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FALCULTY OF SCIENCE AND TECHNOLOGY

ARID GROUNDWATER DEPENDENT ECOSYSTEM RESPONSE TO SALINIZATION PROCESSES IN A COASTAL AQUIFER: DERIVING VEGETATION INDICATORS OF THE AQUIFER CONDITION

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1. ABSTRACT

To maintain the groundwater quality represents a critical concern because of the increasing levels of groundwater contamination globally. This goal is particularly important in arid zones, where due to the scarce rainfall the groundwater is a significant source of freshwater supply to society and ecosystems. Here we follow an ecohydrological approach to derive effortless indicators of the aquifers condition, based on the monitoring of phreatohytic vegetation, a particular case of Groundwater Dependent Ecosystems (GDEs). This is the case of *Z.lotus* a deciduous arid shrub from North of Africa and Southeast Spain. This study aims to relate the biological condition of *Z. lotus* with the groundwater condition to explore the feasibility for using vegetation indicators to inform about the salinization levels of groundwater in coastal aquifers. With this goal we: 1) evaluate the salinization levels of an aquifer from the Cabo de Gata-Níjar Natural Park, by wells sampling; 2) determine the brackish water distance gradient based on the use of Vertical Electrical Sounding (VES),the physiological condition of *Z. lotus* through leaf chemical analysis and spectral vegetation indices (NDVI and NDWI) along a salinity gradient. The results showed that the phreatic level, distance from the sea and therefore the salinity and freshwater available to GDE, are reflected in the leaf chemical composition of *Z. lotus.* However, salinity levels did not reflected clearly in vegetation greenness (NDVI) and vegetation water content (NDWI), probably because of *Z. lotus* showed salt tolerance within the range of salinity found in the aquifer. As a conclusion, we propose leaf ion concentration as a good indicator of groundwater salinization, while the spectral indices are good indicators of vegetation health but not for the groundwater salinization. *Z.lotus* is probably the only terrestrial GDE in the arid zones of Europe and its study is essential for the management and conservation of this ecosystem.

Key words: Cabo de Gata-Níjar Natural Park, brackish groundwater, leaf chemical composition, NDVI, NDWI, *Ziziphus Lotus*, Southeast Spain, salt tolerance.

RESUMO

Manter a qualidade das águas subterrâneas constitui uma preocupação crucial devido aos crescentes níveis de contaminação dos lençois freáticos a nível mundial. Este tópico é particularmente importante nas zonas áridas, uma vez que as precipitações, que representam uma fonte importante de abastecimento de água doce subterrânea para a sociedade e para os ecosistemas, são escassas nas zonas áridas. Neste estudo utilizamos uma abordagem ecohidrológica para obter indicadores de esforço da condição dos aquíferos, com base na monitorização da vegetação freatófita, um caso particular de Ecossistemas Dependentes de Águas Subterrâneas (GDEs: Groundwater dependent ecosystems). Como exemplo de vegetação freatófita das zonas áridas analisou-se o *Z.lotus* que é um arbusto de folha caduca do Norte de África e Sudeste de Espanha. Este estudo teve como objetivo relacionar a estado biológico do *Z. lotus* com o estado das águas subterrâneas para explorar a viabilidade de utilização de indicadores de vegetação para informar sobre os níveis de salinização das águas subterrâneas dos aquíferos costeiros. Para isso: 1) avaliaram-se os níveis de salinização do aquífero do Parque do Cabo de Gata-Níjar Natural, através de amostragem de poços; 2) determinou-se o gradiente de distância de água salobra com recurso a uma sondagem elétrica vertical (SEV), a condição fisiológica do *Z. lotus* através da análise química foliar e os índices espectrais de vegetação (NDVI e NDWI) ao longo de um gradiente de salinidade. Os resultados mostraram que através da análise química das folhas de *Z. lotus* foi possivel determinar o nível freático, a distância ao mar, a salinidade e a água doce disponíveis para os GDEs. No entanto, os níveis de salinidade não se refletiram claramente no verdor da vegetação (NDVI) e no teor de água da vegetação (NDWI), provavelmente por *Z. lotus* apresentar tolerância ao sal dentro da gama de salinidade presente no aquífero. Em conclusão, recomendamos como bom indicador da salinização das águas subterrâneas a concentração de íons nas folhas. Em contrapartida, sugerimos que os índices espectrais de vegetação são bons indicadores da saúde da vegetação, mas não são bons para a quantificação da salinização das águas subterráneas. *Z. lotus* é provavelmente o único EDAS terrestre nas zonas áridas da Europa e o seu estudo é fundamental para a gestão e conservação deste ecossistema.

Palavras-chave: Parque Natural de Cabo de Gata-Níjar, Água subterránea salobra, composição química das folhas, NDVI, NDWI, *Ziziphus lotus*, Sudeste de Espanha, tolerância salina.

2. INTRODUCTION

2.1. Groundwater dependent ecosystems (GDEs): concept and threats

Groundwater is a valuable source of freshwater supply on Earth. For arid and semi-arid ecosystem the groundwater is a significant freshwater supply for industrial and agricultural activities and human consume. Groundwater maintains the water temperature and chemistry conditions required by ecosystems, animals and plants they support (Brown et al. 2009). In addition, groundwater maintains several types of ecosystems, called Groundwater dependent ecosystems (GDEs). Murray et al. (2006) considered such ecosystems, as those whose structure and functionality depend of access to the groundwater. According to Eamus and Froend (2006), there are six types of ecosystems depending on groundwater: rivers, springs, wetlands, lakes, phreatophytes and subterranean ecosystems.

GDEs are threatened by activities that alter the quantity or quality of groundwater discharging at or near surface. The threats are divided in three types: i) contamination by nutrients is due to nitrates and phosphorus which are associated with agricultural and rural residential land uses, ii) pesticides are used in urban areas associated with agriculture intensive, and iii) the contaminations from industrial and manufacturing chemical are other example of contamination of this kind of ecosystems. (Brown et al. 2009).

The phreatophytic vegetation health is connected with the quality of the aquifer which supply them water. There are historical records of vegetation behavior in relation to observed changes in groundwater availability (Naumburg et al. 2005, Froend et al.2009). The groundwater fluctuations affect vegetation reliant on groundwater. The effects can be changes in physiology, structure, and community dynamics. Plant salt stress is increasing globally because of climate change and inappropriate water use by humans and field management. Thus, the impact on GDEs influences the environmental conditions of the ecosystems and the human welfare. The integrity of GDEs can be affected as a consequence of the water demand by domestic and agriculture used and, in turn, the territory can increase or modify the natural fluctuation on the water table. Ecological integrity lack affects to the ecosystem services provided by GDEs.

Every day the world demand fresh water supply for agriculture, industry, drinking water use, etc. It is probably its demand will continue grow. As result of growing water demand, the need to ensure the protection of groundwater and ecosystems associated to it. The development of effective strategies to protect GDEs and species depend on this kind of ecosystem as their requirements of groundwater, and whether this provision has declined (Eamus & Froend, 2006). Water requirements for different dependent ecosystems and their diverse ecological communities have not been adequately evaluated. In order to evaluate the dependence on groundwater ecosystems, there are methods which are largely indirect or based on the assumption of the use of groundwater by plants and animals as proof of dependency, but until now they are more empirical than experimental. In the case of terrestrial vegetation, the development of techniques based on the ratios of stable isotopes of oxygen and hydrogen from natural origin, has been a great advance (White, 1985; Sternberg & Swart, 1987; Ehleringer & Dawson, 1992; Lin & Sternberg, 1992; Thorburn et al., 1992). The use of this technique leads to the main ideas about when the vegetation access to different sources of water, knowing their reliance on groundwater from rainwater. This technique is still widely used in Australia (Thorburn et al. 1993; Mensforth et al. 1994; Thorburn & Walker, 1994). However, it is recognized that the application of stable isotope techniques to the problem of discrimination of the water sources used by the plant uses. First, it requires a difference in isotopic composition between the water contained in the soil and groundwater, it is not always present. Second, these techniques are most effective when combined with flow measurements (Thorburn et al., 1993). Finally, it is a very expensive technique difficult to incorporate into management actions. Due to in fact that the uses of stable isotopes have difficulties, also there have been used more indirect means to evaluate the dependence of groundwater. Most of them are based on a water balance explicitly or implicitly, with discrepancies between annual precipitation and actual evapotranspiration, transpiration attached to the discharge of local or regional groundwater (Paijmans et al., 1985, Schulze et al ., 1996) Other approaches are based on the interpretation and quantification of the observed changes in the flora and fauna in relation to the observed changes in surface water or groundwater levels (Froend & McComb, 1994, Hancock et al. , 1996; Froend et al., 1997). Until recently, legislative and policy focused on protecting water supplies for human uses, and the laws had a little consideration of ecosystems which depended of groundwater. The over-exploitation of groundwater can be caused impact on the ecosystems. For instant, the implementation of inappropriate policy can caused degradation of groundwater-dependent ecosystems (Aldous et al.2011). The aim to protect groundwater-dependent ecosystems is to achieve the water sector, through control and management of groundwater exploitation.

2.2. Saltwater intrusion: a major problem of the coastal aquifer

Since groundwater systems in coastal areas are in contact with saline water, one of the major problems is saltwater intrusion. The seawater intrusion process is consistent to a hydrodynamic imbalance in general is governed by variations piezometric. These variations in conductivity are essentially related the layered nature of the sediments but also horizontal variations, which gives the system a marked anisotropy. Occasionally, the existence of low permeability beds generates semiconfinement situations and even light confinement can result in different hydrodynamic equilibrium states, i.e. the formation of independent interfaces with different degrees of diffusion. When seawater intrudes into a coastal aquifer, the following exchange reaction takes place:

$$Na^{+} + 1/2Ca^{2+}\text{-}X^{2} \longrightarrow 1/2Ca^{2+} + Na\text{-}X$$

Where X indicates the soil exchanger. Na^{+} is taken up by the exchanger, whereas Ca^{2+} is released into de water (Chen at al. 2007). Saline groundwater can result not only from seawater intrusion into aquifer but also from the presence of beach deposits, dissolution of evaporite deposits, return flow from irrigated land; and anthropic saline wastewaters. (Daniele et al, 2011) Seawater intrusion in coastal aquifers can be the result of intensive pumping fresh groundwater, or due to reduced stream flow (i.e. due to construction of dams or leads), which leads to reduced groundwater recharge in the deltas and floodplains. The intense evaporation in areas with shallow groundwater levels can also lead to salinization. Variations in salinity levels may occur due to natural climate change or to over-pumping and irrigation practices that stimulate the precipitation of dissolved solids, such as salts, on farmland. Seawater intrusion is a potential issue which a lot of countries have to deal. Especially in semiarid/arid regions, aquifers are essential water sources, vulnerable to climate change and anthropogenic factor.

Previous hydrogeochemical studies in the area show that the aquifer is salty which can be result from seawater intrusion, dissolution of evaporate deposits, return flows from irrigation and anthropic saline wastewaters (Daniele et al.2011 and García et al.2003). In order to verify that the saline groundwater, four wells were analyzed in Torregarcía area.

2.3. A proposal to study the aquifer conditions based on an ecohydrological approach: Groundwater dependent ecosystems (GDEs) as indicators of the groundwater conditions

In water-limited environments, such as arid and semiarid zones, plant growth is often controlled by stochastic pulses of water that directly affect plants' ability to adapt and survive. Ecohydrology is providing new theoretical frameworks and methodological approaches for understanding the complex interactions and feedbacks between vegetation and hydrologic flow. The composition and structure of plant communities are directly influenced by spatiotemporal patterns in water availability. In this project, we would like to understand the water-plant relationship in a semi-arid zone. As the global water supply and quality are connected with the land use change and therefore identify the issues to solve it.

The phreatophytic vegetation can be used as indicators of GDE condition. The GDEs are threatened by insufficient supply of groundwater. Understanding the plant communities associated to a GDE can provides knowledge about the groundwater fluctuations and conditions. Thus, it is possible to predict the potential impacts water-regime modification through the study of the groundwater-vegetation relationships. Three main parameters can be measured at community level to elucidate changes in the groundwater conditions (Eamus et al. 2006): *i*) changes in the community structure and abundance can appear as a response of the alteration of groundwater regime; *ii*) as some species are more vulnerable to prolonged dry periods (character), the changes in species diversity and composition can also indicate the alteration of groundwater regimen, and *iii*) the fullness/density of phreatophytic vegetation can measure the health of GDE vegetation.

