoon, especially for Zn (3900 mg/kg) and Pb (1500 mg/kg) (*Marin-Guirao et al.,* 2005a, b). Bioaccumulation of metals mainly occurs in filter feeders and some invertebrates (*Albaladejo et al.,* 2009; *Marin-Guirao et al.,* 2008, 2009). Some authors have reported human health risk as a number of mollusks are collected and locally consumed (*Maria-Cervantes et al.,* 2009).

5.3. Impacts from nutrient inputs and eutrophication issues

Sewage discharges from urban areas are usually considered as the main source of phosphorus in aquatic systems, while agriculture is often considered as the main source of nitrogen. The significant increase in agricultural activity in the Campo de Cartagena during the last century has led to an increase of the nutrient inputs to the different water compartments and the generation of impacts on water quality, benthic vegetation, and phytoplankton jellyfish quantities and dynamics. Nutrient inputs occur superficially, mainly at the mouth of the Albujón *rambla* where the flow became permanent since the 1980s'. Although no permanent gauging station exists, a long term monitoring system evidenced a steady flow of 7.7 hm^3/year (*Baudron et al.,* 2015; *FIEA,* 2011). Nutrient inputs also take place through submarine groundwater discharge from the Quaternary aquifer, although they are often not considered in detail due to the misunderstanding of groundwater processes and to the lack of a specific network of observation wells.

Estimation of the anthropogenic nutrient discharge into the Mar Menor, focusing on the Albujón *rambla*, has been covered in several studies (*Baudron et al.,* 2015; *Garcia-Pintado et al.,* 2007; *Martinez-Fernandez et al.,* 2005; *Velasco et al.,* 2006). During a monitoring of this stream in the 02/2003 to 04/2004 period, it was found that 50% of the 250 t/year of total dissolved inorganic nitrogen (DIN) came from agricultural sources, while 70% of the 52 t/year of total phosphate (TP) and 91% of total organic carbon (TOC) came from urban point sources (*Garcia-Pintado et al.,* 2007). In a tentative calculation, the same authors estimated the order of magnitude of groundwater discharge of nutrients to be 350 t/year DIN and 17 t/year TP. A further monitoring of the Albujón *rambla* (July 2012), which includes a combination of geochemical and isotopic tracers as ^{222}Rn and ^{224}Ra, revealed that most of the Albujón *rambla* discharges were driven by the release of brines from small private desalination plants (*Baudron et al.,* 2015).

The net amount of nutrients into the Mar Menor through the *ramblas* usually falls as a result of plant uptake and/or denitrification in the surface streams (*Garcia-Pintado et al.,* 2007). In addition, salt marshes around the lagoon may play an important role since they are able to retain high quantities of nutrients, acting as 'green filters' or 'buffer zones' (*Conesa and Jimenez-Carceles,* 2007; *Gonzalez-Alcaraz et al.,* 2011, 2012, 2013; *Jimenez-Carceles et al.,* 2008). Hydrological changes linked to agricultural irrigation have affect local-native plant communities in lowland wetlands, resulting in the replacement of valuable halophilic salt marsh and salt steppe plant communities by more generalist and opportunistic taxa, such as *Phragmites australis* (reed beds) (*Carreño et al.,* 2008; *Martinez-Lopez et al.,* 2015).

Until the early 1970s, the Mar Menor was markedly oligotrophic and primary production was mainly benthic, with seagrass being the main macrophyte (*Perez-Ruzafa et al.,* 2009). During the first years of the 1980s, following the enlargement of El Estacio (artificial man-made channel communicating with the Mediterranean Sea), the bottom of the lagoon began to be covered with a different species of seagrass macrophyte. In the early 1990s, a dense meadow of invasive macroalgae was covering most of the bottom. Nitrate concentrations were low (less than 0.62 mg/L NO_3^-) contrasting with higher values of phosphates (*Perez-Ruzafa et al.,* 2009, 2012, 2013). In the late 1990s nitrate concentrations were ten times higher, especially during spring and summer and near the *ramblas* mouth (*Perez-Ruzafa et al.,* 2009). In years 2010 to 2012, high nitrate levels (up to 1 mg/L) along the western coast of Mar Menor were found to be mainly associated with the discharge from the Albujón *rambla* (*Baudron et al.,* 2015).

Given the current nutrient values, with an excess input of nitrogen, phosphorus is the limiting factor of biological productivity in the lagoon. Thus, given that the source of phosphorus is primarily urban, the sewage treatment plants program conducted in the 2001-2010 period (*Rodenas and Albacete,* 2014) has substantially contributed to maintain the Mar Menor water in a relatively good quality, reducing considerably the phosphorus released into the lagoon. Some authors suggest that the relatively low density of phytoplankton is due to the control exerted from the higher levels of the food web (top-down), such us the gelatinous plankton and ichthyoplankton, which maintain low chlorophyll levels, although they maintain very high populations of jellyfish (*Perez-Ruzafa et al.,* 2009). Alternatively, other authors indicate that the high biomass of the main primary producer (macroalgae) increased the resistance of the lagoon to eutrophication processes through the high uptake of nutrients from the water column and their retention in the sediments, avoiding high phytoplankton densities (*Lloret and Marin,* 2009, 2011; *Lloret et al.,* 2008; *Marin et al.,* 2009). According to these authors, if climate change predictions attains predicted values, the current ecological status of the lagoon is likely to collapse, since future environmental conditions could make the invasive macroalgae unable to reach values of net photosynthesis greater than zero, and eutrophication processes are expected to appear (*Lloret et al.,* 2008). In any case, the relative oligotrophic conditions of the lagoon are expected to change and clear eutrophication processes may appear.

