

Evaluation of salinization and sodification in irrigated areas with limited soil data: Case study in southern Portugal

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Evaluación de la salinización y sodificación en áreas de riego con datos limitados del suelo: estudio de caso en el sur de Portugal
Avaliação da salinização e sodificação em áreas de regadio com dados limitados do solo: estudo de caso no sul de Portugal

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ABSTRACT

Due to its high land productivity, irrigated agriculture has an increasing role in food production. In the Alentejo region (southern Portugal) the irrigated area has grown since the completion of the Alqueva dam in 2002. Climatic change patterns foreseen for the Mediterranean region (more heat extremes, less precipitation and river flow, increasing risk of droughts and decrease in crop yields) are prone to soil salinization and sodification in irrigated areas in the region. The Roxo dam has some of the higher records of water salinity and sodicity in Portugal, which makes the Roxo irrigated area (RIA) a very interesting case study. This paper aimed at two main objectives for the RIA: (i) evaluate soil salinization and sodification, and make spatial predictions of soils susceptibility to these degradation types; (ii) monitor current salinity and sodicity of the water, and simulate the effect of empirical based scenarios of water salinity and sodicity. The RIA (8250 ha) extends ~20 km along the Roxo river (northern Aljustrel), in Cenozoic sedimentary formations. Main soils mapped are: Luvisols (~40%), Fluvisols and Regosols (~20%), Gleysols and Planosols (~20%) and Vertisols (~10%). However, there are only five soil profiles with detailed analytical data from a more recent soil survey with 83 profile descriptions in the RIA and surrounding area. Irrigation water of the Roxo dam and drainage water of the Roxo river were monitored almost monthly during Jul/2014-Nov/2015 and Jun/2016-Jan/2017, for determination of electrical conductivity (EC), sodium adsorption ratio (SAR), and other parameters. Soil salinity was not a significant problem in the RIA but a potential abundance of sodic soils was found that need future confirmation. A qualitative soil salinity index applied to the RIA suggests that soils most susceptible to salinity occur to a much smaller extent when this index is obtained from the soil profile data (approach B) than when it is based on information of the soil map (approach A). During the monitoring periods, both the water of the Roxo dam and of the Roxo river were slight to moderate saline for crop growth, with no restrictions for soil infiltration. The Roxo dam received water from the Alqueva dam for the first time between June and September 2016, and a small, though regular, decrease of the water EC (0.99 to 0.76 dS m⁻¹) was observed during the same period. Three scenarios of irrigation water, identified by Low/High EC-SAR (L-L, H-H, L-H) were simulated with the Watsuit model. Low EC water (L-L and L-H) represent wet years and show no risk of soil salinity in the rootzone. However, the risk of waterlogging increases in sodic soils, especially with the scenario (L-H). High EC water (H-H) represents dryer years and results in severe saline conditions in the rootzone. In all three scenarios, prosodic and sodic soils are most sensible to degradation by salinization, sodification or both.

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RESUMEN

Debido a su alta productividad de la tierra, la agricultura de regadío tiene un papel creciente en la producción de alimentos. En la región de Alentejo (sur de Portugal) la superficie de riego ha crecido desde la terminación de la represa de Alqueva en 2002. Los cambios climáticos previstos para la región mediterránea (más extremos de calor, menos precipitación y caudal de río, mayor riesgo de sequía y disminución de la productividad de los cultivos) favorecen la salinización y la sodificación del suelo en las áreas de regadío de la región. La represa del Roxo tiene algunos de los mayores registros de salinidad y sodicidad del agua en Portugal, por lo que el área de riego del Roxo (RLA) es un estudio de caso de particular interés. Este trabajo tiene dos objetivos principales para el RLA: (i) evaluar la salinización y sodificación de los suelos, y predecir espacialmente su susceptibilidad a estas formas de degradación; (ii) monitorear la salinidad y sodicidad del agua, y simular el efecto de escenarios de la salinidad y sodicidad del agua. El RLA (8250 ha) se extiende por ~20 km a lo largo del río Roxo (norte de Aljustrel), en formaciones sedimentarias cenozoicas. Los principales suelos son: Luvisoles (~40%), Fluvisoles y Regosoles (~20%), Gleysols y Planosoles (~20%) y Vertisoles (~10%). Sin embargo, sólo hay cinco perfiles de suelo con datos analíticos detallados, obtenidos a partir de un levantamiento de suelos más reciente con 83 descripciones de perfil en el RLA y área circundante. El agua de riego de la presa de Roxo y las aguas de drenaje del río Roxo fueron monitoreadas casi mensualmente durante Jul/2014–Nov/2015 y Jun/2016–Ene/2017, para determinar la conductividad eléctrica (EC), la tasa de adsorción de sodio (SAR) y otros parámetros. La salinidad del suelo no fue un problema significativo en el RLA, pero se encontró una abundancia potencial de suelos sódicos que necesitan confirmación futura. Un índice cualitativo de salinidad del suelo aplicado al RLA sugiere que los suelos más susceptibles a la salinidad ocurren en una extensión mucho menor cuando el índice se obtiene de los datos de los perfiles del suelo (enfoque B) que cuando se basa en información del mapa de suelos (enfoque A). Durante los períodos de monitoreo, tanto el agua de la presa de Roxo como la del río Roxo tuvieron ligera a moderada salinidad para las plantas y ausencia de restricciones para la infiltración del suelo. La presa de Roxo recibió agua de la presa de Alqueva por primera vez entre junio y septiembre de 2016, y durante el mismo período se observó una pequeña, aunque regular, disminución de la EC del agua (0,99 a 0,76 dS m⁻¹). Se simularon tres escenarios de agua de riego, identificados por Low/High EC-SAR (L-L, H-H, L-H), con el modelo Watsuit. Las aguas de baja EC (L-L y L-H) representan los años húmedos y no muestran riesgo de salinidad del suelo en la zona radicular. Sin embargo, el riesgo de encharcamiento aumenta en los suelos sódicos, especialmente con el escenario (L-H). El agua de alta EC (H-H) representa años de secado y origina condiciones salinas severas en la zona radicular. En los tres escenarios, los suelos prosódicos y sódicos son más sensibles a la degradación por salinización, sodificación o ambos.

RESUMO

O regadio tem um papel crescente na produção de alimentos devido à sua alta produtividade da terra. No Alentejo, a área irrigada tem crescido desde a conclusão da barragem de Alqueva, em 2002. As alterações climáticas previstas para a região mediterrânica (calor mais extremo, menos precipitação e menos caudal nos rios, maior risco de secas e diminuição da produtividade das culturas) favorecem a salinização e sodização do solo nas áreas regadas. A albufeira do Roxo tem dos registos mais altos de salinidade e sodicidade da água em Portugal, fazendo do regadio do Roxo (RLA) um estudo de caso com especial interesse. Este trabalho teve dois objetivos principais para o RLA: (i) avaliar a salinização e sodização dos solos e prever espacialmente a sua susceptibilidade a essas formas de degradação; (ii) monitorar a salinidade e a sodicidade da água e simular o efeito no solo de cenários de salinidade e sodicidade da água. O RLA (8 250 ha) estende-se por ~20 km ao longo do rio Roxo (norte de Aljustrel), em formações sedimentares Cenozóicas. Os principais solos cartografados são: Luvisolos (~40%), Fluvisolos e Regossolos (~20%), Gleysolos e Planossolos (~20%) e Vertissolos (~10%). No entanto, existem apenas cinco perfis de solo com dados analíticos detalhados, resultantes de um levantamento de solos mais recente com 83 descrições de perfis no RLA e área circundante. A água de rega da barragem do Roxo e a água de drenagem do rio Roxo foram monitorizadas quase mensalmente entre Jul/2014–Nov/2015 e Jun/2016–Jan/2017 para determinar a condutividade eléctrica (EC), taxa de adsorção de sódio (SAR) e outros parâmetros. A salinidade do solo não foi um problema significativo no RLA, mas verificou-se uma potencial abundância de solos sódicos que justifica uma futura confirmação. Um índice qualitativo de salinidade do solo aplicado ao RLA sugere que os solos mais susceptíveis à salinidade ocorrem numa extensão muito menor quando o índice é obtido a partir de dados dos perfis de solo (abordagem B) do que quando é baseado na informação da carta de solos (abordagem A). Durante os períodos de monitorização tanto a água da barragem do Roxo como a do rio Roxo registaram ligeira a moderada salinidade para as culturas e ausência de restrições para a infiltração no solo. A barragem do Roxo recebeu água da barragem de Alqueva pela primeira vez entre Junho e Setembro de 2016 e, coincidentemente, observou-se uma pequena mas regular redução da EC da água do Roxo (0,99 para 0,76 dS m⁻¹). Simularam-se três cenários de água de rega, identificados por Low-High EC-SAR (L-L, H-H, L-H) com o modelo Watsuit. Água com baixa EC (L-L e L-H) representa anos húmidos e não apresenta risco de salinidade na zona radicular. No entanto, o risco de encharcamento aumenta em solos sódicos, especialmente no cenário (L-H). Água com elevada EC (H-H) representa anos mais secos e origina salinidade severa. Em todos os cenários os solos prosódicos e sódicos são os mais sensíveis à degradação por salinização, sodização ou ambas.