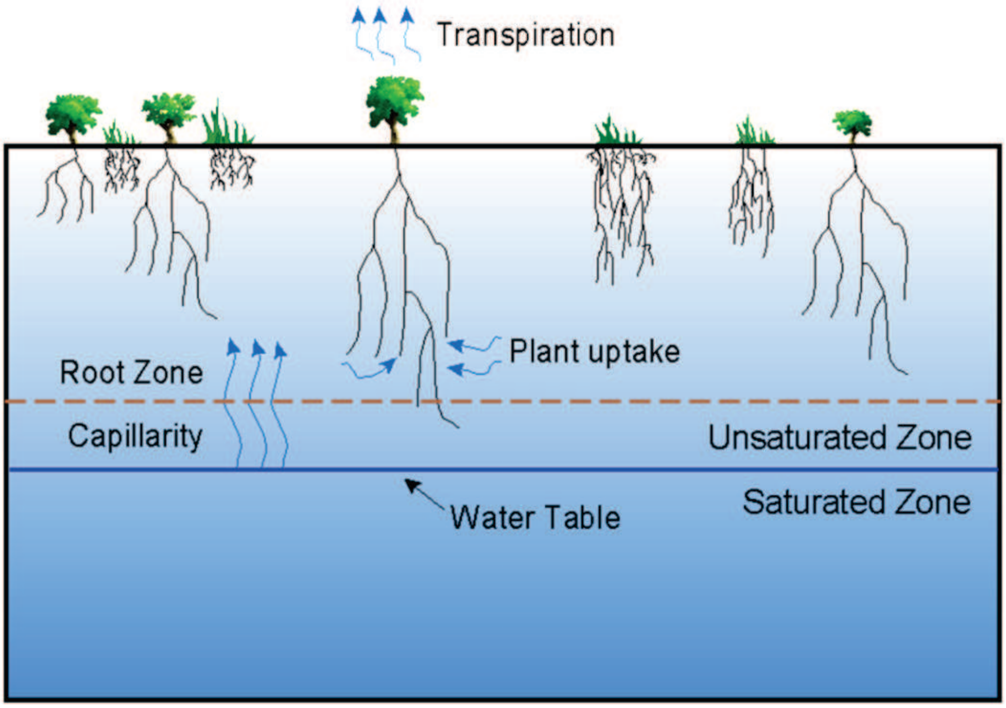


Figure 1. *Phreatophytic vegetation and groundwater relationship*

According to Erdman 2000, there is a correlation of phreatophytes leaf data with groundwater data. Deleterious effects of salinity are thought to result from low water potentials, ion toxicities, nutrient deficiencies, or a combination of these factors (Khan et al. 2000). Nutrient deficiencies can occur in plants when high concentrations of Na^+ in the soil reduce the amounts of available K^+ and Mg^{2+}. In addition, Na^+ may have a direct toxic effect, such as when it interferes with the function of potassium as a cofactor in various reactions. Many of the deleterious effects of Na^+, however, seem to be related to the structural and functional integrity of membranes. Current reports using metabolomics techniques have detected the global metabolic shift under salt stress observing the sets of metabolites that more frequently increased, enhancing the plant osmotic potential. Inorganic solutes and sugars and amino acids are the metabolites that most frequently increase under salt stress. (Peñuelas et al, 2011). In addition, the photosynthesis is sensitive to several stresses, including excess irradiance, water stress, high or low temperature, elevated CO_2, soil nutrient supply, air pollution, and others. Thus, the elevated salinity in the plant causes restricting CO_2 entry into leaves, or non-stomatal limitations that result in inhibitions or down-regulation of photosynthesis (Gorai et al, 2010).

2.4. The arborescent matorrals of *Ziziphus lotus*: a groundwater dependent ecosystem to study the condition of coastal aquifers in arid SE Spain.

In arid ecosystems the shallow groundwater can play an important role in the productivity even much that the local rainfall (Jobbágy et al.2011, Eamus et al.2006). Also, the evapotranspiration is important because more than 90% of all precipitation input to the system return to the atmosphere via evapotranspiration (Cavanaugh et al. 2011). It is aware that there are shrubs and tree species can have maximum rooting depth of many meters which suggests that they can take water directly from groundwater. These species are denominated as phreatophytic vegetation (Figure 1) (Haase et al.1995, Naumburg et al.2005).

The arborescent matorral of *Ziziphus lotus* (azufaifares) (Figure 2) is a phreatophytic vegetation of conservation concern at the European level. This ecosystem is broadly distributed in the northern Africa, however in Europe is considered like a priority habitat (code 5520*, Habitat Directive) that only occur in the arid environments of SE Iberian Peninsula. In addition, it holds a number of species with high degree of endemicity. The *Z. lotus* is a significant plant in the area. It provides shade, shelter and food for small animals that live in the area. It should also emphasize that the *Z. lotus* provide moisture to the upper soil layer that plants grow around it are beneficing. These characteristics make *Z. lotus* a valuable multi-purpose shrub for semi-arid to arid ecological areas.

Figure 2. *Ziziphus lotus in Cabo de Gata-Níjar Natural Park (Almería, Spain)*

Over the last 30 years this ecosystem has became to extinction rick because of the expansion of greenhouses. The main impacts on this coastal ecosystem are intensive groundwater exploitation, waste water spilling and proximity to urban areas. Agriculture intensification has impacted on this ecosystem by the habitat fragmentation and the overexploitation of the coastal aquifers. As a result, currently only three populations survive in the Cabo de Gata-Níjar Natural Park. To keep these populations in a favorable conservation status, it is necessary to develop monitoring programs that enable the development of adaptive management strategies. During the last twelve years the study area has been monitory by satellite. The dates show vegetation deterioration but the cause is not known. The development on the Mediterranean coast of the Iberian southeast has contributed to the disappearance or disturbance of this habitat, as the pressure by the growth of crops under plastic (greenhouses). The alteration of this habitat is particularly relevant in the most conserved areas, which will be surrounded and fragmented by urbanization and the construction of greenhouses and other crops. A significant example of destruction of highly conserved areas of this habitat on the coast is the El Toyo Retamar, which destroyed a large ex tension of this habitat (260 ha) for the construction of houses, golf courses, etc. (with the added effect of exploitation of the aquifer water, which lowers the water table may affect the operation of adjacent conservation areas). Another example is the construction of the pipeline Algeria-Europe in the “El Pedregal” beach, where there is an area with well-developed individuals of *Z. lotus*, although with a certain degree of disturbance. Annually, another disturbance is the congregation of vehicles and people around the shrine of Torregarcía annually where the people spend all the day in the area which involves treading ground vehicle, people step and the abandonment of waste.

3. HYPOTHESIS AND OBJETIVES

Groundwater is an important resource in arid zones as the primary source of water for agriculture, industrial and human consumption. As mentioned previous, the *Z. lotus* is considered like a priority habitat in Europe (Directive 92/43 EU) and it deserves a monitoring and protection. Moreover, the management and protection of groundwater source is very important to achieve a good ecology state in the ecosystem according with the Water Framework Directive (Water Framework Directive, WFD). The development of the ecological role of this shrub desert is only possible if we consider its phreatic character (Tirado, R., 2009, Gorai et al., 2010), since only the access to deep water layers could explain the activity maintaining vegetative productivity in arid Mediterranean during the summer. According to these features, the *Z. lotus* ecosystem should be considered as an ecosystem whose structure and integrity depend on the maintenance of the physical and chemical conditions of groundwater.

At present there are only three well-developed populations of *Z. lotus* (with individuals scattered across several areas of Almería and Murcia) that survive in the Natural Park Cabo de Gata-Níjar. To maintain these populations in favorable conservation status, it is necessary to develop monitoring programs that enable the development of adaptive management strategies (Hair & Carrique, 2004, Castro et al., 2011). Such programs should be based on knowledge of the dependencies of vegetation groundwater, an objective to which we intend to contribute to this work. The purpose of understanding the relationship between vegetation and groundwater dynamics, the manage and maintenance of a healthy ecosystem is crucial while providing water for human needs (Naumburg et al. 2005).

In this Master thesis we explore the interaction of semiarid ecosystem and groundwater in the Cabo de Gata-Nijar Natural Park in Almeria (Spain) through the study of phreatophytic vegetation which obtains its water from phreatic sources and is sensitive to changes in the hydrogeological regime. James et al. (2000) used phreatophytic vegetation as alternatives method to analyze groundwater contamination. According with it, we have sought if phreatophic vegetation could be a possible indicator for knowing the quality of coastal aquifer, in particular the possible salinization in them. Thus, the main objective of this Master Thesis was to derive vegetation indicators to evaluate salinization processes in coastal aquifers. Particularly, we assessed the response of the preatophytic species, *Z. lotus*, to a brackish distance gradient by focus on changes in the leaf chemical condition and in spectral indices, such as the Normalized Difference Vegetation Index (NDVI), and the Normalized Difference Water Index (NDWI) as indicators of vegetation health. These last indices were measured in the field at individual level, but they are typically data obtained from remote sensors in satellites. In this way, we sought for vegetation indicators that would be used at ecosystem level and for large regions. The study was in dry season (spring and summer) because it is when *Z. lotus* has its fruits and green leaves. The analysis of *Z. lotus* quality and testing of aquifer quality is required to determine the relationship of phreatophic vegetation and groundwater in this semiarid zone in Spain.

4. MATERIALS & METHODS

4.1 Study area

The study focused in a coastal ecoydrological system of the Cabo de Gata-Níjar Natural Park (Almería, Spain), a maritime-terrestrial protected area located in the southeastern Iberian Peninsula (Figure 3). This area with a mean annual rainfall (2012) of 145.4mm and mean temperature is 20ºC which can become more than 30ºC in summer, is considered one of the most arid zones of Europe (Figure 4). The rainfalls occur mainly in autumn and winter. The annual rainfall, concentrated in 26 days on average, is lower than evapotranspiration. Thus, it is considered as a water-limited environment, since the water stress is the most limiting factor of the ecosystems (Armas et al. 2011, Cabello et al. 2012). These bioclimatic conditions enhance the groundwater role as a key resource for water supply, both in ecosystems and people.

Figure 3. *Study area. Location of the main population of the Ziziphus lotus aquifer dependent ecosystem (✱, Cabo de Gata-Níjar Natural Park, Almería (Spain)*

Cabo de Gata-Nijar Natural Park is also internationally recognized as a biosphere reserve on account of the contrasts it contains between marine, coastal and terrestrial environments where we can find numerous species of plants and animals. In spite of the fact that it's semi-arid climate with low rainfall and a low water table, Cabo de Gata-Nijar is one of most unusual Europe's ensembles of flora (more than 1000 endemic species). One of these plants, adapted to the harsh local climatic conditions is the wild jujube *Ziziphus lotus,* which is analyzed in this work.

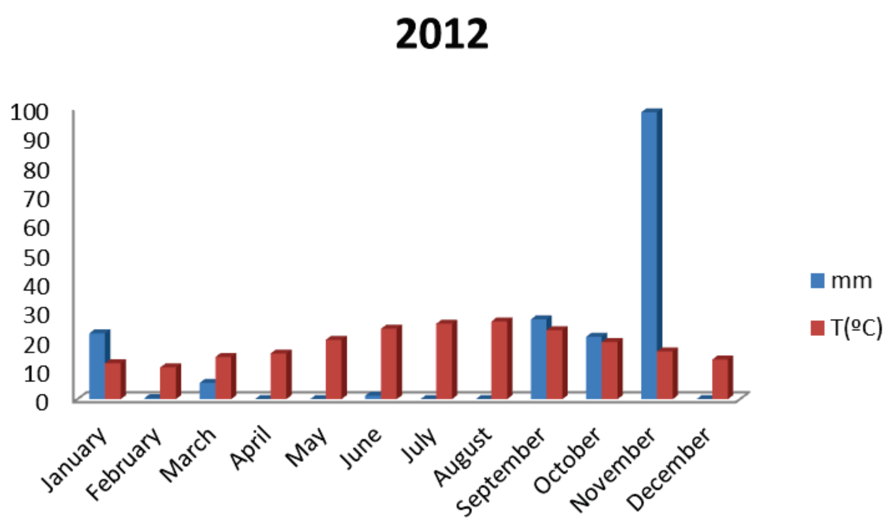


Figure 4. *Annual precipitation (mm) and temperature (ºC) in Almeria (2012) (INE. Monthly Bolletin of Statistics).*

The ecohydrological system we study is developed on the Hornillo aquifer is an aquifer which encloses all the coastal plains of the western part of the Cabo de Gata-Nijar Natural Park. Apart from that this aquifer is very fragmented by geological faults, there is little information on its structure and quality of the aquifer and there are not many available wells there. The level and chemical composition of the water table change depending on the site (Sola Gómez et al., 2008). For this reason, we selected as a plot study the land between two the main faults in the area to focus on the relationship between *Z. lotus* and groundwater. Both faults overlapped with two arid water streams (ramblas), “Rambla de Retamar” at the West, and “Rambla de las Amoladeras” at the East). We use a road as a northen limit, and the Mediterranean sea as the southern limit (Figure 5).

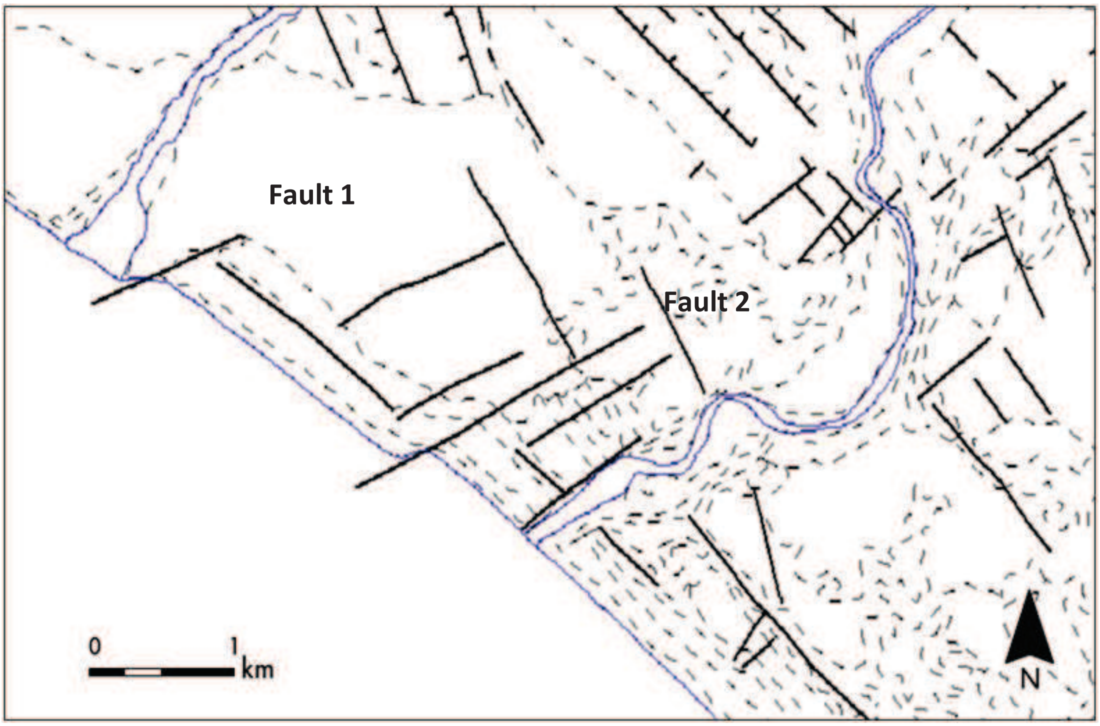


Figure 5. *Tectonic map of the study area. Source IGME*

4.2. Main characteristics of the coastal aquifer and the *Z.lotus* groundwater dependent ecosystem

The coastal aquifer

The aquifer consists of gravel and sand deposits, and it is an unconfined and detrital aquifer. The aquifer is developed in Quaternary materials- alluvial and deltaic- sandy-loam soil and Pliocene conglomerates. Previous works founded that the aquifer shows evidence of seawater intrusion as a result both of the low rainfall in the area and the amount of groundwater extracted (Daniele et al. 2011).