5.4. Presence of emerging-organic contaminants of concern

The presence of organochlorine pesticides was confirmed in biota and sediment sampled in summer 1995 close to the most relevant watercourses -Albujón and Carrasquilla *ramblas*- but other pesticides, such as triazines, were not detected (*Perez-Ruzafa et al.,* 2000). From spring 2009 to winter 2010, 82 semi-volatile organic pollutants (persistent organic pollutants, different groups of pesticides and others) were found in lagoon water samples for the first time and in the Albujón *rambla*, sampling included regular periods and two flash flood events of September 2009 (*Moreno-Gonzalez et al.,* 2013a). The most ubiquitous pollutants detected in the Mar Menor lagoon were chlorpyrifos (up to 45.8 ng/L), chlortal-dimethyl (up to 5.2 ng/L), terbuthylazine (up to 12.9 ng/L), propyzamide (up to 63.1 ng/L) (all of them plaguicides, with maximum detected values in autumn 2009), and naphthalene (up to 27.2 ng/L in spring 2009). The highest concentration for the majority of pollutants was detected in autumn as consequence of air and surface/ground water inputs, but specially from terrigenous materials deposited in sediments by two intense flash flood events (*Moreno-Gonzalez et al.,* 2013b). On the other hand, in watercourses, the most commonly detected analytes were propyzamide (up to 372 ng/L), triazine compounds (e.g., terbutryn up to 4968 ng/L), and chlorpyrifos (up to 3597 ng/L), with a distinct seasonal pattern of insecticides during summer and herbicides in winter. Inputs to the Mar Menor of many pesticides during periods of heavy rain representing more than 70% of total yearly input (*Moreno-Gonzalez et al.,* 2013a), with the highest annual input corresponding to terbuthylazine-desethyl (2.8 kg), chlorpyrifos (1.5 kg) and terbutryn (1.3 kg). The impact of flood events in the distribution of persistent organic contaminants in the lagoon is therefore considered of main relevance (*Leon et al.,* 2015).

Also, bioaccumulation of polycyclic aromatic hydrocarbons (PAHs), organochlorine pesticides (OCPs) and polychlorinated biphenyls (PCBs) was detected in cockle, oyster and noble pen shell, in sampling campaigns of spring and autumn 2010 (*Leon et al.,* 2013). PAH concentrations ranged from 8.98 to 370 µg/kg [dw], PCBs from 0.15 to 42.36 µg/kg [dw], and DDXx (dichlorodiphenyl-) from below detection limit to 240.6 µg/kg [dw]. The bioaccumulation of PAHs was similar for three bivalves being higher close to seaports and wastewater effluents.

Seasonal occurrence and distribution of surfactants (Linear Alkylbenzene sulfonates, LAS, nonylphenol polyethoxylates, NPEOs, and polyethoxylates Alcohol AEOS), contaminants of urban origin primarily, revealed the inputs. After several campaigns carried out between spring 2009 and winter 2010, surfactants concentration in lagoon water were found between 0.3 to 63 µg/L, with a highest annual input through the Albujón *rambla* corresponding to LAS (406 kg) and their metabolites (sulfophenyl carboxylic acids, 482 kg). In sediments the values range between 44 and 1665 µg/kg (*Traverso-Soto et al.,* 2015). The physicochemical occurrence and distribution of surfactants in the system could be explained by *i*) a combination of different sources (surface and groundwater inputs, treated and untreated wastewater effluents, towns, and seaports), and *ii*) jointly *in-situ* (degradation, adsorption, between others) and biological processes, with a special emphasis on degradation during warmer months (*Traverso-Soto et al.,* 2013, 2015).

The presence of drug compounds was confirmed in recent studies, and the ecological risks should be analyzed in future research. Between summer 2009 and winter 2011, several sampling campaigns were carried to analyze pharmaceuticals in water sources from different origins (Albujón *rambla*, lagoon water and sediments) (*Moreno-Gonzalez et al.,* 2014, 2015). The wastewater treatment plants were found that the main source of such products, estimated around 11 kg/year, corresponding mainly to antibiotics (46%), discharged into the Mar Menor through the Albujón *rambla*. Concentrations higher than 1000 ng/L were found for azithromycin, clarithromycin, valsartan, acetaminophen and ibuprofen (*Moreno-Gonzalez et al.,* 2014). A total of twenty pharmaceuticals were found in lagoon water, at concentrations from trace amounts (ng/L) to 168 ng/L (azithromycin), and fourteen pharmaceuticals in sediments from trace amount (ng/g) to 50.3 ng/g (xylazine) (*Moreno-Gonzalez et al.,* 2015).

6. Mitigation measures for human pressures and impacts

6.1. Towards a sustainable water balance

To reduce water consumption, and the imbalance between renewable water availability and demand in the Campo de Cartagena basin, the following measures have been suggested by various authors.