KEY WORDS
Water quality, electrical conductivity, SAR, waterlogging, Alentejo.

PALABRAS CLAVE
Calidad del agua, conductividad eléctrica, SAR, encharcamiento, Alentejo.

PALAVRAS-CHAVE
Qualidade da água, condutividade eléctrica, SAR, encharcamento, Alentejo.

LIST OF ACRONYMS

| | |
|-----|---|
| DWF | Depth to Waterlogging Features |
| RW | Water of the Roxo river |
| EC | Electrical Conductivity |
| SAR | Sodium Adsorption Ratio |
| ECe | EC in the saturation extract |
| SMP | Soils Map of Portugal (scale 1:50 000) |
| ESP | Exchangeable Sodium Percentage |
| SSI | Soil Salinity Index |
| IW | Irrigation Water |
| TWI | Topographical Wetness Index |
| RIA | Roxo Irrigation Area |
| WRB | World Reference Base for Soil Resources |

1. Introduction

Due to its high land productivity, irrigated agriculture has an increasing role in food production. At global scale, in 2005, one hectare of irrigated land was more than twice as productive as one hectare of rainfed cropland (Fuglie 2008). However, it is well known that poorly managed irrigation can also lead to soil salinization, sodification and other soil degradation processes. Worldwide, FAO estimates that 34 Mha (11 percent of the irrigated area) are affected by some level of salinity, and an additional 60-80 Mha are affected to some extent by waterlogging and related salinity (FAO 2011).

The irrigated area operating in Portugal was about 540,000 ha in 2009, which meant a significant decrease of more than 30% in relation to the total area registered in 1999 (DGADR 2014). However, this overall decrease concealed an important increase of the irrigated area in the Alentejo region, mainly after completion of the Alqueva dam in 2002. The area already irrigated by the Alqueva is about 120,000 ha and there is a new plan to expand it to about 165,000 ha (EDIA 2017). Southern Portugal (Alentejo and Algarve regions) has the most pronounced Mediterranean climate in the country and, therefore, land productivity and crop diversity in these regions can profit very much from water availability, not only during summer but even all year round. In spite of that benefit, there is the risk

of soil degradation by salinization and sodification as a consequence of inappropriate irrigation management in face of the future prospects of climate change for the Mediterranean region (EEA 2017): large increase in heat extremes, decrease in precipitation and river flow, increasing risk of droughts, decreasing crop yields, and increasing irrigation demand, in particular in southern Europe, which will increase competition between different water users.

Soil salinization and sodification are among the main types of soil degradation, both at global and European scale (FAO and ITPS 2015; CEC 2006). Water-soluble salt accumulation increases electrolyte concentration in the soil solution and, for most plants, reduces their capability to absorb water and growth. Therefore, crop productivity is negatively related to its sensitivity to soil salinity. High levels of exchangeable sodium have a negative impact in the physical properties of most soils, especially in medium and fine texture soils. Sodidity induces dispersion of soil colloids, which leads to massive soil structure development, low infiltration capacity (when sodicity affects the topsoil), low water and air permeability and soil drainage (when sodicity affects the subsoil). Hence, water table recharge also tends to decrease, while runoff and soil erosion increase, causing negative impacts on land productivity, and other soil dependent ecological services. The Status of the World's Soil Resources (FAO and ITPS 2015) also mention waterlogging – the rise in water table – as a type of soil degradation which may contribute to soil salinization and crop productivity reduction. Waterlogging results from poor soil infiltration/drainage, either due to impervious layers in the subsoil or to the rising of a deeper water table, usually in soils located in lower parts of the landscape.

Soils with electrical conductivity in the saturation extract (ECe) greater than 4 dS m⁻¹ are commonly considered as affected by salinity, though more sensitive crops suffer potential yield decrease below this limit (Richards 1954; Ayers and Westcot 1985). The subqualifier *protosalic* was introduced in the last revision of the WRB for soils with ECe above the same limit (IUSS Working Group WRB 2015).

The accumulation of salts in soils depends on several factors, being the annual balance between precipitation and evapotranspiration of utmost importance. Salts tend to accumulate in the soil if the annual evapotranspiration exceeds the precipitation, and there is no wet season with a significant excess of water to leach the salts. In irrigated soils the balance of salts depends also on the salt concentration in the irrigation water and on the total water applied. Additionally, the topography and the soil properties determine the sites and the soils most prone for salt accumulation in the rootzone. Surface and subsurface flow and the occurrence of shallow water tables are conditioned by terrain morphology. Soil properties, namely horizon permeability and depth to low permeable layers, determine how easily salts are leached away from the upper soil horizons.

Although very high sodium contents may have negative effects on plant nutrition, the most common negative effects of sodicity are a consequence of the deterioration of soil physical characteristics. Traditionally, the classification of sodic soils required an exchangeable sodium percentage (ESP) greater than 15 (Richards 1954). Currently, soil sodicity effects are recognized with much lower ESP, and are also associated with high levels of exchangeable magnesium. The last revision of the WRB (IUSS Working Group WRB 2015) introduced the subqualifier *protosodic* for soils with ESP greater than six, and changed the qualifier sodic for soils with exchangeable Na plus Mg greater than 15 and ESP greater than six.

Soil sodification in irrigated areas also depends on the quality of the irrigation water, usually expressed by the SAR (Sodium Adsorption Ratio). The higher the SAR of the irrigation water, the higher the ESP of the soil in equilibrium with that water, and in turn the higher the salt concentration needed in the irrigation water to prevent the dispersion of soil colloids and maintain better infiltration and/or drainage rates (Ayers and Westcot 1985). Soil sodicity in subsoil horizons can be less evident, increasing the risk of developing waterlogging and accelerating secondary soil salinization.

Prevention of soil salinization, sodification and waterlogging is a basic condition for sustainable

soil management in irrigated areas. Monitoring of the irrigation water quality and the installation of surface and sub-surface drainage systems are, among others, recommended practices (FAO 2017). Soil characterization and soil mapping at an adequate scale is also a basic technical requirement for land use evaluation for irrigated agriculture, which could also provide soil properties baselines for monitoring programs in irrigated areas.

In Portugal, several irrigated areas have been developed by the public sector, usually managed by organizations of farmers and other stakeholders. In spite of some research studies about irrigation management and soil salinity in southern Portugal, mainly at field or plot scale (e.g. Ramos et al. 2009, 2011) there is a lack of studies at a larger scale, namely at the scale of large irrigated areas with common irrigation management, encompassing the water reservoir itself and all the infrastructures to deliver the water to farmers' field. The irrigation management at this scale has a unique perspective and a pivotal role that could be used to promote better water and soil sustainable management among farmers. For instance, a monitoring program for soil and water quality and an integrated analytical and predictive tool, could provide early on information about soil salinity status at field scale. Monitoring sites most prone to soil salinity, sodicity and other soil degradation processes, would allow to anticipate the degree and extent of the degradation, warn farmers potentially affected, collaborate with them to define strategies and to implement action plans to prevent and/or mitigate each specific problem.