The hydrochemical processes in the aquifer derive from the water-rock interaction, and seawater intrusion. The water-rock interaction determines the chemical equilibrium between the liquid and solid phases. Basically, the processes involved are ion exchange carbonate dissolution and precipitation, but may also be relevant redox processes, especially the sulphate reduction. In addition, the checmical composition of the mixing water (fresh and salty water) depends on the hydrodynamics of seawater intrusion. The intervention of the cation exchange process between the water and the sediment can substantially modify the chemical composition of water, so that from an initial mixture of water NaCl character may be found facies types that meet the following sequence, which summarizes the evolution of the water in a process of encroachment by salt water to the mainland, where exchange processes involving reverse:

$$NaCl \longrightarrow CaCl_2 \longrightarrow Ca(HCO_3)_2$$

The Phreatophytic vegetation

Vegetation in the area corresponds with shrublands and grasslands communities adapted to extreme and arid conditions. The predominant community is the "azufaifal", and arborescent matorral dominated by *Ziziphus lotus*. This is a xerophytic shrub belongs to the Rhamnaceae, very common in arid and semiarid areas of northern Africa, but it is limited in Europe just to Southeastern Iberian Peninsula. The *Z. lotus* is deciduous that has the ability to withstand drought has been attributed to a combination of avoidance and tolerance mechanisms, including osmosic adjustment. *Z. lotus* shows sensitive stomata closure (Maraghi et al.2011) and develops deep root systems to reach moist soil layers and groundwater sources, functioning essentially as phreatophytes (Gorai M. et al, 2010). Its high stomatal density in leaves, most of the time opened (Figure 6) suggests that the plant has huge water requirements even during the drought summer period.

In this ecosystem, *Z. lotus* acts as an "ecosystem engineer" that modifies its surrounding environment (Tirado 2005). Other authors have shown as this plant and other phreatophytes species provide hydraulic lift, redistributing water into the soil and providing supplemental moisture in the upper soil layers, helping to the other plant to get water from the soil (Prieto et al. 2010). It is observed the spatial distribution of many shrubby species around of *Z.*

lotus, which cause a positive interaction between plants by nurse-plant effect that mean, enhanced growth and survival of seeding living under *Z. lotus* (Tirado 2003). Thanks to the huge structure of *Z. lotus*, creates a microhabitat inside them which softens the arid conditions of the environment (soil temperature under the canopy is significantly lower, and the relative humidity higher), serving as a refuge for many species of plants, rodents, reptiles and birds.

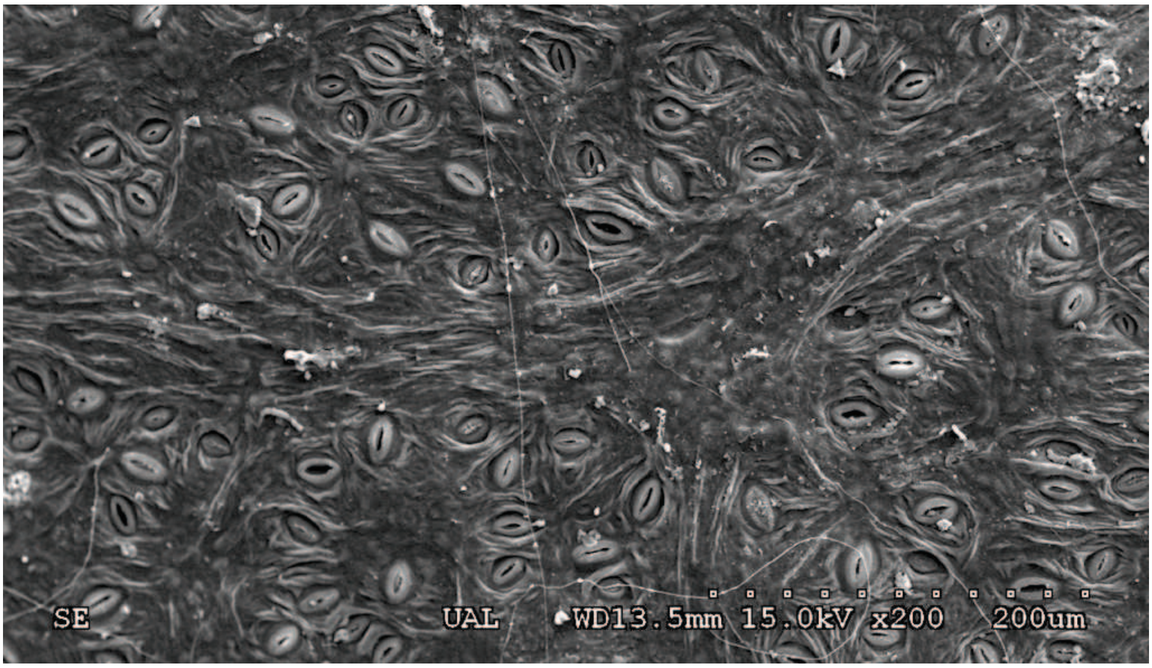


Figure 6. *Ziziphus lotus has a high stomatal density , what reflect its water requirement (x200 by electron microscopy)*

Z. lotus plants cover more than 15% surface area and they dominate 46% of the bush cover in the area. The distribution of *Z. lotus* community is controlled by climatic factor as absence of frost, pronounced water deficit during the dry season (high temperatures and absence of rainfall) and high solar radiation over all year. The shrubs has intricately branched stems and smaller flowers and fruits. It is a shrub that reaches 2–5 m and is found in depressions with deep sandy soil for stabilized sand fields. *Z. lotus* dormant from October through March and flowers in May and June and produce fruits in August. This shrub exhibits a high optimal temperature for germination (35ºC) and may be able to tolerance low water potentials during germination (Gorai M. et al, 2010).

In the study area, *Z. lotus* and other plants accumulate sand under the canopy, constitutes geomorphological structures called “Nebkhas” in North of Africa. The nebkha is therefore not drifting sand but is almost stable. Both run-off and sand storms play a role in this nebkha building since they occur in depressions and along the stream network. The nebkha is used to find shelter and food by insects, amphibians, rodents, lizards and snakes.

4.3. Experimental design

To carry out the project, we design a methodology with the following steps:

1) Evaluation of the salinization level of the aquifer by well sampling;
2) Selection and estimation of a brackish distance gradient as proxy to a groundwater salinity gradient; and
3) Analysis of the chemical composition and spectral behavior of *Z. lotus* along the gradient to derive vegetation indicators that informs us of the condition of the aquifer.

4.3.1. *Assessment of the salinization levels of the aquifer: wells sampling*

In May and June 2013, the groundwater samples were sampled from four different wells around the area (Figure 7). The water samples were collected in polyethylene sample bottle (100mL). The samples were acidified with HN03 5% in situ to prevent absorption or precipitation of metals and then storage at 4ºC. Physico-chemical parameters (pH, Electrical conductivity and temperature) of the groundwater were measured in the field (Figure 8).

Figure 7. *Water sample were collected in four different wells in Torregarcía area, Almería (Spain)*

The water quality analysis of samples for major ions was conducted at the Servicios Centrales de Investigación of University of Almería. The ions (Na^{+}, K^{+}, Ca^{2+}, Mg^{2+} and B^{3}) were determined by inductively coupled plasma mass spectroscopy (ICP-MS) which a method for the analysis of inorganic elements, as it uses small volumes of samples, is fast, and applied to a wide range of materials.

Figure 8. *Field work: a) Water sampling b) Measurement of pH, Electrical Conductivity and Temperature.*

We also evaluate the quality of the water by the Sodium Adsorption Ration (SAR), which indicates if the water is suitable for irrigation. The SAR was calculated from this equation:

$$SAR = \frac{Na^{+}}{\sqrt{\left(Ca^{2+} + Mg^{2+}\right)/2}}$$

According with International SAR Standards: SAR<3: suitable for irrigation
SAR 3-9: use may be restricted
SAR >9: unsuitable for irrigation

4.3.2. *Seeking for a groundwater salinity gradient: a brackish water distance gradient (geophysics study)*

Because of the scarcity of wells in the area, we decided to do a geophysics study based on Vertical Electrical Sounding (VES), which determined the brackish water distance gradient, as a proxy of a groundwater salinity gradient. The VES was run between the two main faults of the area, and considering a perpendicular gradient to distance from the sea. The picture below shows the location of transect where VES was made (Figure 9).

Figure 9. *Vertical Electrical Sounding (VES) measured between to fails in Torregarcía, Cabo de Gata-Nijar, Almeria (Spain)*

The VES is a geophysical method based on the estimation of the electrical conductivity or resistivity of the medium. The estimation is performed based on the measurement of voltage of electrical field induced by the distant grounded electrodes. This method is used at shallow depth (the first 300m). The subsoil consists of formations of different resistivities, the measure resistivity do not correspond to any of them, but will have an intermediate value. The principle of this method is to insert an electric current, of known intensity, through the ground with the help of two electrodes (power electrodes – AB) and measuring the electric potential difference with another two electrodes. The investigation depth is proportional with the distance between the power electrodes. Figure 10 shows the electrical sounding scheme where the depth of investigation increases as the distance AB opens.

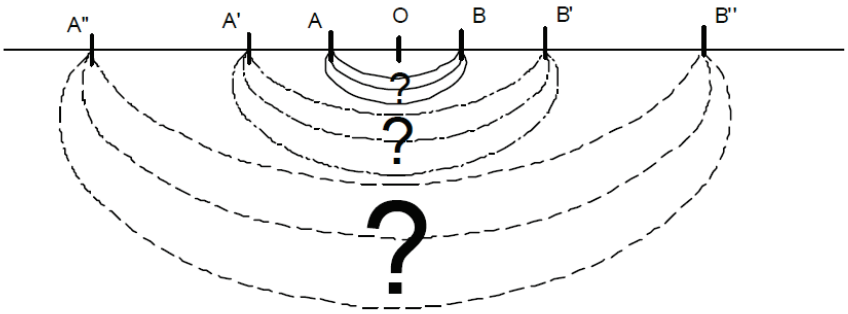


Figure 10. *Electrical sounding scheme (Source: Sanchez F.(2011))*

The equipment GEOTRON was used to measure the apparent resistivity (Figure 11). The model uses two circuits; one of them sent an electrical current through the electrodes A and B by a battery of 12volt. The electrical current is measured by an ammeter connected to the electrodes by wire coils 500 meters, makes we can move the line to get to know deeper data as we get away from the center point of measurement. To receive an electrical current a millivoltmeter is used, M and N electrodes consisting of two porous porcelain vessel filled with a solution of distilled water and copper sulfate connected by cables 1, 10 and 50 m.

All electrodes must be pre-moistened for better leading power, because in summer the soil is very dry. The nature of the material and water table are given by apparent resistivity. The uncertainty of the SEV can be 5% in favorable circumstances, from 10% in normal and 10% to 20% if the soil is very heterogeneous, with failures, anisotropy, dips greater than 20 degrees. Interpretation depth varies between 0.2 and 0.3 by the distance between the electrodes A and B.

***Figure 11**. Field work: a) Class A or B electrode and wire coil 500 meters in the field. b) Photography Geotron device used in the field (symmetric Schlumberger)*

4.3.3. *Assessment of the physiological condition of Z. lotus along the brackish groundwater distance gradient*

Leaf chemical analysis

The leaf chemical analysis of samples for major ions was also conducted at the Servicios Centrales de Investigación of the University of Almería. The samples were treated with a high pressure acid digestion and the ions (Na^{+}, K^{+}, Ca^{2+}, Mg^{2+} and B^{3-}) were determined by inductively coupled plasma mass spectroscopy (ICP-MS).

The leaf samples were obtained from 10 different individuals, and were collected in aluminium foil and immediately freezed (they were introduced in carbonic anhydride) to prevent post-sampling hydrolysis of some compounds and afterwards to lyophilize it to completely dry it until the extraction process. Once the samples were in the laboratory, leaves were cleaned with a brush to remove dust and dirt particles that were on the leaves for later in the analysis there is no interference. Then leaf samples were dried in a forced air oven at 80 ° C for 24h. The samples after being dried were ground to reduce the particle size and obtain a suitable sample for analysis. They were stored in a refrigerator at 4 ° C.

To eliminate the organic matter (high pressure acid digestion) (Figure 12) ,a 0.3g plant sample was placed into digestion tubes with 8mL nitric acid conc. and 2ml hydrogen peroxide. Tubes were heated to 190ºC for 30 min allowed to cool. Quantitatively transfer the contents of the digestion tube into a 25 mL volumetric flask, dilute to volume with deionized water. Once finished the acid digestion, the ions were determined by inductively coupled plasma mass spectroscopy (ICP-MS) (Table 3).