On-farm technological and management measures, such as deficit irrigation (*Perez-Pastor et al.*, 2008; *Egea et al.*, 2010), waste water reuse (*Lopez-Galvez et al.*, 2014), use of desalinated water (*Martinez-Alvarez et al.*, 2014; *Martin-Gorriz et al.*, 2014), new irrigation water saving technologies (sub-surface irrigation, reservoir covers, or plastic covers) (e.g., *Maestre-Valero et al.*, 2013) and irrigation scheduling tools (e.g., *Tapsuwan et al.,* 2014) have been extensively assessed in the area. These solutions can only lead to an effective water imbalance reduction if farmers are incentivized or subsidized to reduce water consumption (*Berbel and Mateos*, 2014). Investments over the last decades in drip irrigation technology have not led to an effective reduction of irrigation water as could be expected (*Alcon et al.*, 2011; *CHS*, 2014). These evidences may suggest that proposed measures had little scope to significantly reduce the imbalance in the Campo de Cartagena basin.

The use of economic and institutional instruments have been analyzed, including water pricing, water markets and insurance programs. Results from *Alcon et al.*, (2014) suggest that farmers are willing to pay twice as much as current irrigation water price to ensure water supply reliability through governmental supply guaranteed programs. However, *Perez-Blanco et al.* (2015) have shown that water pricing schemes may be unsuccessful to reduce water use in this area. Results from *Perez-Blanco and Gomez-Gomez* (2013) show that drought insurance programs may potentially induce to annual groundwater abstractions savings at a cost of one order of magnitude lower than farmers willingness to pay for water security by risk adverse. *Rey et al.* (2015) also suggest implementing farmers' drought insurance initiatives as a potential solution in this area to manage water supply uncertainty.

Regarding integrated water resources management, the first challenge to overcome the imbalance in the Campo de Cartagena basin would involve the inclusion of the groundwater resources as a fully integrated component of water planning and management strategies (e.g., *CHS*, 2014; *Molina and Melgarejo*, 2015). So far, the quantitative status of the groundwater resource in this basin has only been passively monitored, but it has not been systematically monitored and managed. However, a tentative evaluation of the groundwater management sustainability under limited data availability has been recently proposed (*Senent-Aparicio et al.,* 2015); using for that purpose readily available parameters and under a pressure-state-response framework. This methodology, based on sustainability indices, has highlighted the problems of groundwater pollution and overexploitation. Coordinated use of the resource will reduce the risks that users, mainly farmers, face during drought periods. Currently, sufficient data and information is available, most of it has been reviewed in this paper, on the properties and functioning of the aquifers. We strongly believe that a higher effort is required to include all this knowledge into a decision support system (DSS) able to integrate groundwater evaluation techniques and numerical hydrogeological modelling. This DSS would provide to water authorities, with accurate evaluation and forecasting, useful tools for making an effective conjunctive use of surface and groundwater resources.

6.2. Aquifer cross-contamination mitigation

Long-term groundwater models, that are currently being developed in tandem with incoming advanced statistical studies based on long-term geochemical and hydrodynamic data, could provide additional insights into important questions that relate to aquifer cross-contamination and to the groundwater flow pattern in general (*Jimenez-Martinez et al.,* 2011; *Baudron et al.,* 2013a, 2014). For example, why do groundwater levels in the Pliocene and Messinian aquifers follow such similar temporal evolution trends? Is it simply due to a similar withdrawal pattern or does it reflect a direct connection to neighboring long-screen boreholes? How did upward aquifer cross-contamination affect groundwater chemistry during early groundwater exploitation? Until which level does aquifer cross-contamination attain a regional scale rather than being locally limited to the area around long-screen boreholes?

Although the underground condition makes this a difficult task to address, a series of measures can be adopted to reduce or mitigate the pollution of the deeper aquifers with better water quality. According to *CHS* (2014) it has an estimated cost of 113 M€. The measures include: *i*) reducing extractions; *ii*) improving the agricultural practices, mainly fertilizers application, to reduce the contamination of the Quaternary aquifer; *iii*) sealing the Quaternary section on the long-screen boreholes to avoid aquifer cross-contamination by nitrates in the Pliocene and Messinian aquifers; *iv*) sealing of abandoned wells; and *v*) performing exhaustive control of the construction characteristics for new drilled wells.

6.3. Remediation-restoration of the mining district

As the large affected area impairs a complete environmental site restoration from technical and socio-economic reasons, the research of suitable problem-oriented techniques through field studies stands as the primary focus. While no legal provision exists for further restoration plans, from a cultural point of view, some ideas and efforts to preserve the mining heritage have been developed for the present time (*Conesa et al.,* 2008).