The Roxo dam and the associated infrastructures of the Roxo irrigated area (RIA) were built between 1963 and 1968, and the first irrigated crops date from 1969 (Marques 2016). The RIA is one of the oldest irrigated areas in southern of Portugal, and the Roxo dam has some of the highest water salinity levels recorded in Portuguese dams (SNIRH 2017). It has been connected to the Alqueva dam since 2010, but the water transfer started only in 2016, which raises new questions about its effect on the water quality of the Roxo dam. Another issue in the RIA, like in most irrigated areas in the region, is its great lack of soil information, especially of soil analytical data, in spite of the available soil

map for southern Portugal (scale 1:50 000). For these reasons, as well as for its irrigation infrastructures, technologies, and dominant crops produced, the RIA is representative of other irrigated areas in southern Portugal. Moreover, because the Roxo dam has higher records of water shortage, and water salinity and sodicity it is also a very interesting regional case study. This work aimed at two main objectives for the RIA: (i) evaluate soil salinization and sodification, and make spatial predictions of soils susceptibility for these degradation types with the limited available soil data; (ii) monitor current salinity and sodicity of the irrigation water and drainage water, and simulate the effect of some empirically based scenarios of water salinity and sodicity in the soil.

2. Material and Methods

2.1. The Roxo irrigation area

The Roxo irrigation area (RIA) is located near Aljustrel, Alentejo region (southern Portugal) with an area of about 8 250 ha which spans ~20 km along the Roxo river, in the SE-NW direction (**Figure 1**). It is located on the Cenozoic sedimentary formations of the Alvalade basin, which have very diverse nature and thicknesses, from about 10 m to more than 100 m depth. Clayey and sandy deposits, nearly horizontal, from the Upper Miocene, Pliocene and Pleistocene are predominant. Plio-Pleistocene deposits are the most levelled and occur mainly in the north margin of the Roxo river (Schermerhorn et al. 1984). The altitude decreases from SE to NW, from about 120 m to its lower point at 47 m high (**Figure 1**). Smooth slopes are predominant: almost 30% of the area has a slope gradient less than 1%, most of it modelled in the Plio-Pleistocene formation in the north bank of the Roxo

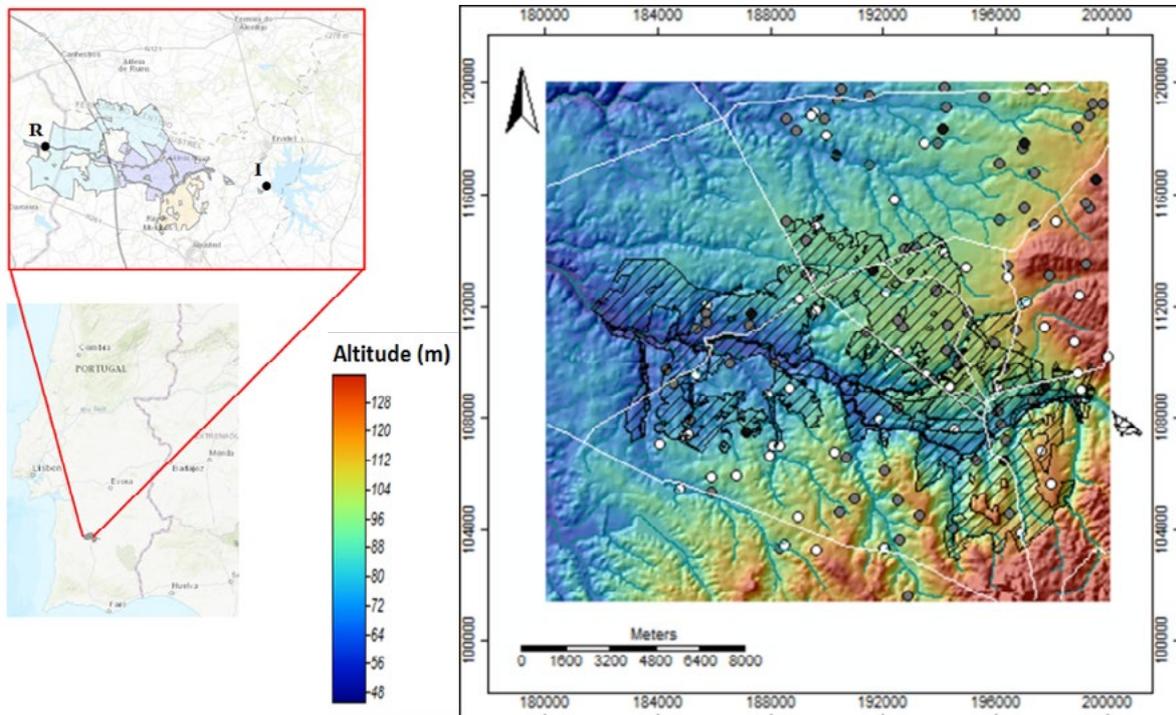


Figure 1. Left: The Roxo irrigation area (RIA) and water sampling locations for (I) irrigation water (Roxo dam), and for (R) drainage water, downstream in the Roxo river (maps from ABR et al. 2016). Right: Digital elevation model with the RIA delimited in black colour; dots are soil profiles without data (white), with morphological description (grey) and with analytical data (black).

river and 80% of the RIA has slope gradients less than 4% (Figure 2).

2.2. Soils

Dominant soils in the RIA based on the Soils Map of Portugal (SMP) (SROA 1970) and expressed as the Reference Soil Groups (IUSS Working Group WRB 2015) are (Figure 2): Luvisols (~40%), Fluvisols and Regosols (~20%),

Gleysols and Planosols (~20%) and Vertisols (~10%). The SMP (1:50 000) was elaborated during the sixties of the last century. Although it covers the entire southern Portugal, reference soil profiles with analytical data are very limited, and there is great uncertainty about their location. A more recent soil survey (1997) was realized in the area potentially irrigated by the Alqueva dam, which included most of the RIA (IDRHa-DS 2003). Figure 1 shows the location of the soil profiles characterized in the RIA and

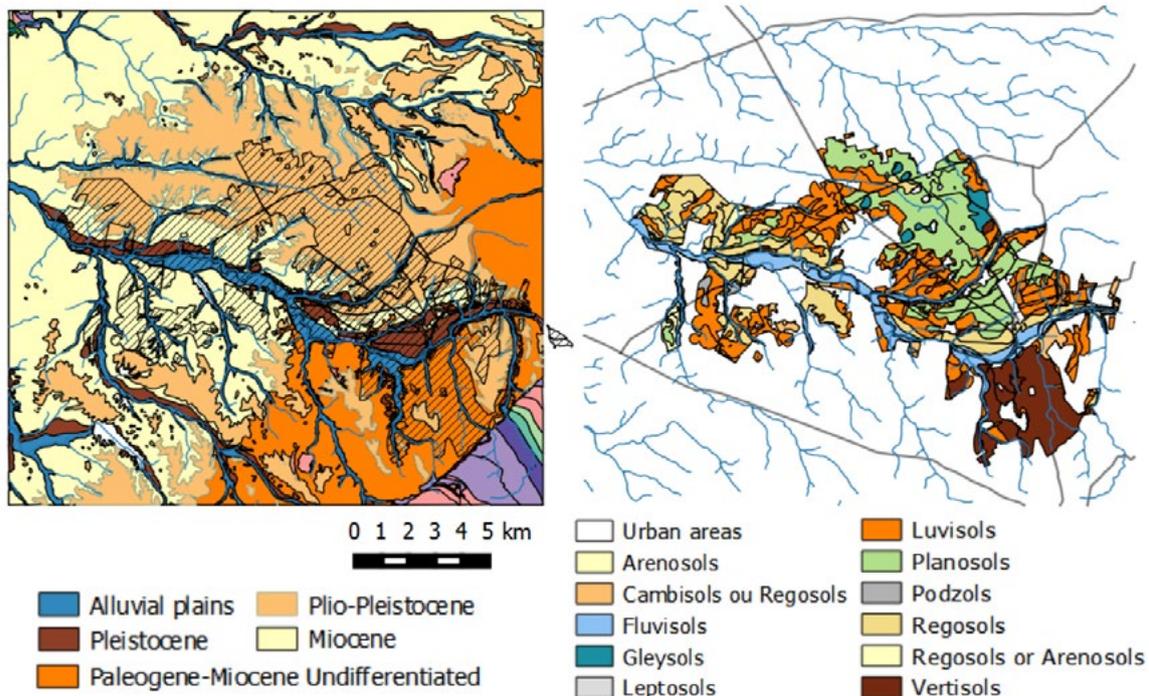


Figure 2. Left: Geological map (Schermerhorn et al. 1984) of the RIA and surrounding area; legend limited to main geological formation. Right: Soils Map of Portugal (SROA 1970) of RIA, with legend by WRB 2014.

surrounding areas with similar topography and geology. A total of 133 georeferenced soil profiles are registered (54 inside the RIA), but only 83 were found to have significant data: 83 soil profiles have soil morphological descriptions (36 inside the RIA), of which 16 have simplified analytical data (seven inside the RIA) and only nine have quite complete analytical data (only five profiles in the RIA – Table 2).