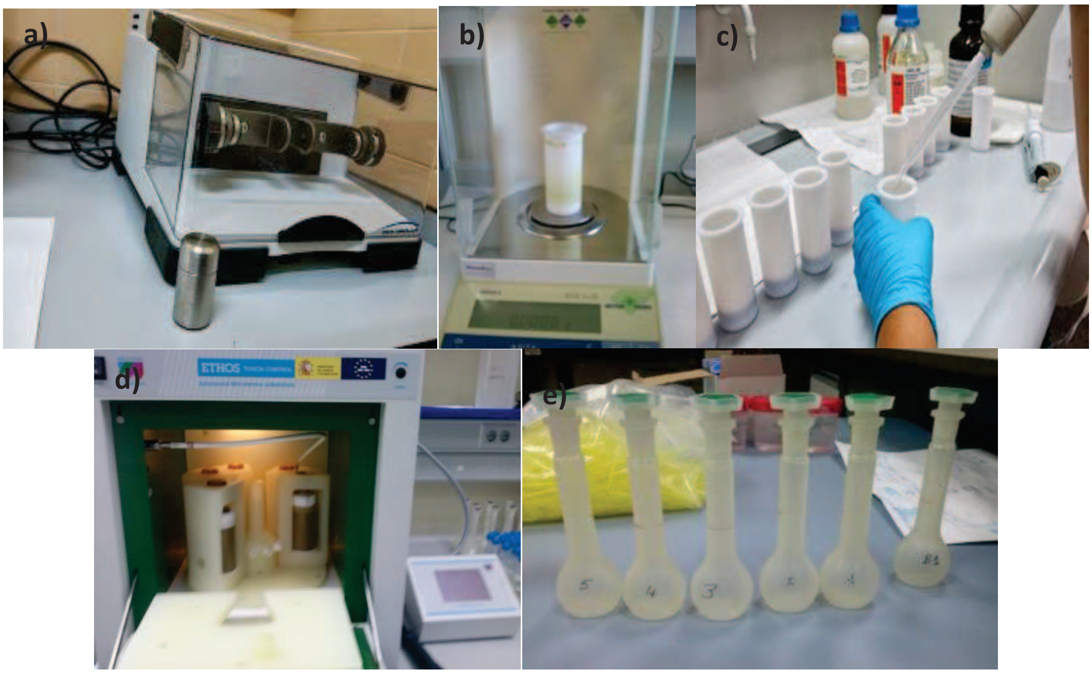


Figure 12. *Laboratory work: a) Advanced grinding technologies, b) Electronic scale, c) Added the reagent to the samples, d) Advanced special microwave, e) Volumetric flask*

Vegetation greenness (NDVI) and Vegetation water content (NDWI)

To evaluate the physiological condition of *Z. lotus* we used field spectral radiometric measures, as the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI). To do so, we used two 4-channel sensors for incident light (Skye SKR1850D/A 39993 and SKR1870D 39992, Figure 13a) and two 4-channel sensors for reflected light (Skye SKR1870ND 39991 and SKR1850ND/A 39994, Figure 13b). Two of these sensors (SKR1850) have the ability to simultaneously detect and measure four separate bands corresponding with those of the MODIS sensor, and the other two sensors (SKR1870) have the ability to simultaneously detect and measure four separate SWIR bands.

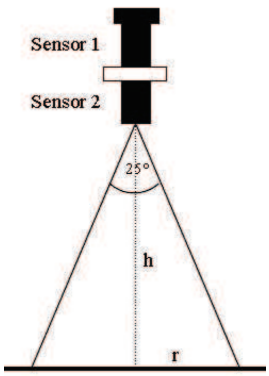
a) b) c) d)

Figure 13. *Sensors used in the field survey: 1a) two 4-channel sensors for incident light; 1b) two 4-channel sensors for reflected light; 1c) IR120 infra-red remote temperature sensor; GPS 16X-HVS.*

The sensors were paired for the incident and reflected light sensor MODIS bands and for the incident and reflected light sensor SWIR bands (Figure 14). For both sensors, MODIS and SWIR bands, the bandwidths centred at wavelengths from 470 nm up to 860 nm and from 1240 nm up to 2135 nm, respectively. The sensor with SWIR bands (SKR1870) gives a fifth output channel that shows the internal temperature of the sensor. This was used to correct the IR channel outputs.

Attached to the sensors structure were an IR120 infra-red remote temperature sensor (Figure 13c) and a GPS 16X-HVS (Figure 13d). IR120 offers a non-contact means of measuring the surface of an object by sensing the infrared radiation given off. It was used in the measurement of leaf of *Z. lotus*.

On the field, the sensors were taken by positioning perpendicularly with the ground and the sky with a height of +/-20 cm above the *Z. lotus* leaf. The sensors collected data at every second. Therefore, in order to have plant reliable measure, in each point we collected data during 3 seconds and afterwards we calculated the average of those 3 records.



Sensor 1 (Figure 13a) is fitted with the cosine correcting head and is measuring incident light.

Sensor 2 (Figure 13b) is narrow angle and measuring reflected light

Both incident and reflected light is measured simultaneously by two identical sensors, to eliminate fluctuations in solar radiation

The area of ground in view to the sensor is then defined by the height above the ground as show this figure.

Figure 14. *Drawing sensor positioning in the field survey.*

The Normalized Difference Vegetation Index (NDVI)

The goal of the analysis was to quantify the physiological condition of the *Z. lotus* individuals along the salinity gradient. The NDVI is a spectral index derived from the infrared and near infrared reflectance, related to the photosynthesis activity that can be used as an indicator of vegetation health. Usually, NDVI is estimated by the use of satellite images to give an indication of "greenness" and to identify the spatial variability of the greenness canopy. However, here to compare the information provided by the chemical analysis.We measured the NDVI (Normalized Difference Vegetation Index) in each *Z. lotus* which the chemical analysis is done.

Green plants absorb solar radiation for use in photosynthesis in the photosynthetically active radiation (PAR) spectral region. Leaf cells are able to reflect and transmit solar radiation in the near-infrared spectral region which carries approximately half of the total incoming solar energy. On other hand, the cell structure of the leaves strongly reflects near-infrared light and the strong absorption by chlorophyll in the red.

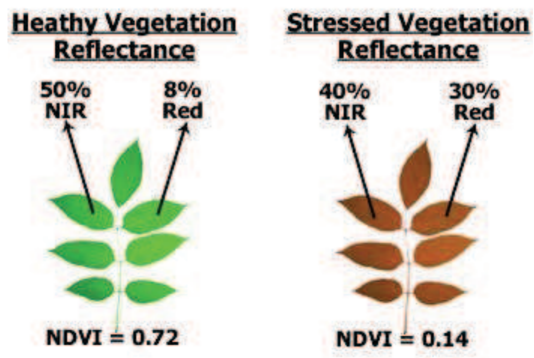


Figure 15. *The Normalized Difference Vegetation Index (NDV) can be used to inform about the health of the vegetation.*

The NDVI is calculated from the differences in the Near Infrared (NIR) and Visible (VIS) (red):

$$NDVI = \frac{(\text{NIR} - \text{VIS})}{(\text{NIR} + \text{VIS})}$$

The NDVI values range from 0 to 1, considering 0 as dry vegetation and 1 as green vegetation (Figure 15). Once the feasibility to detect vegetation had been demonstrated, users tended to also use the NDVI to quantify the photosynthetic capacity of plant canopies. The NDVI provides an indicator of the vigor and density of vegetation at the surface.

The Normalized Difference Water Index (NDWI)

The NDWI can be used to indicate the presence of water in the plant tissue (Gao 1996). The NDWI is calculated as the differences in the Near Infrared (NIR) and Short Wave Infrared (SWIR):

$$NDWI = \frac{(\mathrm{NIR} - \mathrm{SWIR})}{(\mathrm{NIR} + \mathrm{SWIR})}$$

NDWI values range from -1 to 1. The NIR reflectance is affected by leaf internal structure and leaf dry matter content and the SWIR reflectance shows changes in both the vegetation water content and the spongy mesophyll structure in vegetation canopies. NDWI is a good indicator for water content in vegetation and it is less sensitive to atmospheric scattering effects than NDVI.

Figure 16. *Field work: NDVI and NDWI measurements (Torregarcía, Almeria)*

5. RESULTS

5.1. Aquifer salinization levels and brackish groundwater distance gradient

Salinization levels

Therefore the groundwater samples showed high level of salinity. Water samples from all wells had high values of electrical conductivity due to the water contains more ionic substances, particularly soluble salts. Thus, the electrical conductivity (EC) ranges between 4046.66 µS/cm and 13000 µS/cm. The groundwater also showed an alkaline character with pH values ranging from 6.92 to 7.54. The water temperature was between 19.36ºC and 24.80ºC (Table 1).

Table 1. Groundwater physical-chemical measurements. Electrical Conductivity (EC), pH and Temperature (T) from wells of the coastal aquifer of the coastal plain of the Cabo de Gata-Níjar Natural Park (Almería, Spain)

	EC (µS/cm)	pH	T (ºC)	Distance from the sea (m)
Well 1	4046.66	7.43	19.36	1712.642
Well 2	5360.00	7.54	23.27	2617.618
Well 3	4483.33	7.53	20.86	735.065
Well 4	13000.00	6.94	23.83	571.514

Fifth ions were analyzed in water by ICP-MS (Na^+, Ca^{2+}, Mg^{2+}, K^+ and B^{3-}) (Table 2, Figure 17). All of them are common in natural water but their concentrations depend on the water characteristic. The dominant cation was Na^+, following by Ca^{2+} and Mg^{2+} with secondary importance. Finally, K^+ and B^{3-} are almost absent. These results indicate that the groundwater is salty (Na^+) and has a huge hardness (Ca^{2+} and Mg^{2+}).

Table 2. ICP-MS analysis of groundwater samples from the coastal aquifer of the coastal plain of the Cabo de Gata-Níjar Natural Park (Almería, Spain)

	B (ppm)	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)
Well 1	2.69±0.24	708.43±245.06	24.21±1.69	123.73±15.82	112.33±10.30
Well 2	2.91±0.36	979.53±338.40	24.54±1.75	157.70±23.15	181.87±17.24
Well 3	2.20±0.05	539.10±3.77	28.96±0.52	148.80±1.02	133.50±1.23
Well 4	5.12±0.05	2386.00±31.95	583.73±1.89	107.13±4.66	360.43±6.67

The SAR (Sodium Adsorption Ratio) results showed that the water from all the wells is suitable for irrigation (Table 3).

Table 3. Sodium Adsorption Ratio (SAR) in each well

	SAR
Well 1	1.999
Well 2	1.866
Well 3	1.274
Well 6	1.124

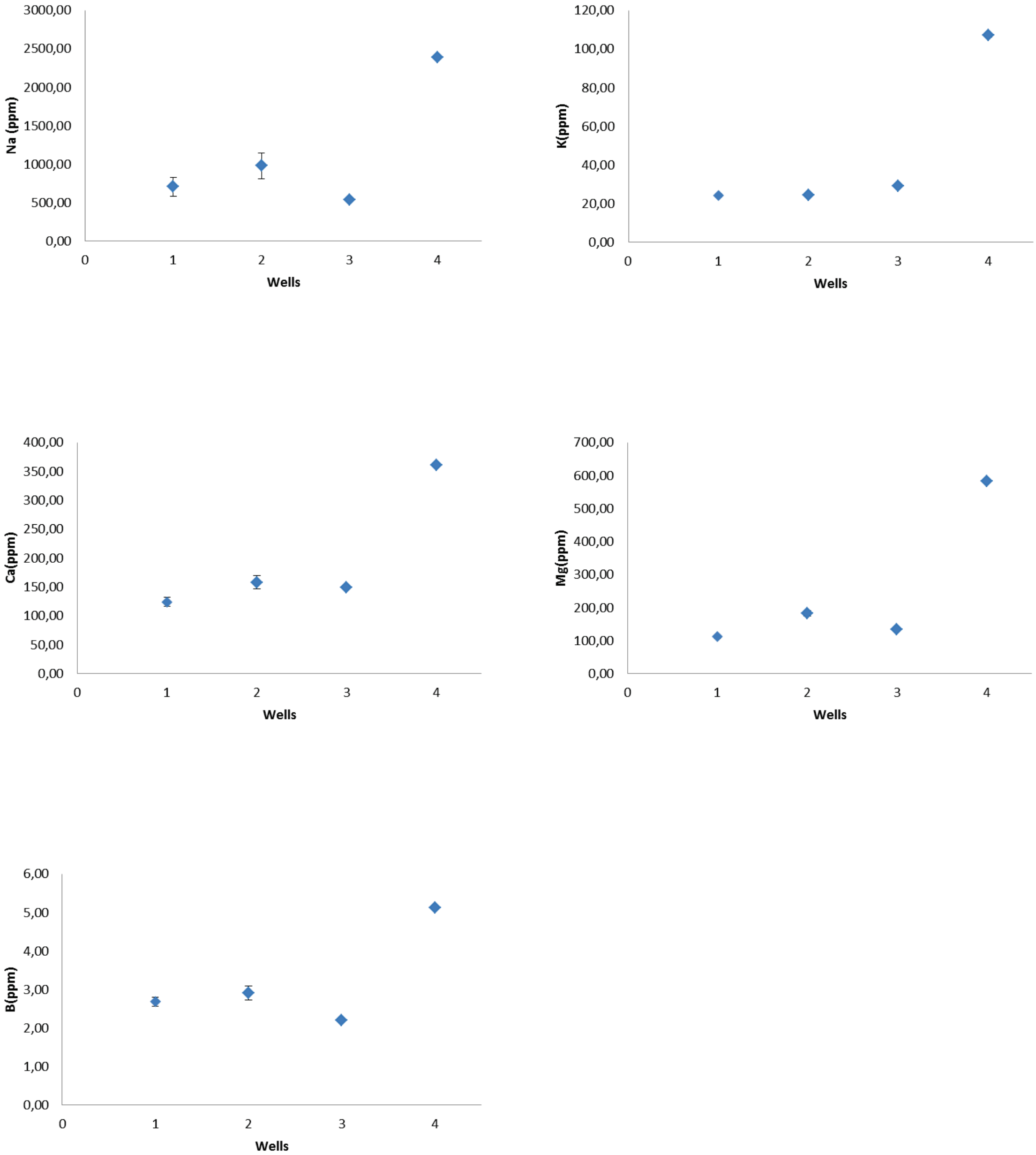


Figure 17. *Charts of ions concentrations (Na^+, K^+, Mg^{2+}, Ca^{2+} and B^{3-}) measured in the wells*

Distance to brackish groundwater

From the results obtained by the VES, we confirmed a distance to brackish groundwater gradient related with the spatial distance to the sea. The resistivity data showed that there were geological substrates with brackish water. The superficial layers had high apparent resistivity (>1000Ω.m), which correspond to conglomerate materials with discontinue distribution. The interface was located where the apparent resistivity was lower than 100 Ω.m (Table 4).