The first mitigation measure should be mining wastes top soil stabilization in the headwaters of the temporary streams (*ramblas*), in order to locally minimize the metals polluted sediments and water input into the Mar Menor lagoon (*Conesa and Jimenez-Carceles*, 2007). Most of the previously developed remediation strategies have concentrated on heavy metals mobility control and acid mine drainage risk mitigation. Since plants can protect soil against water and wind erosion, research on plant species capable of growing on mine tailings or riverbeds and shores with polluted wastes has been carried out (*Conesa et al.,* 2006). First restoration attempts go back to 1982, when a soil cover of 0.5 m was deposited over wastes to allow colonization by the vegetation (*Gomez-Ros et al.,* 2013). However, exfiltration processes did not prevent the uplift transport of some metals to the soil surface, leading to the soil profile contamination. Phytoremediation (*Conesa et al.,* 2007a; *Clemente et al.,* 2012), soil amendments (including demolition wastes (*Murcia et al.,* 2007) or pig slurry and marble waste (*Zornoza et al.,* 2013), phyto- and chemical- stabilization of mine tailings (*Conesa et al.,* 2007b; *Zanuzzi et al.,* 2013)), and open limestone channel as a reactive barrier (*Alcolea et al.*, 2012), are the three most applied techniques until now in the area. However, no cost-benefit analyses have been carried out.

6.4. Mar Menor: from polluted sink to ecological hotspot

Achieving a good ecological status for water bodies by 2015 (extended to 2021, 2027) is the main objective of the European Water Framework Directive (WFD).

The eutrophication problem of the Mar Menor lagoon is one of the main concerns for the Segura River Basin District Water Authority (CHS). Mitigation measures that are considered with a total estimated cost of 426 M€ according to *CHS* (2014), include the following: *i*) improvement of water management measures; *ii*) measures to reduce inputs of treated wastewater into the Mar Menor; *iii*) measures to reduce nutrient inputs to the Mar Menor from groundwater fluxes through a perimeter of pumping battery wells, treatment for contaminant removal of extracted groundwater and subsequent discharge into the Mediterranean Sea; *iv*) measures to reduce irrigation return-flow contributions from agricultural practices outflowing to the Mar Menor through surface and subsurface flows; *v*) implementation of action plans on vulnerable areas to reduce nutrient pollution; *vi*) measures to control brines from private desalination plants that eventually can end up into the Mar Menor; *vii*) environmental restoration measures at the Public Maritime-Terrestrial Domain; and *vii*) protection measures of coastal wetlands and marsh.

There are current research objectives that focuses on the eutrophication problem of Mar Menor from a socioeconomic and management perspective in order to restore the eco-hydrological functionality. Cost-benefit analysis showed that the environmental benefits generated by measures to improve the ecological status of the Mar Menor coastal lagoon can be estimated at 17.4 M€/year (*Perni et al.,* 2011). Classic methods to value costs versus benefits may not be optimal as the complexity of the issues require a more enhanced approach that allows integrating environmental externalities (*Martinez-Paz et al.,* 2013). These same authors applied such an approach to the area and estimated that the overall benefits outweigh costs largely, with an internal rate of return of the investment of almost 10%. Another economic analysis showed that the most cost-effective measures are the restoration of the watercourses that drain into the lagoon and the treatment of polluted groundwater (*Perni and Martinez-Paz,* 2013).

7. Conclusions

The Campo de Cartagena basin and the Mar Menor lagoon is a representative example of a highly human-modified Mediterranean hydro-ecosystem. It comprises multiple complex interrelated pressures and impacts on the hydrological system and dependent ecosystems as a consequence of an intensive landscape exploitation. Investments and management strategies to restore the provision ecosystem services and increase the resilience of the region against future scenarios of climate change require an integrative and holistic analysis and a better understanding of the surface-groundwater processes and feedbacks.

The principal identified impacts from human actions are: water imbalance (28% of consumed water resources are not renewable), aquifer-cross contamination (high areal density, ~1.2 wells per km^2), acid-mine drainage (mine wastes, accounting for ~175 hm^3 on land and ~25 hm^3 in the sea, accumulated mainly between 1957 and 1992), and lagoon eutrophication (NO_3^- up to 1 mg/L). To mitigate these impacts and to guarantee the environmental and economical sustainability of the region, groundwater is a pivotal player in most technological and management measures that are proposed by the scientific community, regional stakeholders and the Basin Water Authority. The most critical measures are: *i*) enforcement of the implementation of improved agricultural practices to reduce leaching to the aquifers; *ii*) implementation of drought plans that include a coordinated management of surface and groundwater resources; *iii*) extension of the area classified as vulnerable by incorporating the aquifers full extension, including Los Victorias Triassic aquifer; *iv*) the sealing the Quaternary section of long-screen boreholes as well as abandoned wells to avoid the aquifer cross-contamination; and *v*) the necessary infrastructure that limits drainage of nutrient and other pollutant inputs from agricultural areas to the Mar Menor lagoon.

These measures can improve the status of the system on the medium-term but on the long-term also action is needed as climate change is likely to affect the surface and sub-surface hydrology of the Campo de Cartagena basin and Mar Menor coastal lagoon in different ways. Sea level rise will change the base level of the *ramblas* and the erosion rates and surface hydrology as a consequence. Sub-surface hydrology will be affected by an increase in sea level as this will raise the groundwater table of the Quaternary unconfined aquifer, change surface-groundwater interaction in the streams (*ramblas*) and potentially increase the discharge of pollutants and nutrients as consequence. The intrusion of saltwater into groundwater systems will also impact coastal ecosystems such as marshes by changing the elevation of the freshwater-saltwater interface. However, since the Quaternary aquifer has a reduced exploitation due to the poor quality status, the most probable scenario will be the so-called flux-controlled system, in which groundwater discharge to the lagoon is persistent despite changes in sea level, with no changes in the sub-surface mass flux of pollutants and nutrients from the aquifer to the lagoon. So far no specific measures are being evaluated or implemented to face these potential climate change impacts in the area.