Analytical methods used in the soil survey were (IDRHa-DS 2003): soil sieving for rock fragments (> 2 mm) and coarse sand (2 - 0.2 mm);

sedimentation and decantation for fine sand (2 - 0.02 mm); pipette method for silt (0.02 - 0.002 mm) and clay (< 0.002 mm); Tinsley method for soil organic carbon; calcimeter of Gehrard for total carbonates, expressed as CaCO₃; potentiometer in a soil:water (or KCl solution) suspension ratio of 1:2.5 for determination of pH in water (pH-H₂O) and pH in a KCl solution (pH-KCl), respectively; conductivity meter for determination of electrical conductivity in a soil:water suspension ratio of 1:2.5; ammonium acetate (pH 7.0) for exchangeable cations and cation exchange capacity, except for soils with

carbonates in which case the Melich method (pH 8.2) was used; ring method for soil bulk density determination and total porosity calculation; and pressure plate apparatus for determination of soil water retention at water potentials: 0, 3, 10, 100 and 1500 kPa.

The abovementioned 83 georeferenced soil profiles with morphological descriptions were used to model spatial predictions of soil susceptibility to salinity in the RIA and surrounding area. The number of soil profiles with the necessary analytical data (Table 2) was not enough to do the same for soil sodicity. Soil salinity spatial predictions used soil properties related with internal soil drainage by two different approaches: (A) drainage classes of mapped soil units of the SMP (SROA 1970); (B) data from the morphological data of soil profiles (IDRHa-DS 2003) followed by geostatistical spatial prediction. In approach (A) the drainage classes of the Soil Survey Staff, applied to soil units of the SMP (SROA 1972), were reduced from seven to four: 1) Very poorly drained to poorly drained; 2) Somewhat poorly drained; 3) Moderately well drained; 4) Well to excessively drained. In approach (B), soil profile descriptions were used to obtain a numeric indicator of soil drainage, here called 'soil depth to waterlogging features' (DWF) i.e. features associated to gleyic or stagnic properties. Soil features taken into account were mainly the occurrence of (IUSS Working Group WRB 2015): reductimorphic colours and/or oximorphic colours, iron–manganese concretions or nodules, albic material and abrupt textural difference. The depth used is the upper limit of the horizon or layer with evident waterlogging features. For a better comparison of both methods (A and B) the soil DWF was also divided into four classes, based on the following WRB depth limits: 1) less than 40 cm; 2) 40 - 75 cm; 3) 75 - 150 cm; 4) greater than 150 cm.

Soil information from both approaches was combined with topographical data using a digital elevation model (DEM) of the study area (Figure 1). The DEM was prepared combining vector data models (points, contour lines, drainage water lines and water planes) with altimetry. A TIN model was obtained by triangular interpolation, and then converted to a raster model with 25 m wide cells. The final DEM was filtered three times with a 3 x 3 filter. Several well-known ter-

rain parameters were calculated accordingly to Boehner and Selige (2006), namely: slope, aspect, cross and longitudinal curvature, flow accumulation, vertical distance to channel network, valley depth and the topographical wetness index (TWI) based on Moore et al. (1991) – basically, the logarithm of the quotient between the flow accumulation and the slope.

Different digital soil maps were produced for the soil DWF in the RIA, combining linear regression with topographic parameters, kriging and kriging with external drift, both for the global RIA and for stratified areas based on geology and/or lithology.

A soil salinity index (SSI) was calculated making the ratio between the TWI and the four soil drainage classes of the mapped soil units or the four classes of soil DWF. Higher values of this qualitative index for soil susceptibility to salinity mean higher tendency for accumulation of salts in the soil, either due to high levels of the TWI (i.e. higher influx of surface and subsurface water and their dissolved salts) or due to the low values of the soil drainage class or the soil DWF class (i.e. less prone to salts leaching).

All maps were prepared with SAGA-GIS (Conrad et al. 2015) and QGIS (QGIS Development Team 2016), graphics and statistical analysis were performed with R (R Development Core Team 2017) and geostatistical prediction with package "gstat" for R (Pebesma 2016).

2.3. Water

A program of water quality monitoring has been implemented in the RIA since July 2014, both for irrigation water and drainage water in natural rivers inside the area (ABR et al. 2016). The results presented here are related to salinity and sodicity for: irrigation water (IW) at the Roxo Dam; drainage water in the Roxo river (RW) at an outlet of the RIA (Figure 1). Water quality in these two points was measured approximately monthly during two main periods: Jul/2014 - Nov/2015 (14 dates) and Jun/2016 - Jan/2017 (eight dates).

The analytical characterization of the water was done according standard methods (APHA

1998): electrical conductivity by conductometry, cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+), C^- and SO_4^{2-} by ionic chromatography, and hydrogencarbonate ions (HCO_3^-) by volumetry. The SAR was calculated by the following equation, where Na^+ , Ca^{2+} and Mg^{2+} are expressed $\text{cmol}_{(+) } \text{L}^{-1}$:

$$\text{SAR} = \frac{\text{Na}}{\sqrt{\frac{\text{Ca} + \text{Mg}}{2}}}$$

The Watsuit model (Rhoades et al. 1992) was used to simulate some scenarios of IW quality supported on empirical results measured in the RIA and in the Alqueva dam (SNIRH 2017). The output for drainage/soil water quality were analysed in respect to soil salinity, sodicity and nutritional imbalances. The Watsuit model divides the soil in four layers, defined by constant proportions of water consumption by plants (40, 30, 20 and 10%) and calculates the chemical composition of the soil water within the rootzone under steady state conditions, which means that cation exchange reactions between the water and the soil are at equilibrium. Main input data are the composition of the irrigation water and chosen constant leaching fractions (LF). Output data includes, among others, the concentration of major cations and anions, EC, SAR, Ca/Mg ratio, expressed as an average for the rootzone and for each soil layer. Though it models sim-

pler conditions than transient models, it is less demanding on input data, and the steady-state conditions with the IW is likely to be the worst-case situation that could result from the water use (Rhoades et al. 1992).

3. Results

3.1. Soils

Table 1 and **Table 2** present, respectively, the soil profile descriptions and the analytical dataset of the IDRHa-DS (2003) for the five soil profiles located in the RIA which are better characterized.