Table 4. Result of the Vertical Electrical Sounding (VES) carried out in Torregarcía area, Cabo de Gata-Nijar, Almeria (Spain)

VES nº1 (error 27.6%)		VES nº2 (error 12.5%)	
Layer 1	Initial apparent resistivity = 2472 µS/cm^2 Thickness = 27.7m	Layer 1	Initial apparent resistivity = 1453 µS/cm^2 Thickness = 55.8m
Layer 2 (interface, brackish water)	Initial apparent resistivity = 65.9 µS/cm^2	Layer 2 (interface, brackish water)	Initial apparent resistivity = 65.9 µS/cm^2

The following scheme is a graphical interpretation of the mixture between saltwater and freshwater in the study area (Figure 18).

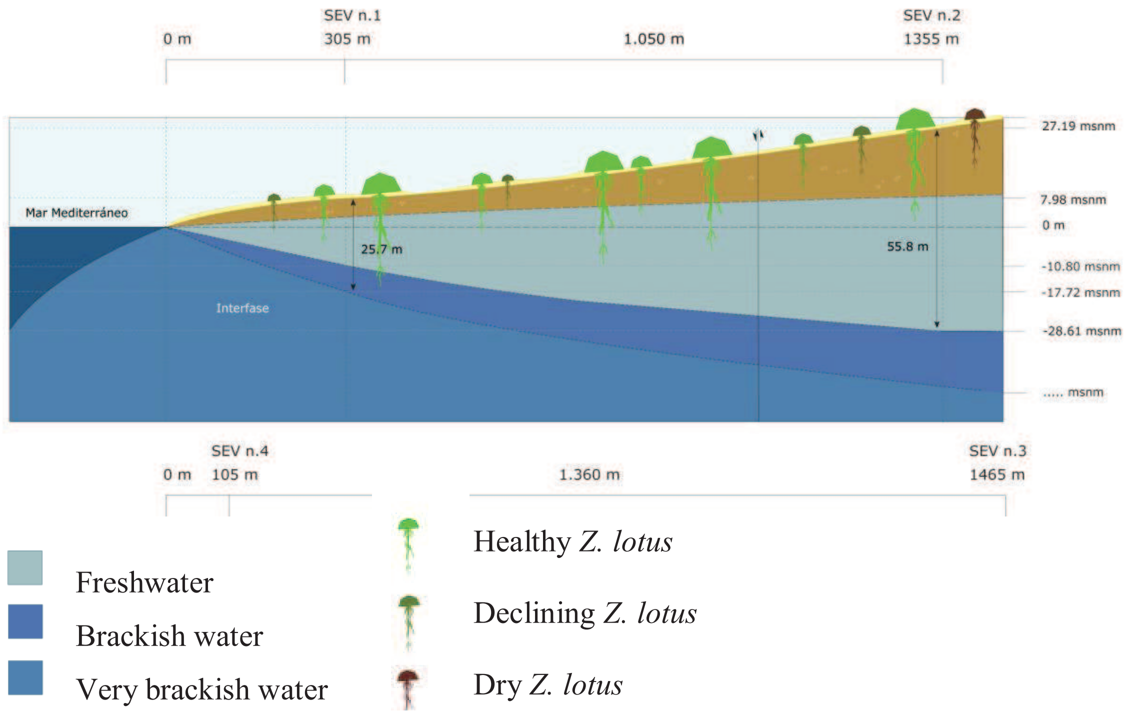


Figure 18. *Groundwater tables as derived from the cut between VES 1-2 in Torregarcía, Almeria (Spain)*

The interface between freshwater and seawater was known by the VES 1-2 which are describe in the section 4 (Methods). At a distance of a 305 m from the sea, the interface was 25.7 m depth, and at 1355 m from the sea it was 55.8 m depth.

5.2. Physiological condition of *Z. lotus* along the brackish groundwater distance gradient

5.2.1. Leaf chemical condition

The total of ions (Na^{+}, K^{+}, Ca^{2+}, Mg^{2+} and B^{3-}) content increased with increases in salinity (Table 5). The total inorganic ions resulted from increased Na^{+}, while K^{+} and Mg^{2+} concentration decreased with an increase in salinity.

Table 5. ICP-MS analysis of *Z .lotus* samples from Torregarcía, Almería (Spain)

Samples	B(mg/kg)	Na(mg/kg)	K(mg/kg)	Ca(mg/kg)	Mg(mg/kg)
Z1	161.26±106.68	314.76±241.00	2885.48±191.74	8679.49±752.74	15579.84±2136.50
Z2	349.47±177.02	313.07±143.86	5418.52±856.46	6052.71±1084.59	23810.79±3528.33
Z3	180.15±102.13	315.39±158.03	4324.66±259.33	9931.04±2376.42	14837.76±2895.00
Z4	288.09±81.21	79.47±19.83	3984.48±703.30	8710.03±1061.25	19229.58±1960.77
Z5	209.45±95.74	384.49±177.80	3671.62±582.86	8375.47±1638.52	12172.80±824.98
Z6	192.17±137.43	719.99±381.11	4136.82±181.06	11280.77±2164.38	13817.46±4542.13
Z7	243.74±198.98	963.78±243.40	3034.86±108.07	13777.88±3625.47	8983.51±2538.85
Z8	215.28±67.83	732.68±376.78	3095.68±91.80	15469.02±1815.47	7292.78±680.49
Z9	285.34±180.30	846.61±385.94	2648.74±263.15	11910.02±2154.38	9365.15±3832.38
Z10	180.66±68.50	1641.79±1197.08	3972.28±457.88	10425.29±1169.13	12433.34±2784.29

The leaf chemical analysis showed a gradual change in the chemical composition of the *Z. lotus* in relation with the distance from the sea (Figure 19). Thus, comparing the results of the brackish distance groundwater gradient with the leaf chemical analysis the *Z. lotus* individuals located over the VES 1-2, it was clear that the chemical composition of the leaves of *Z. lotus* reflected the salinity gradient of the aquifer.

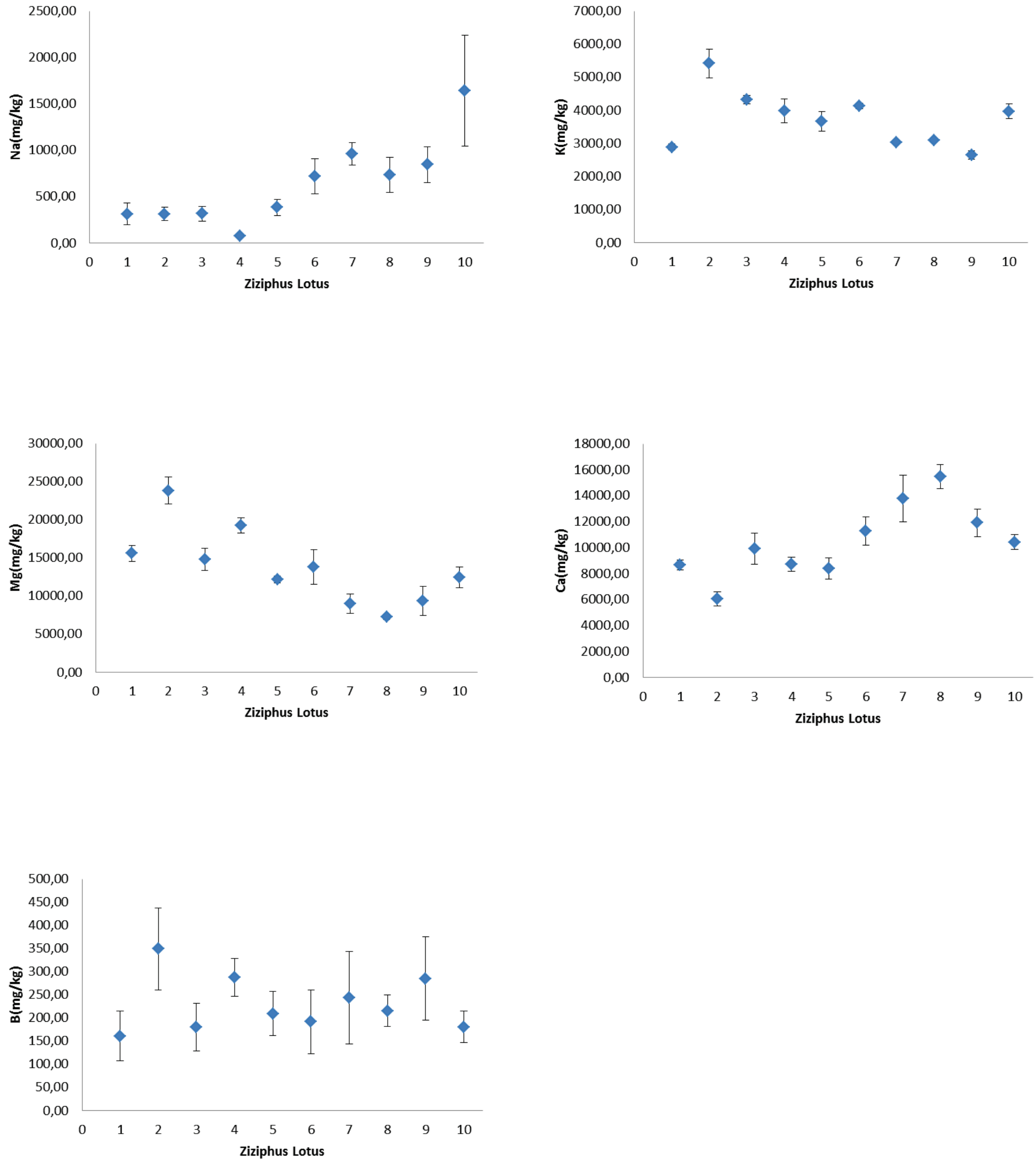


Figure 19. *Ions concentrations (Na^+, K^+, Mg^{2+}, Ca^{2+} and B^{3-}) measured in Z. lotus, along the brackish groundwater distance. Z1 was the furthest Ziziphus individuals to the sea (and hence to the brackish groundwater table) and Z10 was the closest to the sea.*

5.2.2. *Vegetation greenness and Vegetation water content*

Vegetation greenness (NDVI)

It is noticeable, there was small NDVI increasing in the Ziziphus individuals closest to the sea, although the differences of NDVI values along the gradient were also small are approximately constant along of the transect (Figure 20) ranging from 0.492 to 0.698 (Table 5).

Table 6. Vegetation greenness (NDVI) data from *Z. lotus* in Torregarcía, Almería (Spain)

Leaves samples	NDVI
Z1	0.576 ± 0.06
Z2	0.516 ± 0.02
Z3	0.558 ± 0.06
Z4	0.492 ± 0.03
Z5	0.576 ± 0.07
Z6	0.561 ± 0.01
Z7	0.649 ± 0.03
Z8	0.537 ± 0.05
Z9	0.540 ± 0.03
Z10	0.698 ± 0.08

Vegetation Water Content (NDWI)

The differences of NDWI values along the gradient were also small, since it ranged from - 0.307 to - 0.176 (Table 7). Nevertheless, the obtained results showed an increasing in the vegetation water content from the inland to the sea (Figure 21).

Table 7. Vegetation water (NDWI) data from *Z.Lotus* in Torregarcía, Almería (Spain)

Leaves samples	NDWI
Z1	-0.292 ± 0.08
Z2	-0.307 ± 0.02
Z3	-0.278 ± 0.02
Z4	-0.280 ± 0.02
Z5	-0.246 ± 0.05
Z6	-0.285 ± 0.05
Z7	-0.203 ± 0.05
Z8	-0.246 ± 0.05
Z9	-0.278±0.07
Z10	-0.176±0.03

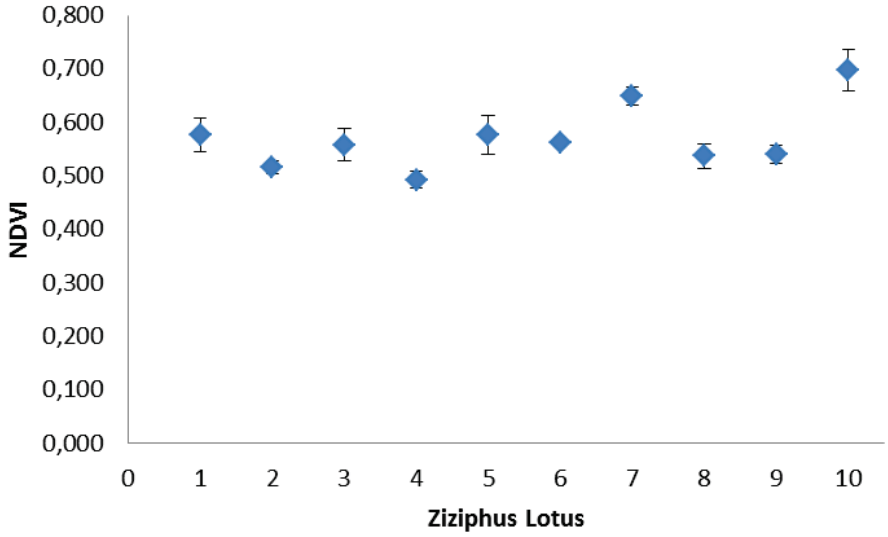


Figure 20. *Vegetation greenness (NDVI) data of Z. lotus along the brackish groundwater distance. Z1 was the furthest Ziziphus individuals to the sea (and hence to the brackish groundwater table) and Z10 was the closest to the sea.*