An effective mitigation of the multiple impacts observed in the region is expected to be achieved only after a wide set of measures will be coordinately adopted. Policymakers face a challenge to promote and support research activities, increase the efforts in monitoring infrastructures, and to foster an integrated and holistic management of water resources including groundwater, to enable a more sustainable development of the regional economy and the survival of its critical ecosystems.

Acknowledgements

The authors gratefully acknowledges support from Spanish Ministry of Economy (Spanish Government) through the Projects GESINH-IMPADAPT (CGL2013-48424-C2-2-R) and EUNCEM (CGL2013-48802-C3-3-R), from the Research Program of Universidad Católica de San Antonio UCAM (PMAFI-06-14), from Fundación Instituto Euromediterráneo del Agua (F-IEA), and from the Region de Murcia Government.

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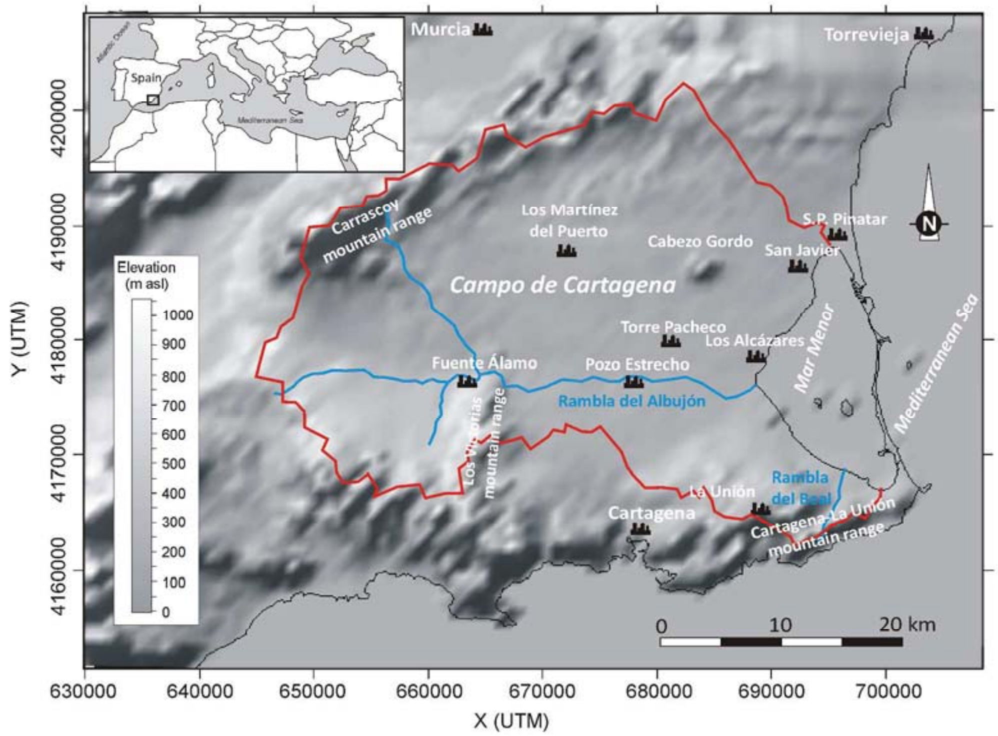

Figure 1. Campo de Cartagena topography showing the basin limit (red line), main populations and temporary water courses (wadis or '*ramblas*', blue line).

Jiménez-Martínez, J., García-Aróstegui, J.L., Hunink, J., Contreras, S., Baudron, P., Candela, L. (2016) The role of groundwater in highly human-modified hydrosystems: A review of impacts and mitigation options in the Campo de Cartagena-Mar Menor coastal plain (SE Spain). Environmental Reviews. doi: 10.1139/er-2015-0089

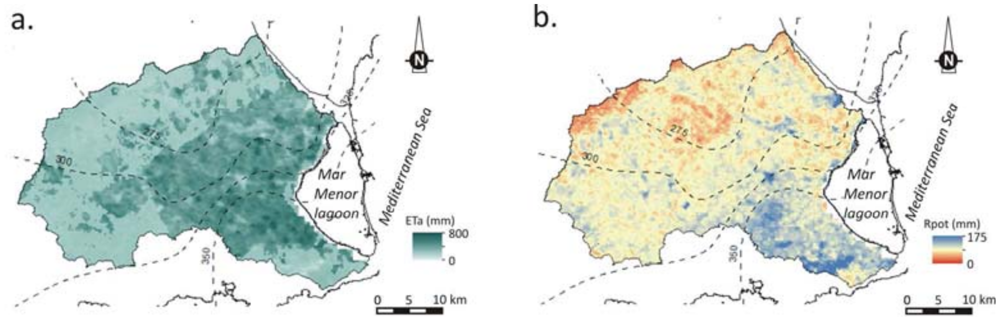

Figure 2. Mean annual values (period 2000-2012) of precipitation (isohyets, dashed lines) computed from 17 climatological stations, actual evapotranspiration ETa (**a.**), and potential recharge Rpot (**b.**) in mm/year, (after Contreras et al., 2014).