Soil salinity was not a significant problem at the time of the soil survey. Electrical conductivity of a soil:water suspension ratio of 1:2.5 ($\text{EC}_{1:2.5}$) can be converted to the electrical conductivity of an extract of a saturated soil paste (EC_{se}) assuming that (Pansu and Gautheyrou 2003) $\text{EC}_{\text{se}} (\varphi / \text{RD}_s) = 2.5 \text{EC}_{1:2.5}$, therefore: $\text{EC}_{\text{se}} = 2.5 \text{EC}_{1:2.5} / (\varphi / \text{RD}_s)$, with φ being the total soil porosity and RD_s the dimensionless soil density (equal to bulk density (φb) in **Table 2**). Most soil horizons in **Table 2**, after conversion have

Table 1. Soil profiles of the RIA better characterized by the study IDRHa-DS (2003)

| Hz. | Depth (cm) | Description |
|--|------------|---|
| 106R – Hypereutric Sodic Regosol (Clayic, Loamic) | | |
| Ap | 0-35 | Strong brown 7.5YR 5/7 (d), reddish brown 5YR 4/5 (w), loam, common fine and medium quartz gravel, moderate medium angular blocky, hard, very sticky and plastic, high compaction, dry, many medium and fine pores, common iron–manganese concretions, common fine roots, abrupt transition to |
| 2CBw | 35-60/75 | Reddish brown 5YR 4/4 (d), yellowish red 5YR 4/6 (w), clay loam, dominant coarse to fine subrounded quartz gravel, loose, slightly hard, very sticky and plastic, high compaction, dry, common medium and coarse pores, very few iron–manganese concretions, few fine and very fine roots, clear, irregular transition to |
| 3C | 60/75-98 | Reddish brown 5YR 4.5/4 (d) and brown 10 YR 5/3 (d), yellowish red 5YR 4.5/6 (w) and brown 10 YR 5/3 (w), clay, very few fine and medium subrounded quartz gravel, massive, extremely hard, very sticky and plastic, extremely high compaction, dry, few pores, very few roots, clear, wavy transition to |
| 4C | 98-110 | Reddish brown 5YR 4.5/4 (d), yellowish red 5YR 4.5/6 (w), clay, abundant medium and fine subrounded quartz gravel, loose to massive, hard, sticky and slightly plastic, high compaction, few coarse pores, very few iron–manganese concretions, abrupt transition to |
| 5C | 110-165 | Clay loam sediment. |

| 118N – Stagnic Luvisol (Hypereutric, Loamic, Sodic) | | |
|---|---------|---|
| Ap | 0-35 | Light yellowish brown 10YR 6/4 (d), yellow 10YR 7/8 (w), sandy loam, common fine and medium gravel, weak medium angular blocky, soft, high compaction, dry, common medium and coarse pores, many iron–manganese concretions, common fine roots, clear transition to |
| Ec | 35-70 | Yellow 10YR 7/8 (d), brownish yellow 10YR 6/8 (w), sandy clay loam to sandy loam, few medium and fine gravel, weak medium angular blocky, slightly hard, extremely high compaction, dry, few coarse pores, common iron–manganese concretions increasing with depth, few fine roots, clear transition to |
| Bc | 70-85 | Reddish yellow 7.5YR 6/8 (d) and pinkish grey 7.5YR 7/2 (d), strong brown 7.5YR 5/8 (w) and pinkish grey 7.5YR 7/2 (w), sandy clay loam, common fine and medium gravel of subrounded quartz, moderate fine angular blocky, slightly hard, extremely high compaction, dry, few coarse pores, common iron–manganese concretions increasing with depth, common fine roots, gradual transition to |
| Bg | 85-115 | Light gray 10YR 7/2 (d), dark red 2.5YR 4/8 (w) and 2.5YR 3/6 (h), clay, moderate coarse prismatic, slightly hard, extremely high compaction, dry, few coarse pores, few fine roots. |
| 123R – Chromic Calcic Vertisol (Hypereutric) | | |
| Ap | 0-30 | Dark brown 7.5YR 3/4 (d), dark brown 7.5YR 3/4 (w), clay, very few medium quartz gravel, slightly calcareous, strong coarse prismatic and weak medium granular, very hard, very sticky and plastic, high compaction, dry, many coarse and fine pores, few common iron–manganese concretions, common fine and medium roots, clear transition to |
| Bw | 30-100 | Dark brown 7.5YR 3/4 (w), clay, very few medium quartz gravel, slightly calcareous, strong coarse prismatic, firm, very sticky and plastic, high compaction, moist, common coarse to very fine pores, slickensides, common fine and very fine roots, clear transition to |
| BCK | 100-160 | Yellowish red 5YR 4/6 (w) and pinkish white 5YR 8/2 (w), clay, strongly to extremely calcareous nodules, strong medium subangular blocky, firm, very sticky and plastic, high compaction, moist, few medium to very fine pores, slickensides, iron–manganese concretions, few fine and very fine roots. |
| 127N – Eutric Sodic Regosol (Clayic) | | |
| Ap | 0-40 | Yellowish red 5YR 5/8 (d), red 2.5YR 5/8 (w), sandy loam, many coarse to fine subrounded quartz gravel, weak medium angular blocky, slightly hard, sticky and slightly plastic, low compaction, dry, many coarse and fine pores, very few common iron–manganese concretions, common roots, dry, clear transition to |
| 2BC | 40-80 | Dark red 2.5YR 4/8 (d), dark red 2.5YR 3/6 (w), sandy clay, abundant coarse to fine gravel of subrounded quartz, weak fine granular to weak medium angular blocky, slightly hard, very sticky and plastic, low compaction, dry, few coarse and fine pores, very few common iron–manganese concretions, common fine roots, dry, gradual transition to |
| 2C | 80-120 | Red 10R 4/8 (d), dark red 10R 3/6 (w), clay, abundant coarse to fine gravel of subrounded quartz, weak fine granular, very sticky and plastic, low compaction, few coarse and fine pores, very few iron–manganese concretions, common fine roots. |
| 144N – Eutric Sodic Stagnic Cambisol (Loamic, Magnesian) | | |
| Ap | 0-28 | Light yellowish brown 10YR 6/4 (d), yellowish brown 10YR 5/6 (w), sandy loam, many fine to coarse gravel of quartz, weak medium subangular blocky and weak fine granular, soft, slightly sticky and plastic, high compaction, dry, very few coarse and medium pores, few iron–manganese concretions, many fine and medium roots, abrupt transition to |
| 2Bw | 28-60 | Very pale brown 10YR 7/3 (w), sandy clay loam, weak coarse prismatic, firm, very sticky and plastic, extremely high compaction, moist, few fine pores, few cracks, very few common iron–manganese concretions, common fine roots, abrupt transition to |
| 2C | 60-105 | Yellow 2.5Y 8/6 (d), pale yellow 2.5Y 7/4 (w), sandy clay loam, common fine and medium gravel, slightly to moderately calcareous in the soil matrix with some strongly calcareous nodules, weak fine to medium prismatic to massive, slightly hard, sticky and plastic, low compaction, moist, common iron–manganese concretions, very few fine roots. |

Table 2. Complete analytical dataset for the better characterized five soil profiles located inside the RIA (data based on IDRHa-DS 2003)