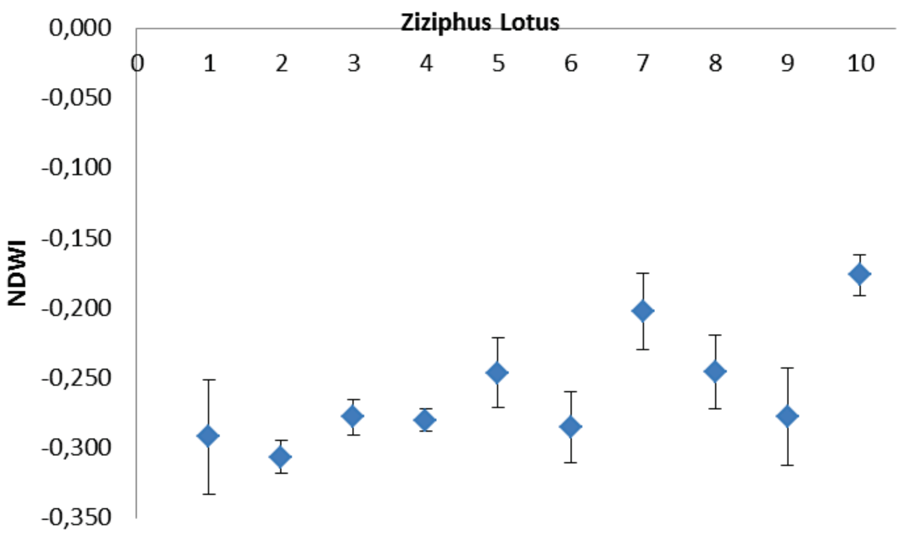


Figure 21. Vegetation water content (NDWI) data of *Z. lotus along the brackish groundwater distance. Z1 was the furthest Ziziphus individuals to the sea (and hence to the brackish groundwater table) and Z10 was the closest to the sea.*

6. DISCUSSION

6.1. Salinization levels of the coastal aquifer

The groundwater showed a huge mineralization since the EC values were higher than 2500 μS/cm and the ions concentration is high. Sodium was the major cation in water from the aquifer what is to be expected because of the groundwater mass is located in the coastal area. The excess of sodium in water was indicative of salinization processes in the aquifer. It can be explained by the seawater intrusion, water-rock interactions and deep circulating flows (Daniele et al.2011). In natural water, boron exists primarily as undissociated boric acid with some borate ions. It is sufficiently soluble in water and boron is a significant constituent of seawater, with an average boron concentration of 4.5 mg/kg (WHO). The natural borate content of groundwater and surface water is usually small. Naturally boron in groundwater is derived from dissolution of evaporate sediments and geothermal (Sánchez et al. 1999). Last studies found out that there is high boron concentration in seawater leads one to consider it as an indicator of marine intrusion processes (Sánchez et al. 1999, Vengosh et al. 2004). However, the elevated boron content in water is related to sources such as anthropogenic origin, soil composition and urban wastewaters. In spite of the fact that the well 4 is not the closest well from the sea, it has the maximum boron concentration. It can be possible because it is in front to of greenhouses (Figure 22).

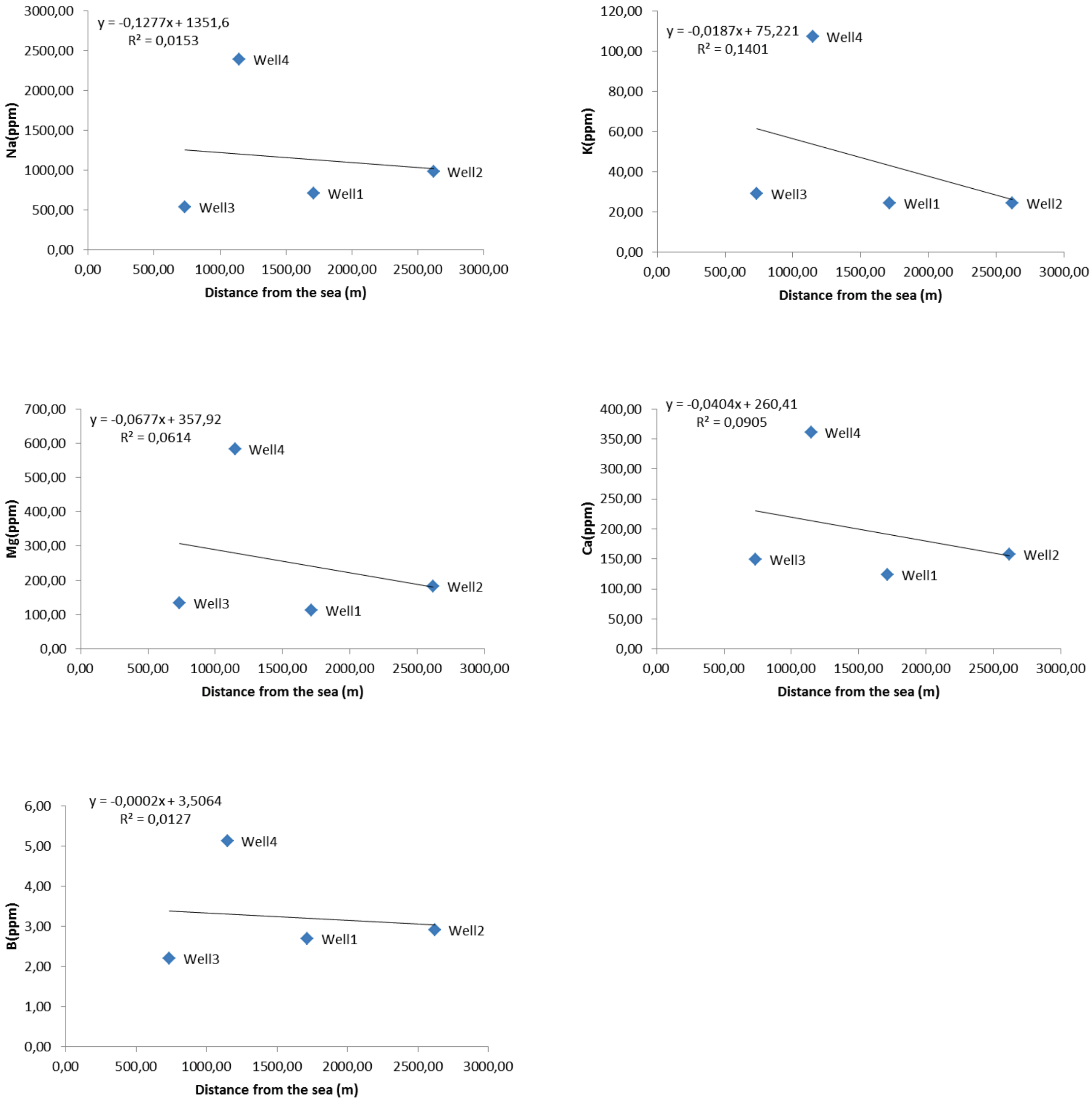


Figure 22. *Relationship between Na^+ and K^+, Mg^{2+} and Ca^{2+} in wells of the coastal aquifer of Cabo de Gata-Níjar Natural Park (Torregarcía area, Almería, Spain).*

The total hardness is caused by calcium and magnesium ions. They can be found in water as Ca^{2+} and Mg $^{2+}$. The Ca^{2+}concentration decrease with distance from the sea while Na^{+} concentration has an inverse behavior (Figure 22). This is due to the Na^{+} is taken up by the exchanger (soil) and the Ca^{2+} is released into the water.

$$Na^{+} + 1/2Ca^{2+}\text{-}X_2 \longrightarrow 1/2Ca^{2+} + Na\text{-}X$$

This equation takes place in coastal aquifers which have seawater intrusion. Potassium occurs in various minerals, from which it may be dissolved through weathering processes. Some clay minerals contain potassium which can be released into the water thought natural processes. Other important source of K^{+} is used of fertilizers, mainly potassium nitrate. As I mentioned previously, the well 4 are close to greenhouses, it can be the cause of the high K^{+} concentration in water (Figure 22). Cation exchange between water and exchanging solid surfaces in the aquifer is significant when relative cation concentration become different along a groundwater. This mean that the processes which occur in the aquifer, are controlled by differences in the behavior of ions in relation to the adsorption capacity of the exchanging solid surface, dispersivity of the aquifer, and the contrast between the composition of the solution that displaces and the solution that is displaced (Cardona et al.2004). The Sodium Absorption Ratio (SAR) (Table 3) is an important tool for predicting the water quality. Water with large SAR values has the potential to affect the use of water for irrigation. All the wells are suitable for irrigation.

6.2. Leaf chemical composition as indicator of the salinity gradient

Considering the obtained results from the *Ziziphus* leaves sampling along the gradient, the leaf chemical composition could be used as a salinization indicator in the aquifer. The elements Na^{+}, K^{+}, Ca^{2+}, Mg^{2+} and B^{3-} analyzed in *Z. lotus* leaves reflected the salinity gradient, following a positive correlation with the brackish distance gradient (Figure 23). It should be noted that *Z. lotus* showed higher salt-tolerancy than expected. So far, this ecophysiological trait of *Z. lotus* has not been referenced in the literature. Nevertheless, other species from the same genus (e.g. *Z. spina-christi* and *Z. mauritiana*) that also live in arid zones are salt-tolerant (Agrawal 2013). This suggests that salt tolerance could be an adaptation factor adopted in response to harsh conditions. Thus *Ziziphus* must have developed physiological processes to tolerant high solute concentration. Several mechanisms could match with this processes: 1) the osmotic adjustment between vacuole and cytoplasm via the accumulation of organic solutes in the latter (Arndt et al.2004); 2) the redistribute water to neighboring plant (Armas at al.2010); 3) the Uptake and exudation of same sort of salty water by roots (Agrawal 2013); 4) the accumulation of compatible solutes such as sugars, proline or glycine betaine in plants benefit stressed cells by protecting and stabilizing macromolecules and structures (Maraghni at al.2011) and; 5) the leaf succulence to increases in spongy mesophyll cells as a response to salt stress (Sohai et al.2009). More research is needed to dilucidate the ecophysiological mechanism associated with the salt tolerance of *Z. lotus*.

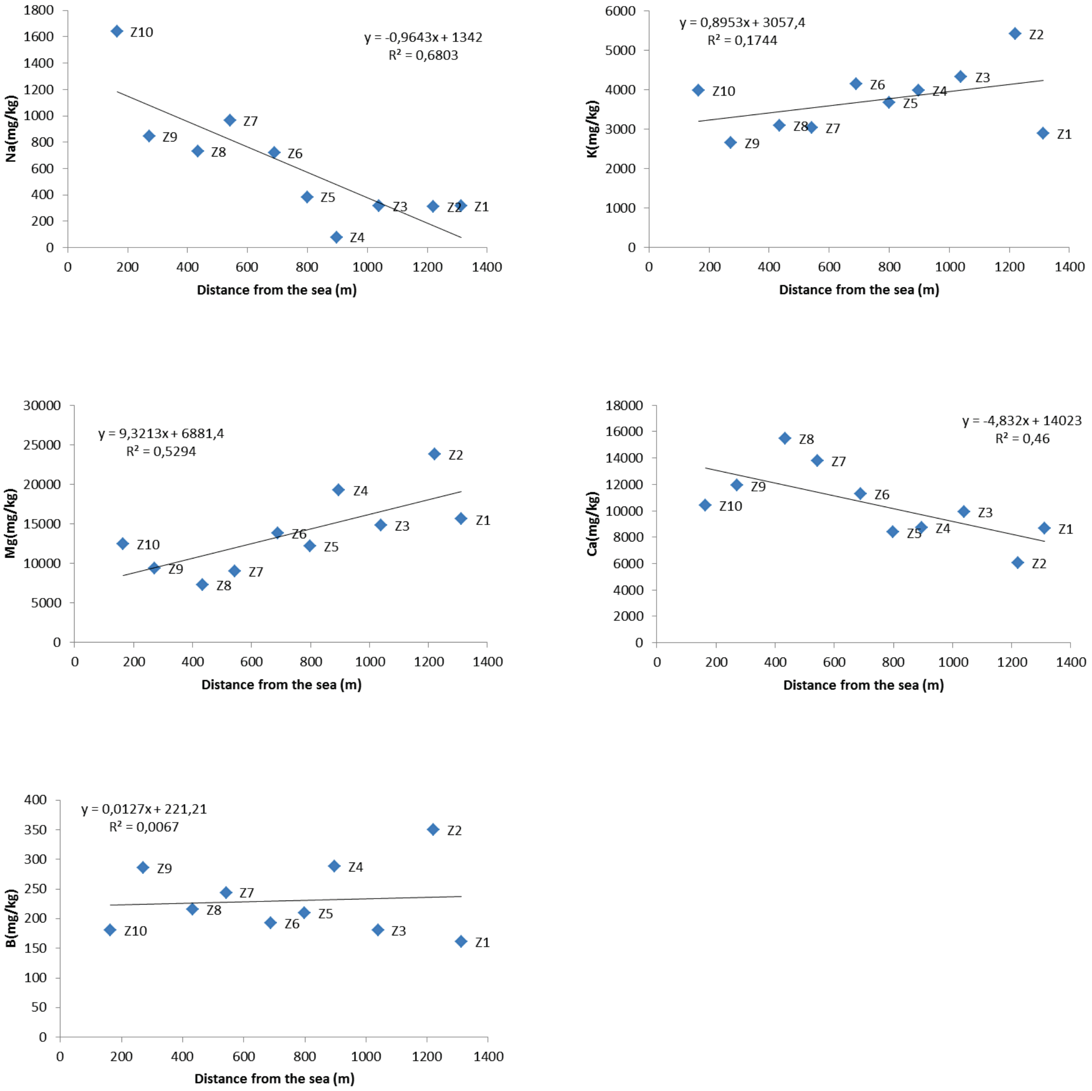


Figure 23. *Distribution of elements (Na^+, K^+, Mg^{2+}, Ca^{2+} and B^{3-}) in relation to the distance from the sea as proxy of salinity groundwater gradient.*

The different ion levels founded in the leaves respond both to the brackish groundwater distance gradient and to nutrient uptake mechanisms. Na^+ was the dominant cation. Concentration of Na^+ and Ca^{2+} increase towards the sea (nearest brackish groundwater table), while K^+ and Mg^{2+} decreased (Figure 23). Potassium is responsible to regulate the opening and closing of stomates, and its concentration is almost invariable in the soil solution, meaning that plants must actively take up and concentrate K^+ using various types of ion transporter. It is demonstrated that there is a competition between Na^+ and K^+ for uptake by plant roots, because Na^+ is similar to K^+ and inside the plant, many K^+ transporters do not discriminate between both cations (Pardo et al.2002). Consequently, the Na^+ uptake is high thereby decreasing the K^+ uptake. Calcium is an essential micronutrient in plants. As a divalent cation, it has structural roles in the cell wall and membrane. A high salinity in plant provoke a high Ca^{2+} concentration, it can be toxic for the plant (Jenks et al. 2007). Magnesium is an essential nutrient too which decrease when Ca^{2+} increase inside the plants (Figure 23). The plant tends to maintain a constant cation concentration; this means that high Ca^{2+} can induce Mg^{2+} deficiency. Boron is essential for cell wall structure and play and important role in membrane processes and metabolic pathways. Nevertheless, boron concentrations have a small range where concentrations are optimal. Above this range, boron becomes toxic and below it, boron is deficient. In spite of the fact that boron is essential for the plants; high boron concentrations, like salinity, are important abiotic stresses that adversely affects sensitive crops in many arid and semi-arid areas. The salinity increased B accumulation in leaves *Z. lotus* leaves contained great mineral salts concentration. There are different levels of regulation of salt uptake or distribution. Dilution of accumulation salts by increased leaf water content seems likely for this species.