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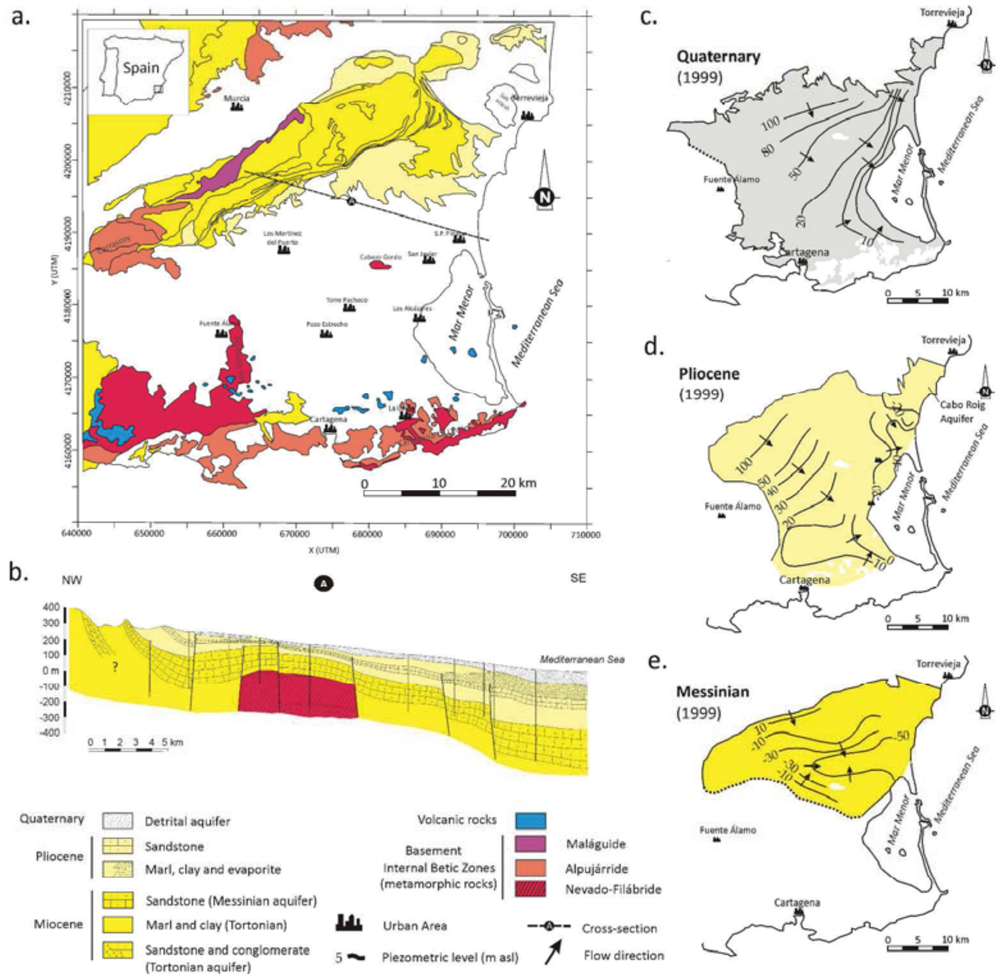

Figure 3. Geological sketch of the study area (**a.**) and cross-section (**b.**). Groundwater level (lines) and flow direction (arrows) in the year 1999 for the Quaternary aquifer (**c.**), the Pliocene aquifer (**d.**), and the Messinian aquifer (**e.**).

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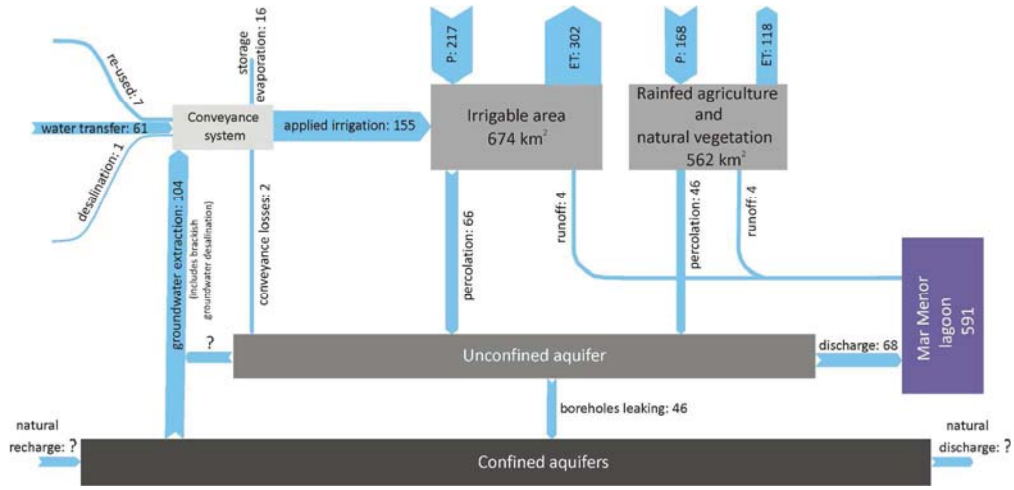

Figure 4. Water balance of the Campo de Cartagena area. Arrows indicate the sense of the water balance components and relative magnitude (average hm^3/year; period 2000-2011). P: precipitation, ET: evapotranspiration. Data source: *CHS* (2014) and *Contreras et al.* (2014).