| Horiz. | Depth cm | Fine earth fraction* | | | | | | | | Exchange cations and CEC* | | | | | | | | Soil water retention at (kPa) | | | | | | | |
|---|-------------|----------------------|-----|-----|------|------|-----|-----|------------------------------|--------------------------------------|---------------------|------------------|------------------|----------------|-----------------|------|------|-------------------------------|----------------|------|-------|-------|-------|-------|-------|
| | | RF | CS | FS | Silt | Clay | SOC | TC | pH _{H₂O} | pH _{KCl} | EC _{1:2.5} | Ca ²⁺ | Mg ²⁺ | K ⁺ | Na ⁺ | EB | CEC | BS | ρ _b | P | 0 | 3 | 10 | 100 | 1500 |
| | | g kg ⁻¹ | | | | | | | | cmol ₍₊₎ kg ⁻¹ | | | | | | | | kg kg ⁻¹ | | | | | | | |
| 106R – Hypereutric Sodic Regosol (Clayic, Loamic)** | | | | | | | | | | | | | | | | | | | | | | | | | |
| Ap | 0-35 | 113 | 247 | 373 | 225 | 155 | 6.7 | 0 | 6.3 | 5.4 | 0.15 | 4.1 | 1.7 | 0.4 | 0.1 | 6.2 | 6.2 | 100.0 | 1.78 | 0.33 | 0.162 | 0.140 | 0.134 | 0.113 | 0.084 |
| 2CBw | 35-60/75 | 597 | 223 | 212 | 179 | 386 | 1.5 | 0 | 6.8 | 5.5 | 0.10 | 6.3 | 2.5 | 0.2 | 0.5 | 9.4 | 11.0 | 85.5 | 1.85 | 0.30 | 0.145 | 0.102 | 0.097 | 0.084 | 0.076 |
| 3C | 60/75-98 | 70 | 113 | 252 | 197 | 439 | 2.4 | 0 | 5.6 | 4.0 | 0.17 | 9.9 | 5.5 | 0.1 | 1.0 | 16.5 | 20.6 | 80.1 | - | - | - | - | - | - | - |
| 4C | 98-110 | 538 | 319 | 133 | 130 | 419 | 1.9 | 0 | 5.6 | 4.0 | 0.29 | 8.9 | 5.5 | 0.1 | 1.3 | 15.7 | 21.0 | 74.8 | - | - | - | - | - | - | - |
| 5C | 110-165 | 1 | 93 | 318 | 203 | 386 | 2.4 | 0 | 6.1 | 3.7 | 0.13 | 8.7 | 5.8 | 0.1 | 1.5 | 16.1 | 20.2 | 79.7 | - | - | - | - | - | - | - |
| 118N – Stagnic Luvisol (Hypereutric, Loamic, Sodic) | | | | | | | | | | | | | | | | | | | | | | | | | |
| Ap | 0-35 | 107 | 456 | 324 | 110 | 110 | 4.8 | 0 | 6.2 | 5.0 | 0.06 | 3.9 | 1.2 | 0.1 | 0.6 | 5.7 | 8.1 | 70.4 | 1.65 | 0.38 | 0.217 | 0.161 | 0.147 | 0.105 | 0.046 |
| Ec | 35-70 | 94 | 408 | 295 | 96 | 201 | 2.4 | 0 | 6.7 | 5.2 | 0.08 | 4.7 | 1.0 | 0.1 | 0.9 | 6.6 | 8.5 | 77.6 | 1.74 | 0.34 | 0.194 | 0.172 | 0.160 | 0.122 | 0.083 |
| Bc | 70-85 | 142 | 319 | 250 | 99 | 331 | 2.4 | 0 | 6.6 | 5.2 | 0.17 | 5.6 | 3.3 | 0.0 | 1.2 | 10.1 | 13.3 | 75.9 | 1.74 | 0.34 | 0.216 | 0.210 | 0.197 | 0.185 | 0.118 |
| Bg | 85-115 | 36 | 176 | 209 | 134 | 481 | 1.9 | 0 | 5.4 | 4.2 | 0.33 | 4.6 | 4.9 | 0.0 | 2.5 | 12.1 | 17.8 | 67.9 | - | - | - | - | - | - | - |
| 123R – Chromic Calcic Vertisol (Hypereutric) | | | | | | | | | | | | | | | | | | | | | | | | | |
| Ap | 0-30 | 6 | 19 | 99 | 177 | 705 | 7.7 | 3.6 | 8.4 | 6.6 | 0.22 | 46.6 | 14.4 | 0.2 | 0.8 | 62.0 | 63.5 | 97.6 | 1.25 | 0.53 | 0.418 | 0.377 | 0.365 | 0.365 | 0.318 |
| Bw | 30-100 | 12 | 19 | 86 | 153 | 742 | 4.3 | 9.5 | 8.8 | 6.8 | 0.22 | 24.0 | 15.4 | 0.1 | 1.4 | 40.1 | 44.9 | 89.3 | 1.30 | 0.51 | 0.380 | 0.377 | 0.375 | 0.361 | 0.333 |
| BCK | 100-160 | 1 | 14 | 96 | 182 | 709 | 2.4 | 151 | 9.2 | 7.3 | 0.29 | 23.1 | 17.7 | 0.1 | 1.7 | 42.6 | 42.6 | 100.0 | - | - | - | - | - | - | - |
| 127N – Eutric Sodic Regosol (Clayic) | | | | | | | | | | | | | | | | | | | | | | | | | |
| Ap | 0-40 | 212 | 333 | 359 | 170 | 139 | 6.3 | 0 | 6.1 | 5.0 | 0.07 | 2.6 | 0.9 | 0.3 | 0.7 | 4.5 | 9.9 | 45.5 | 1.80 | 0.32 | 0.164 | 0.123 | 0.115 | 0.090 | 0.054 |
| 2BC | 40-80 | 368 | 287 | 247 | 99 | 367 | 2.4 | 0 | 6.5 | 5.3 | 0.09 | 3.2 | 1.5 | 0.1 | 0.7 | 5.4 | 5.4 | 100.0 | 1.85 | 0.30 | 0.141 | 0.090 | 0.084 | 0.075 | 0.072 |
| 2C | 80-120 | 742 | 330 | 151 | 81 | 438 | 0.5 | 0 | 5.4 | 4.8 | 0.14 | 3.5 | 2.4 | 0.1 | 0.9 | 6.8 | 11.0 | 61.8 | - | - | - | - | - | - | - |
| 144N – Eutric Sodic Stagnic Cambisol (Loamic, Magnesian) | | | | | | | | | | | | | | | | | | | | | | | | | |
| Ap | 0-28 | 140 | 203 | 574 | 65 | 158 | 5.7 | 0 | 6.1 | 4.9 | 0.06 | 5.0 | 3.0 | 0.1 | 0.7 | 8.8 | 12.5 | 70.4 | 1.51 | 0.43 | 0.271 | 0.177 | 0.169 | 0.133 | 0.062 |
| 2Bw | 28-60 | 27 | 113 | 461 | 93 | 333 | 7.7 | 0 | 6.3 | 4.6 | 0.11 | 5.2 | 7.0 | 0.1 | 1.6 | 13.8 | 18.5 | 74.6 | 1.60 | 0.40 | 0.247 | 0.247 | 0.245 | 0.219 | 0.135 |
| 2C | 60-105 | 90 | 106 | 564 | 111 | 220 | 0.5 | 0 | 7.3 | 6.6 | 0.19 | 5.0 | 7.4 | 0.1 | 2.2 | 15.5 | 15.5 | 89.1 | - | - | - | - | - | - | - |

* RF, rock fragments (> 2 mm); CS, coarse sand (2-0.2 mm); FS, fine sand (0.2-0.02 mm); Si, silt (0.02-0.002 mm); Cl, clay (< 0.002 mm); SOC, soil organic carbon; TC, total carbonates expressed as CaCO₃; pH_{H₂O}, pH_{KCl}, and EC_{1:2.5}, pH in water, pH in a KCl solution and electrical conductivity in all cases in a 1:2.5 soil:water suspension ratio; EB, sum of exchangeable bases; CEC, cation exchange capacity; BS, base saturation; ρ_b, bulk density; P, total porosity; Soil water content at water potentials 0, 3, 10, 100 and 1500 kPa.

** Tentative soil identification according to WRB 2014 (IUSS Working Group WRB 2015) based on soil profile data available in IDRHa-DS (2003).

$EC_{se} < 2 \text{ dS m}^{-1}$ and only two (106R-1 and 118N-3) have EC_{se} slightly above 2 dS m^{-1} and can be classified as slightly saline (Abrol et al. 1988).

In relation to soil sodicity, **Table 3** represents the soil horizons of four out of five soil profiles listed in **Table 2** that are qualified as *sodic* according to the WRB (IUSS Working Group WRB 2015), i.e. $ESP \geq 6$ and exchangeable Na plus Mg $\geq 15\%$ in a layer $\geq 20 \text{ cm}$ thick starting $\leq 100 \text{ cm}$ from the soil surface. Though the soil sample with analytical data is quite limited for the whole RIA, and might reflect some bias, it is a matter of concern that four in five soil profiles (80%) are sodic. These results justify future efforts to increase soil sampling and deepen the knowledge about the soils of the RIA.