6.3. Spectral vegetation indices as indicators of the response of Z. lotus to the salinity gradient

After this study we have figured out that the *Z. lotus* has a wide range of salt tolerance what can hamper the use of spectral indices as indicators of the salinity gradient. The NDVI and NDWI decreased along the gradient, although the drop is not stronger than leaf chemical composition. There was a linear relationship between distance to the sea and NDVI that decreases with increasing distance from the sea (Figure 25). The NDVI is responsive to change in chlorophyll content of plant leaves. High NDVI values reflect greater vigor and photosynthetic capacity of vegetation canopy, whereas lower NDVI values for the same time period are reflective of vegetative stress resulting in chlorophyll reductions and changes in the leaves' internal structure due to wilting (Gu et al.2008). Nevertheless, *Z. lotus* has a great photosynthesis capacity along the gradient. This index ranged from 0.492-0.698 (Table 5). These results accentuate its phreatophic characteristics, being groundwater the only water supply during the summer period in the ecosystem. In fact, in summer, *Z. lotus* is the only green plant in Torregarcía; this means that the greenness is almost due to the *Z. lotus*.

The greenness is related with the amount of chlorophyll. The center of each chlorophyll molecule is a magnesium ion. It guesses that higher magnesium concentration, higher content in plant. Nevertheless the *Z. lotus* leaf analysis shows different results. The *Z. lotus* which has higher magnesium concentration, it is not which has higher NDVI. It can be due to the others cations present in *Z. lotus* such as K^+, Na^+ and Ca^{2+} which decline the chlorophyll in plant (Ogawa et al. 1982). In spite of the fact that the boron is a micronutrient required for all plant nutrition, the higher B^{3+} concentration declines the NDVI in *Z. lotus* because boron is favorable in low concentration (Figure 24).

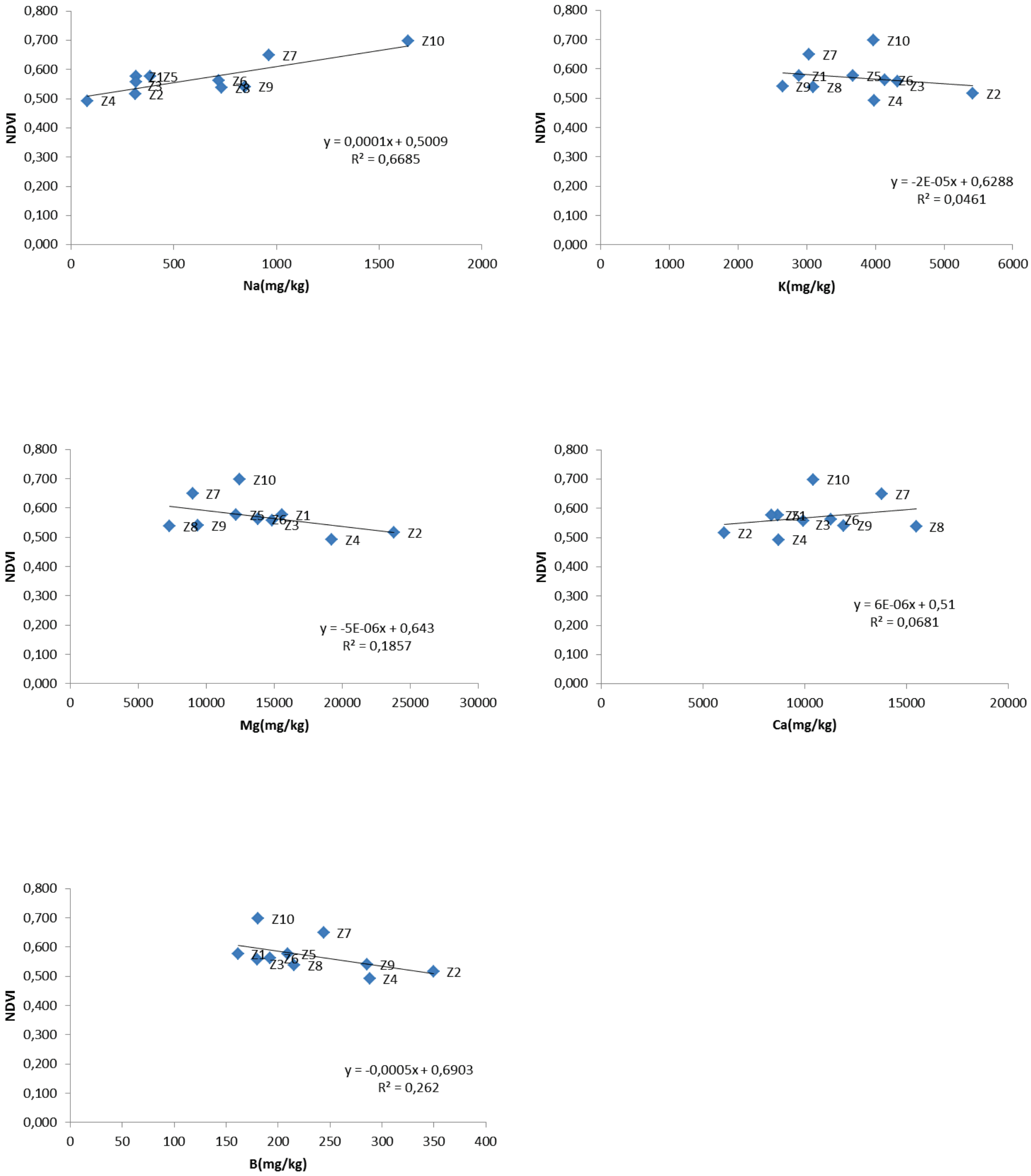


Figure 24. *Relationship between NDVI and each element measured in Z. lotus in the Torregarcía area (Cabo de Gata-Níjar Natural Park, SE Spain).*

The NDWI indicates the presence of water in the plant tissue. The SWIR reflectance shows changes in both the vegetation water content and the spongy mesophyll structure in vegetation canopies, while the NIR reflectance is affected by leaf internal structure and leaf dry matter content but not by water content. The combination of the NIR with the SWIR removes variations induced by leaf internal structure and leaf dry matter content, improving the accuracy in retrieving the vegetation water content. It is to be hoped that the salt contains increases, the water contents decrease in plants whereas there are plants which water contents of leaf increase when increasing salt concentration (Sohai et al.2009). Viewing the graph 25, we see that the water contents of *Ziziphus* increase with proximity of the sea.

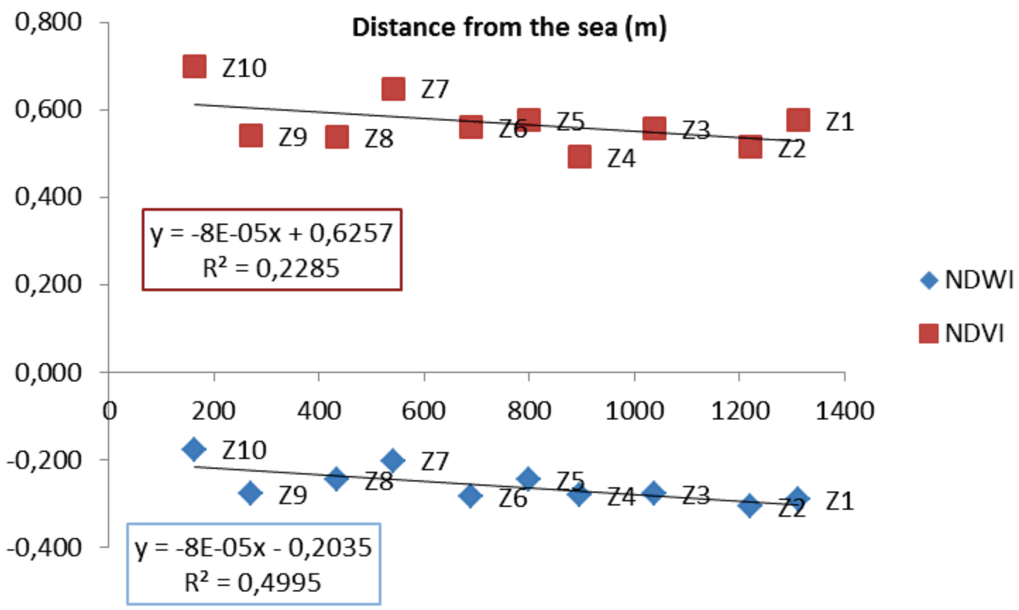


Figure 25. *Relationship between distance from the sea (m) as proxy of salinity gradient and NDVI and NDWI values of Z. lotus*

Z. lotus located in the shallow groundwater, their photosynthesis activity and water contents will be higher because the water are more accessible for them even being salt groundwater while *Z. lotus* located in deeper groundwater , it is more complicate take up the water. The moisture content and green leaves is likely due to water uptake by deep-reaching roots in *Z. lotus* Previous studies show that the *Z. lotus* has a noticeable drought resistance due to that the great capacity to absorb water from a rather dry soil (Gorai et al.2010). *Z. lotus* has green leaves throughout the summer months owing to water uptake by deep-reaching roots.

7. CONCLUSIONS

In arid and semiarid zones, GDEs provides valuable ecosystem services for humans. However, the interest to study them has just recently started. The Water Framework Directive focuses of such ecosystems as they can be threatened by the aquifers contamination. To improve the understanding of the factors determine the health of GDEs, we need to study the relationship between groundwater and both aquatic and terrestrial systems. Here, we studied these relationships in the coastal plain of the Cabo de Gata-Níjar Natural Park, (Almería Spain) to derive vegetation indicators that inform us about the aquifer state. *Z. lotus* is a phreatophyte that maintains its vegetative growth in summer by using a deep-root system able to obtain water from water table. Based on this relation, the results we obtained showed that leaf ion content provides a cost–effective method to assess the groundwater condition. Hence, this plant species may be used as seepage indicators in rapid assessments and surveys of the aquifer conditions. Nevertheless, it is needed more research to elucidate the ability of *Ziziphus* to inform about the aquifer condition. Although spectral vegetation indices (NDVI and NDWI) are good indicators of the vegetation health, it use with *Ziziphus lotus* as indicators for the groundwater conditions may be complex because of the salt tolerance of the species. We consider the current research helps to define groundwater–vegetation relationships in coastal areas and to achieve feasible monitoring systems of the groundwater conditions in arid and semi-arid areas.

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9. REFERENCES

Aldous A., Bach L. (2011) *Protecting groundwater-dependent ecosystems: gaps and opportunities*. National wetlands newsletter 33, 3

Appelo, C. A. J. & D. Postma (1993) *Geochemistry, groundwater and pollution*. Rotterdam: Balkema.

Arndt S., Arampatsis C., Foetzki A., Li X., Zeng F., Zhang X. (2004) *Contrasting patterns of leaf solute accumulation and salt adaptation in four phreatophytic desert plants in a hyperarid desert with saline groundwater.* Journal of Arid Environments 59, 259-270

Asbjornsen H., Goldsmith G., Alvarado- Barrientos M, Rebel K., Van Osch F., Rietkerk M., Chen J., Gotsch S., Tobón C., Geissert D, Gómez-Tagle A., Vache K., Dawson T. (2011) *Ecohydrological advances and applications in plant-water relations research: a review*. Journal of Plant ecology 4, 3-22

Ataie-Ashtiani B., Volker R., Lockington D. (1999) *Tidal effects on sea water intrusion in unconfined aquifers.* Journal of Hydrology 216,17-31

Badano E., Pugnaire F. (2004*) Invasion of Agave species (Agavaceae) in south-east Spain: invader demographic parameters and impacts on native species*. Diversity and Distributions 10, 493-500

Barron O., Silberstein R., Ali R., Donohue R., McFarlane D.J., Davies P., Hodgson., Smart N., Donn M. (2012) *Climate change effects on water-dependent ecosystems in south-western Australia.* Journal of Hydrology 434-435, 95-109

Baudena M., Andrea F., Provenzale A. (2008) *A model for soil-vegetation-atmosphere interactions in water-limited ecosystems.* Water Resources Research 44, W12429

Baudena M., Boni G., Ferraris L., Von Hardenberg J., Provenzale A. (2007) *Vegetation response to rainfall intermittency in drylands: Results from a simple ecohydrological box model.* Advances in Water Resources 30, 1320–1328

Brown L., Milner A., Hannah D. (2007) *Groundwater influence on alpine stream ecosystems.* Freshwater Biology 52, 878–890.

Brown J, Bach L, Aldous A, Wyers A, DeGagné J (2009) *Groundwater-dependent ecosystems in Oregon: an assessment of their distribution and associated threats.* Frontiers in Ecology and the Environment, 9, 97–102.