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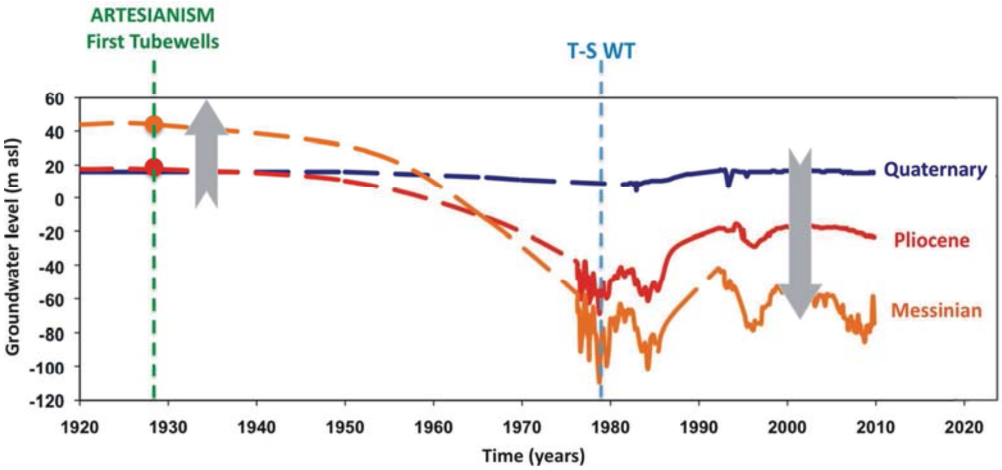

Figure 5. Long term evolution of groundwater level for the Quaternary (unconfined), Pliocene and Messinian (confined) aquifers. Arrows indicate the sense of the vertical hydraulic gradient and relative magnitude, which controls aquifer cross-contamination. Artesianism in the region and first tubewells in 1928. Arrival of the *Tajo-Segura Water Transfer* (T-S WT) in 1979 (after Baudron et al., 2014).

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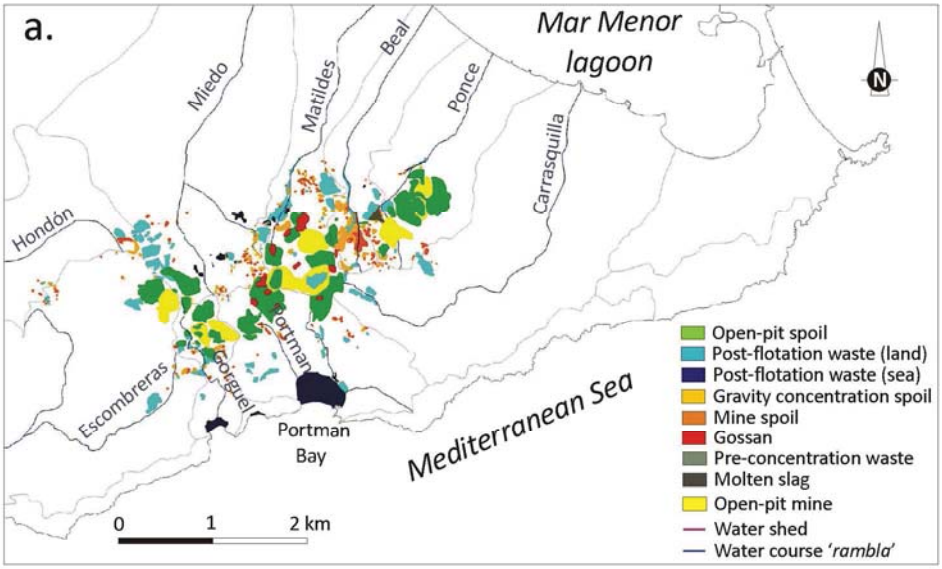