The proposed SSI to evaluate soils tendency for salt accumulation in the RIA requires the TWI (**Figure 3**) and (A) drainage classes for each soil units mapped on the SMP or (B) soil DWF for the entire area obtained from soil profile descriptions – e.g. in **Table 2** all soil profiles have an arbitrary maximum DWF = 200 cm, with the exception of the profile 118N (DWF = 85 cm). Soil DWF was estimated for the entire study area by linear regression (kriging was excluded because DWF

revealed a pure nugget variogram) with slope and TWI as predictors ($r^2_{adj} = 0.24$, $F = 13.84$ (2, 80), $p = 6.9 \times 10^{-6}$). Among the topographical variables listed in **Table 4**, slope and TWI are the best correlated with DWF, though with a low correlation. To improve the spatial prediction of the soil DWF, the study area was stratified according to geology and/or lithology categories. Among the best correlations obtained (**Table 4**), alluviums (a) and sedimentary rocks of the Plio-Pleistocene (PQxSR) show the highest. Hereafter we consider only the PQxSR stratum because it is larger than (a) and has great coincidence with most levelled areas of the RIA where many hydromorphic soil units are mapped. Slope and TWI are again the best correlated variables with soil DWF. These two variables were used as auxiliary variables for the spatial prediction of the DWF by kriging with external drift (**Figure 3**) using a spherical variogram model with sill 257 cm^2 and range $1\,917 \text{ m}$ (nugget 0), which produced a kriging variance $< 522.4 \text{ cm}^2$ in 95% of the PQxSR stratum area.

Finally, the SSI (**Figure 4**) was obtained dividing the TWI by the class numbers of (A) the soil drainage or (B) the soil DWF.

Table 3. Four in five soil profiles located in the RIA (**Tables 1 and 2**) are qualified as sodic according to the WRB 2014 (IUSS Working Group WRB 2015)

| Prf-Hr* | Horiz | Depth | Text | ESP | ESMP |
|---------|-------|---------|------|---------------|------|
| Ref | | cm | | ----- % ----- | |
| 106R-4 | 4C | 98-110 | C | 6.2 | 32.2 |
| 106R-5 | 5C | 110-165 | CL | 7.4 | 36.3 |
| 118N-1 | Ap | 0-35 | SL | 6.9 | 21.7 |
| 118N-2 | Ec | 35-70 | SCL | 10.3 | 21.8 |
| 118N-3 | Bc | 70-85 | SCL | 8.7 | 33.4 |
| 118N-4 | Bg | 85-115 | C | 14.3 | 41.7 |
| 127N-1 | Ap | 0-40 | SL | 7.5 | 17.0 |
| 127N-2 | 2BC | 40-80 | SC | 12.1 | 39.4 |
| 127N-3 | 2C | 80-120 | C | 7.9 | 29.5 |
| 144N-2 | 2Bw | 28-60 | SCL | 8.6 | 46.4 |
| 144N-3 | 2C | 60-105 | SCL | 14.0 | 61.8 |

* Prf-Hr, horizon reference; Text, texture classes (S, sand, C, clay, L, loam); ESP, exchange sodium percentage; ESMP, exchange sodium plus magnesium percentage.

Table 4. Correlation coefficients between soil DWF and topographical variables for all soil profiles and for soil profiles in areas stratified by dominant geology and/or lithology

| Topographic variables* | All | Geological stratification** | | | | Lithology SR*** | (Selected) PQxSR |
|------------------------|--------|-----------------------------|--------|--------|--------|-----------------|------------------|
| | | a | M | PM | PQ | | |
| N (soil profiles) | 83 | 10 | 27 | 16 | 24 | 34 | 18 |
| Slope | 0.504 | 0.943 | 0.231 | 0.319 | 0.283 | 0.523 | 0.564 |
| Aspect | -0.004 | 0.156 | 0.169 | -0.150 | 0.104 | 0.147 | 0.234 |
| Cross Curv | 0.174 | 0.543 | 0.034 | -0.015 | 0.205 | 0.268 | 0.176 |
| Long Curv | 0.042 | -0.380 | 0.045 | -0.075 | 0.282 | 0.131 | 0.246 |
| Flow Acc | -0.129 | -0.368 | -0.318 | -0.412 | -0.090 | -0.074 | -0.033 |
| Vert Dist CN | 0.151 | 0.819 | 0.235 | 0.214 | -0.008 | 0.282 | 0.368 |
| Vall Depth | 0.320 | 0.287 | -0.087 | 0.132 | -0.076 | 0.148 | -0.182 |
| TWI | -0.443 | -0.784 | -0.148 | -0.341 | -0.325 | -0.482 | -0.669 |

* N, number of soil profiles; slope, aspect, cross and longitudinal curvature, flow accumulation, vertical distance to channel network, valley depth and topographic wetness index (TWI);

** a, alluvium; M, Miocene; PM, Paleogene-Miocene Undifferentiated; PQ, Plio-Pleistocene;

*** SR, sedimentary rocks (e.g. sandstones with variable clay content; no recent sediments).

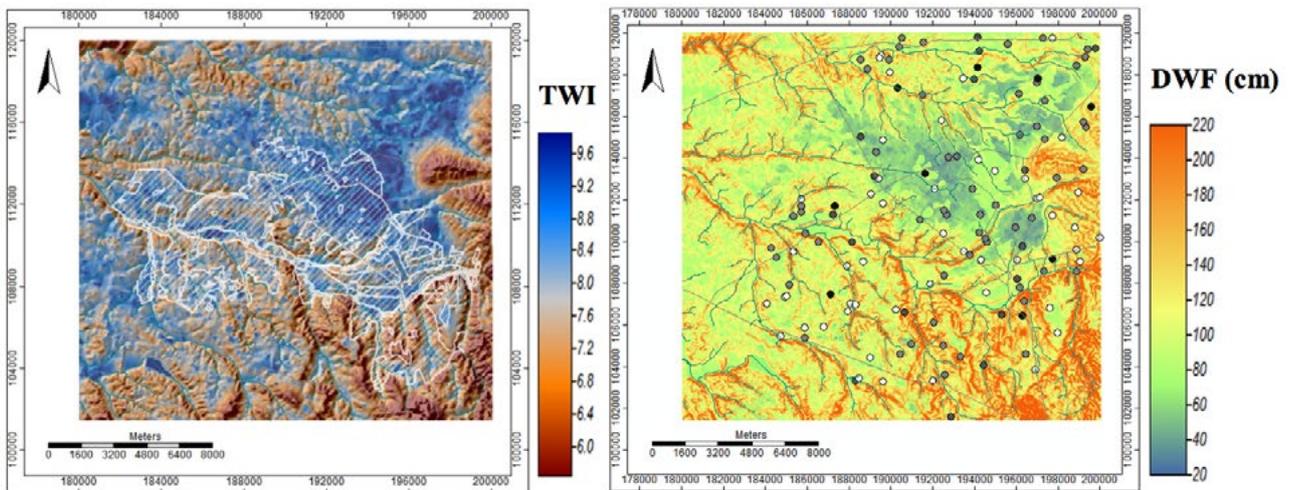


Figure 3. Left: Wetness index (TWI) map and the RIA delimited in white. Right: Soil DWF map predicted by kriging with external drift and linear regression (dots legend in **Figure 1**).

3.2. Water

Results of the water quality monitored at the entry point of the irrigation network and at the exit of the drainage network are expressed by its main statistics in **Table 5**, and by EC and SAR evolution in **Figure 5**, for two time spans: Jul/2014 - Nov/2015 (14 dates) and Jun/2016 - Jan/2017 (eight dates). Both displays (**Table 5** and **Figure 5**) show clearly higher values in all

parameters for the river water, at the RIA exit point, when compared with the irrigation water in the Roxo dam. The RW more than doubled the mean and median of the IW for SO_4^{2-} , Ca^{2+} , Cl^- , Mg^{2+} , Na^+ and electrical conductivity, and almost doubled for SAR, HCO_3^- and K^+ .