Cabello J. Alcaraz-Segura D., Ferrero R., Castro A., Liras E. (2012) *The role of vegetation and lithology in the spatial and inter-annual response of EVI to climate in dryland of Southeastern Spain.* Journal of Arid Environments 79, 76-83

Camacho F., Eberle A., Lanjeli S., Martínex B., Lopez-Baeza E. (2009*) Diseño de un índice espectral optimizado para la estimación del contenido en agua de la vegetación con datos MODIS.* Teledetección: agua y desarrollo sostenible. XIII Congreso de la Asociación Española de Teledetección, 449-452

Camilio J., Breshears D., Zou C., Law D. (2010) *Ecohydrology controls of soil evaporation in deciduous drylands: How the hierarchical effects of litter, patch and vegetation mosaic cover interact with phenology and season*. Journal of Hydrology 74, 595-602

Cardona A., Carrillo J., Huizar R., Graniel E. (2004) *Salinization in coastal aquifers of arid zones: an example from Santo Domingo, Baja California Sur, Mexico.* Environmetal Geology 45, 350-366

Castro AJ, Martín-López B, García-LLorente M, Aguilera PA, López E, Cabello J (2011) *Social preferences regarding the delivery of ecosystem services in a semiarid Mediterranean region.* Journal of Arid Environments 75, 1201–1208

Cavanaugh M., Kurc S., Scott R. (2011) *Evapotranspiration partitioning in semiarid shrubland ecosystem: a two-site evaluation of soil moisture control on transpiration.* Ecohydrology 4. 671-681

Chen K., Jiao J. (2007) *Seawater intrusion and aquifer freshening near reclaimed coastal area of Shenzhen.* Water Science & Technology: Water Supply 7, 137-145

Collins D., Bras R. (2007) *Plant rooting strategies in water-limited ecosystems*. Water resources research 43, W06407

Conti G., Díaz S. (2013) *Plant functional diversity and carbon storage – an empirical test in semi-arid forest ecosystems.* Journal of Ecology 101, 18-28

Cooper D., Sanderson J., Stannard D., Groeneveld D. (2006) *Effects of long-term water table drawdown on evapotranspiration and vegetation in an arid region phreatophyte community.* Journal of Hydrology 325, 21-34

Daniele L., Vallejos A., Sola F., Corbella M., Pulido-Bosch A. (2011) *Hydrogeochemical processes in the vicinity of a desalination plant (Cabo de Gata, SE Spain)*. Desalination 277, 338-347

Davis M., Forman A., Fajer J. (1979) *Ligated chlorophyll cation radicals: their function in photosynthesis II of plant photosynthesis.* Proceeding of the National Academy of Sciences of the United State 76, 4170-4174

Eamus D., Froend R., Loomes R., Hose G., Murray B. (2006) *A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation*. Australian Journal of Botany 54, 97-114

Edelstein M., Ben-Hur M., Cohen R., Burger Y., Ravina I. (2005) *Boron and salinity effects on grafted and non-grafted melon plants.* Plant and Soil 269, 273-284

Ehleringer JR, Dawson TE (1992) *Water uptake by plants: perspectives from stable isotope composition.* Plant, Cell & Environment 15, 1073–1082.

Erdman J., Christenson S. (2000) *Elements in Cottonwood stress as an indicator of groundwater contaminated by landfill leachate*. GWMR 120-126

Fan Y., Li H., Miguez-Macho G. (2013) *Global patterns of groundwater table depth.* Science 339, 940

Froend R., Sommer B. (2010) *Phreatophytic vegetation response to climatic and abstraction-induced groundwater drawdown: Examples of long-term spatial and temporal variability in community response.* Ecological Engineering 36, 1191-1200

Froend RH, McComb AJ (1994) *Distribution, productivity and reproductive phenology of emergent macrophytes in relation to water regimes at wetlands of south-western Australia.* Marine and Freshwater Research 45, 1491–1508.

Froend RH, Halse SA, Storey AW (1997) *Planning for the recovery of Lake Toolibin, Western Australia*. Wetlands Ecology and Management 5, 73–85.

Gao B. (1996) *NDWI – A normalized difference water index for remote sensing of vegetation liquid water from space.* Remote Sensing of Environment 58, 257-266

García J., Sánchez A., Castillo E., Marín I., Padilla A., Roso J. (2003) *Hidrogeoquimica de las aguas subterráneas en la zona de Cabo de Gata.* Tecnología de la intrusión de agua de mar en acuíferos costeros :países mediterráneos 84-7840-470-8

Gorai M., Ennajeh M., Khemira H., Neffati M. (2009) *Combined effect of NaCl-salinity and hypoxia on growth, photosynthesis, water relations and solute accumulation in Phragmites australis plants.* Elsevier Flora 205, 462-470

Gorai M., Ennajeh M., Khemira H., Neffati M. (2010) *Influence of NaCl-salinity on growth, photosynthesis, water relations and solute accumulation in Phragmites australis*. Springer

Gorai M., Maraghni M., Neffati M. (2011). *Relationship between phenological traits and water potential patterns of the wild jujube Ziziphus lotus (L.) Lam. in southern Tunisia.* Plant Ecology & Diversity 3, 273-280

Gu Y., Hunt E., Wardlow B., Basara J., Brown J., Verdin J. (2008) *Evaluation of MODIS NDVI and NDWI for vegetation drought monitoring using Oklahoma Mesonet soil moisture data.* Geophysical research letter 35, L22401

Hancock CN, Ladd PG, Froend RH (1996) *Biodiversity and management of riparian vegetation in Western Australia.* Forest Ecology and Management, 85, 239–250

Hasse P., Pugnaire F., Fernández E., Puigdefábregas J., Clark S.C. Incoll L.D. (1996) *An investigation of rooting depth of the semiarid shrub Retama sphaerocarpa (L.) Boiss. by labeling of groundwater with a chemical tracer*. Journal of Hydrology 177, 23-31

Herczeg A., Dogramaci S., Leaney F. (2001) *Origin of dissolved salts in a large, semi-arid groundwater system: Murray Basin, Australia*. Marine Freshwater Research 52, 41-52

Hu Y., Schmidhalter. (2005) Drought and salinity: A comparison of their effects on mineral plants. Journal of Plant Nutrition and Soil Science 168, 541-549

Humphreys W. (2006) *Aquifer: the ultimate groundwater-dependent ecosystems.* Australian Journal of Botany 54, 115-132

Jackson R., Jobbágy E., Nosetto M. (2009) *Ecohydrology in human-dominated landscape*. Ecohydrology 2, 383-389

Jalali M. (2005) *Major ion chemistry of groundwaters in the Bahar area, Hamadan, western Iran.* Environ Geol 47, 763-772

Jenks M., Hasegawa P., Jain S. (2007) *Advances in Molecular Breeding toward drought and salt tolerant crops.* Springer

Jonnágy E., Nosetto M., Villagra P., Jackson R. (2001) *Water subsidies from mountains to deserts: their role in sustaining groundwater-fed oases in a sandy landscape.* Ecological Applications 21, 678-694

Jochen H., Jackson R. (2002) *Rooting depths, lateral root spreads and below ground/ above-ground allometries of plants in water-limited ecosystems*. Journal of Ecology 90, 480-494

Khan M., Ungar I., Showalter A. (2000) *Effect of salinity on growth, water relations and ion accumulation of the subtropical perennial halophyte, Atriplex griffithii var. stochsii.* Annals of Botany 85, 225-232

Lagarde F., Louzizi T., Slimani T., El Mounden H., Kaddoour K., Moulherat S., Bonner X. (2012) *Bushes protect tortoises from lethal overheating in arid areas of Morocco*. Environmental Conservation 39, 172–182

Lee J., Song S. (2007) *Evaluation of groundwater quality in coastal areas: implications for sustainable agriculture*. Environ Geol 52, 1231-1242

Lin GH, Sternberg L da S (1992) *Effect of growth form, salinity, nutrient and sulfide on photosynthesis, carbon isotope discrimination and growth of red mangrove (Rhizophora mangle L.).* Functional Plant Biology 19, 509–517

Ma F., Yang Y., Yuan R., Cai Z., Pan S. (2007) *Study of shallow groundwater quality evolution under saline intrusion with environmental isotopes and geochemistry.* Environmental Geology 51, 1009-1017

Maraghni M., Gorai M. Neffati M. (2010) *Seed germination at different temperatures and water stress levels, and seedling emergence from different depths of Ziziphus lotus.* South African Journal of Botany 76, 453–459

Markewitz D., Davidson E., O. Figueiredo R., Victoria R., Krusche A. (2001) *Control of cation concentratios in stream waters by surface soil processes in an Amazonian watershed*. Nature 410

Mata-Gonzalez R., Hunter R., McLendon T. Martin D. (2005) *Phreatophytic vegetation and groundwater fluctuations: A review of current research and application of ecosystem response modeling with an emphasis on great basin vegetation.* Environmental Management 35, 726–740

Mensforth LJ, Thorburn PJ, Tyerman SD, Walker GR (1994) *Sources of water used by riparian Eucalyptus camaldulensis overlying highly saline groundwater.* Oecologia 100, 21–28

Mitchell P., Veneklaas E., Lambers H., Burgess S. (2009) *Partitioning of evapotranspiration in a semi-arid eucalypt woodland in south-western Australia*. Agriculture and forest meteorology 149, 25-37

Newman B. (2004) *Ecohydrology of Arid and Semi-arid environments*. CUAHSI

Ogawa T., Grantz D., Boyer J., Govindjee (1982) *Effects of cations and abscisic acid on chlorophyll a. Fluorescence in Guars cells of Vicia faba*. Plant physiology 69, 1140-1144

Paijmans K, Galloway RW, Faith DP *et al.* (1985) *Aspects of Australian wetlands. Division of Water and Land Resources Technical Paper*. CSIRO, Canberra

Pardo J., Quintero F. (2002) *Plants and sodium ions: keeping company with enemy.* Genome Biology, 3(6)

Pataki D., Billings S., Naumburg E., Goedhart C. (2008) *Water sources and nitrogen relations of grasses and shrubs in phreatophytic communities of the Great Basin Desert.* Journal of Arid Environments 72, 1581– 1593

Pugnaire F., Armas C., Maestre F. (2001) *Positive plant interaction in the Iberian southeast: mechanisms, environmental gradients, and ecosystem function*. Journal of Arid Environments 75, 1310-1320

Pugnaire J., Sole A., Gutierrez L., del Barrio G., Boer M. (1999) *Scales and processes of water and sediment redistribution in drylands: results from the Rambla Honda field site in Southeast Spain.* Earth-Science Reviews 48, 39-70

Sánchez F. (2011) *Propección geofísica: Sondeos Eléctricos Verticales*. Dpt Geología Universidad Salamanca, España

Sánchez F., Pulido A. (1999) *Boron and the origin of salinization in an aquifer in southeast Spain.* Earth & Planetary Science 328, 751-757

Schulze E-D, Mooney HA, Sala OE et al. (1996) *Rooting depth, water availability, and vegetation cover along an aridity gradient in Patagonia*. Oecologia 108, 503–511

Sola F., Daniele L., Vallejos A., Sánchez-Martos F. (2008) *Integración de datos litológicos, hidrogeológicos y geofísicos para el estudio del acuífero detrítico costero de Cabo de Gata (Almería, SE España).* Geo-Temas 10, ISSN: 1567-5172

Sola F., Daniele L., Sánchez-Martos F., Vallejos A., Urízar R., Pulido A. *Influencia de la desaladora de rambla morales (Almeria) sobre las características hidrogeológicas del acuifero del que se abastece.* Hydrogeology department. University of Almeria

Sommer B. Froend R. (2011) *Resilience of phreatophytic vegetation to groundwater drawdown: is recovery possible under a dry climate?* Ecohydrology 4, 67-82

Soylu M. Istanbulluoglu E., Lenters J., Wang T. (2011) *Quantifying the impact of groundwater depth on evapotranspiration in a semi-arid grassland region.* Hydrology and Earth system sciences 15, 787-806

Subramani T., Elango L., Damodarasamy S. (2005) *Groundwater quality and its suitability for drinking and agricultural use in Chithar River Basin, Tamil Nadu, India*. Environ Geol 47, 1099-1110

Tavakkoli E., Rengasamy P., McDonals G. (2010) *High concentrations of Na+ and Cl– ions in soil solution have simultaneous detrimental effects on growth of faba bean under salinity stress.* Journal of experimental Botany 61, 4449-4459

Thorburn PJ, Walker GR (1994) *Variations in stream water uptake by Eucalyptus camaldulensis with differing access to stream water.* Oecologia 100, 293–301

Thorburn PJ, Walker GR, Woods PH (1992) *Comparison of diffuse discharge from shallow water tables in soils and salt flats.* Journal of Hydrology 136, 253–274

Thorburn PJ, Hatton TJ, Walker GR (1993) *Combining measurements of transpiration and stable isotopes of water to determine groundwater discharge from forests.* Journal of Hydrology 150, 563–587

Tillman F.D., Callegary J.B., Nagler P.L., Glenn E.P. (2011) *A simple method for estimating basin-scale groundwater discharge by vegetation in the basin and range provine of Arizona using remote sensing information and geographic information systems.* Journal of Arid Environments 82, 44-52

Tirado R. (2009) 5220 *Matorrales arborenscentes con Ziziphus. Ministerio de Medio Ambiente, y Medio Rural y Marino.* Secretaría General Técnica.

Tirado R., Pugnaire F. (2003) *Shrub spatial aggregation and consequences for reproductive success.* Oecologia 136, 296-301

Tirado R., Pugnaire F. (2005) *Community structure and positive interactions in constraining environments.* OIKOS 111, 437-444

Vengosh A., Kloppmann W., Marei A., Livshitz Y., Gutierrez A., Banna M., Guerrot C., Pankratov I., Raanan H. (2005) *Sources of salinity and boron in the Gaza strip: natural contaminant flow in the southern Mediterranean coastal aquifer*. Water Resources Research 41, W01013

Veste M., Staudinger M., Küppers M. (2008) *Spatial and temporal variability of soil water in drylands: plant water potential as a diagnostic tool.* For. Stud. China 10, 74–80

Zencich S., Froend R., Turner J., Gailitis V. (2001) *Influence of groundwater depth on the seasonal sources of water accessed by Banksia tree species on a shallow, sandy coastal aquifer.* Oecologia 131, 8-19

Zhou H., Chen Y.N., Li W., Chen Y.P.(2010) *Photosynthesis of Populus euphratica in relation to groundwater depths and high temperature in arid environment, northwest China.* Photsynthetica 48, 257-268