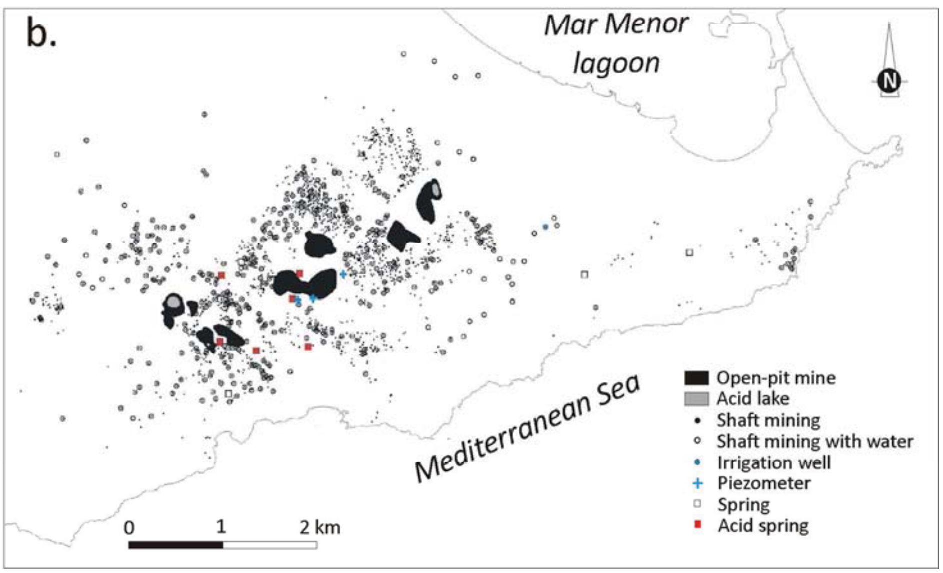

Figure 6. Cartagena-La Unión Mining District. **a.** Mining and metallurgical wastes distribution (modified from Garcia, 2004) and the main temporary water courses (wadis or '*ramblas*'). **b.** Location of the shafts mining and open-pits, water wells, springs and lakes (after Robles-Arenas, 2010).

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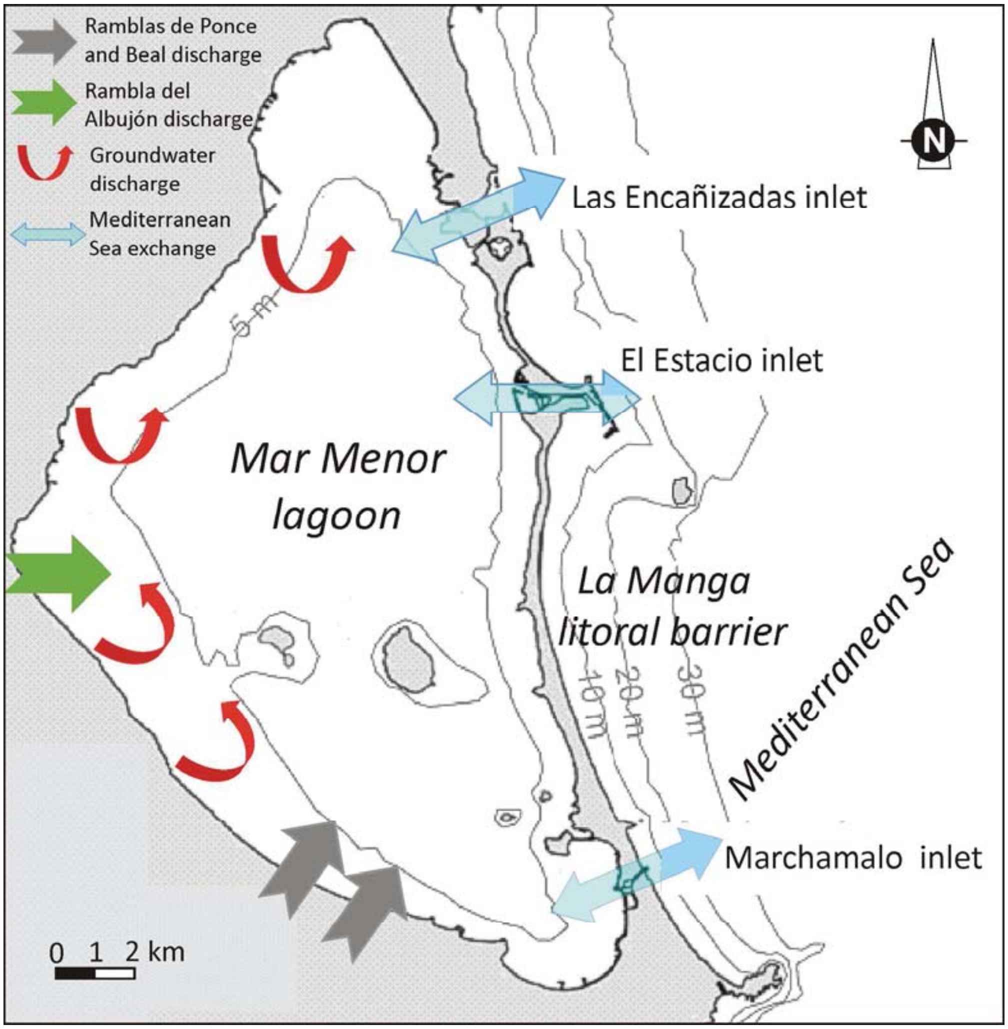

Figure 7. Block diagram of the Mar Menor lagoon showing the isobaths and the flow components of discharge and exchange.

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Table 1. Sectorial water use (hm^3/year) and sources of water for the Campo de Cartagena management zone (hydrographic basin district). Average values for 2000-2010 period.

Source/Sector	Irrigation	Industrial	Services	Households	Total
Reclaimed-Reused	7	-	2	-	9
Desalinated	1	-	0	5	6
External (imported water)	61	12	2	11	87
Groundwater	104*	2	1	2	109
Total	173	15	5	17	210

*value estimated from hydrological modelling (see Figure 4 and *Contreras et al.,* 2014), which includes desalinated brackish groundwater.

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