EC and SAR were much more stable for IW (EC~1 dS/m and SAR~2-3) than for RW

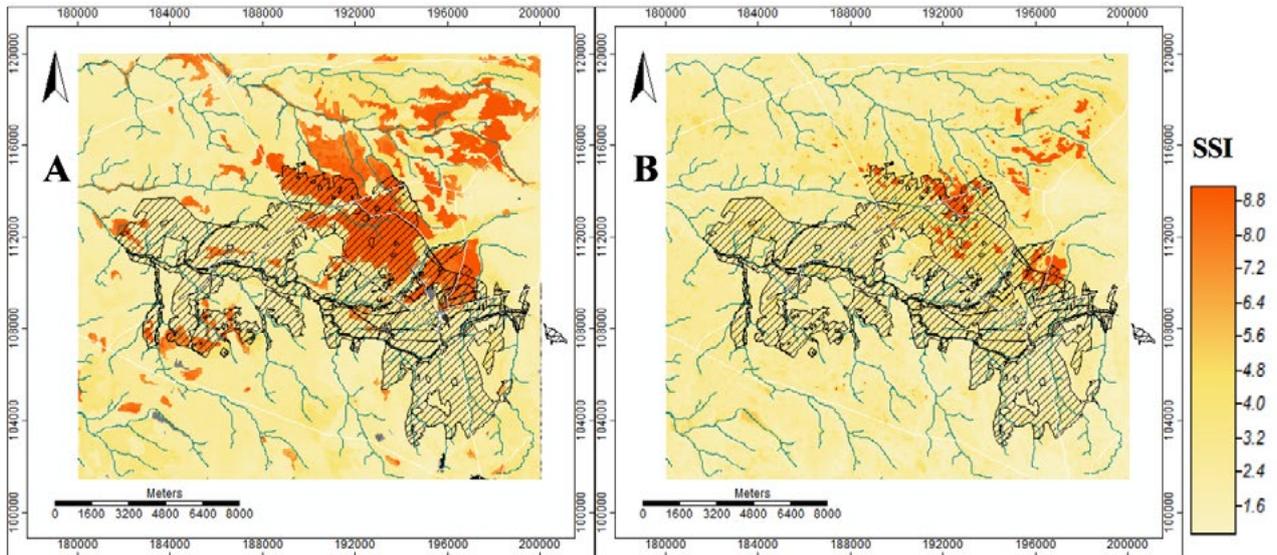


Figure 4. Maps of the qualitative soil salinity index (SSI) calculated with (A) the drainage classes of the mapped soil units and (B) with the soil DWF. Higher SSI means higher susceptibility for salt accumulation in the soil. The RIA is delimited in black.

Table 5. Water quality statistics in the Roxo dam and the Roxo river sampled in Jul/2014-Nov/2015 (14 dates, months six to 23) and Jun/2016-Jan/2017 (eight dates, months 30 to 37)

| Statistics | CE | SAR | Ca ²⁺ | Mg ²⁺ | Na ⁺ | K ⁺ | Cl ⁻ | HCO ₃ ⁻ | SO ₄ ²⁻ |
|--|--------------------|------|--------------------|------------------|-----------------|----------------|-----------------|-------------------------------|-------------------------------|
| | dS m ⁻¹ | | mg L ⁻¹ | | | | | | |
| Irrigation water (Roxo dam) | | | | | | | | | |
| N | 21 | 22 | 22 | 22 | 22 | 14 | 14 | 22 | 22 |
| Max. | 1.17 | 2.95 | 65.2 | 41.7 | 117.6 | 3.5 | 287.7 | 196.3 | 46.9 |
| 3 rd Qu. | 0.98 | 2.74 | 51.9 | 35.6 | 102.7 | 3.2 | 260.3 | 184.8 | 45.7 |
| Median | 0.90 | 2.42 | 47.8 | 33.5 | 91.2 | 3.0 | 252.6 | 172.6 | 42.2 |
| Mean | 0.91 | 2.46 | 47.2 | 33.2 | 90.4 | 2.9 | 237.5 | 171.8 | 39.9 |
| 1 st Qu. | 0.86 | 2.31 | 44.5 | 32.5 | 82.9 | 2.7 | 221.7 | 157.3 | 38.2 |
| Min. | 0.76 | 1.77 | 23.5 | 17.7 | 47.4 | 1.7 | 135.4 | 148.0 | 3.6 |
| Water from Roxo river at the exit of the RIA | | | | | | | | | |
| N | 20 | 22 | 22 | 22 | 22 | 14 | 14 | 22 | 22 |
| Max. | 2.29 | 4.65 | 174.5 | 92.2 | 283.1 | 6.7 | 760.0 | 310.5 | 446.0 |
| 3 rd Qu. | 2.12 | 4.10 | 138.3 | 79.7 | 238.7 | 4.9 | 716.8 | 277.8 | 296.5 |
| Median | 2.02 | 3.67 | 123.1 | 74.2 | 211.5 | 4.1 | 644.5 | 235.2 | 180.4 |
| Mean | 1.95 | 3.51 | 116.1 | 71.1 | 197.4 | 4.3 | 585.6 | 234.0 | 208.0 |
| 1 st Qu. | 1.84 | 3.07 | 100.6 | 67.4 | 168.2 | 3.7 | 521.1 | 208.3 | 117.2 |
| Min. | 1.28 | 1.34 | 2.2 | 33.0 | 46.7 | 2.3 | 57.9 | 87.6 | 15.2 |

(EC = 1.3-2.3 dS/m and SAR = 1.3-4.7), which revealed greater seasonal behaviour, especially for SAR, with higher values in summer (Figure 5). According to Ayers and Westcot (1985), both the IW and the RW were slight to moderate saline for crop growth (0.7-3.0 dS/m) and without restrictions for soil infiltration, though the IW was in the lowest class (SAR = 0-3 and EC > 0.7 dS/m) and the RW in the next one (SAR = 3-6 and EC > 1.2 dS/m).

In spite of the stability of the EC and SAR for the IW there is a small but steady decrease of the EC from June to September 2016 (months

30-33, marked in Figure 5, left) that might reflect a significant change in the IW provided by the Roxo dam. For the first time in Jun/2016 the Roxo dam started to receive water from the Alqueva dam, which added up to almost 15.8 Mm³ during four months, roughly 50% of the IW used in that period (Marques 2017). Water monitoring in the Alqueva dam since 2003 has shown that EC and SAR records (EC < 0.7 dS m⁻¹ and SAR~1-2) are usually lower than those observed in the Roxo dam (SNIRH 2017). However, EC > 1.0 dS m⁻¹ and SAR > 2 have been registered occasionally, and there is even one case of SAR > 4.

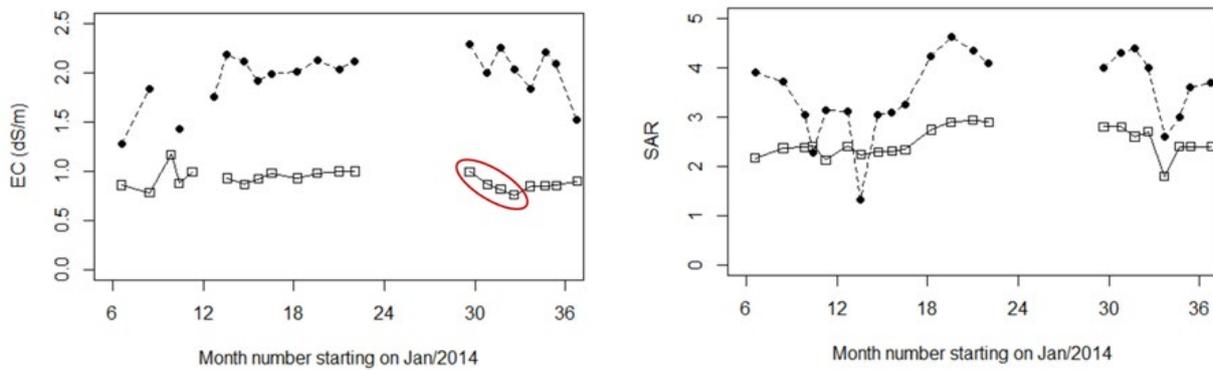


Figure 5. EC (left) and SAR (right) of irrigation water (squares, continuous line) and river water (filled circles, dashed line) measured between Jul/2014-Nov/2015 (months 6-23) and Jun/2016-Jan/2017 (months 30-37). EC of the blended IW (June to September 2016) enclosed in the red line.

Table 6. Scenarios of IW salinity and sodicity and Watsuit model predictions for the soil water averaged for the whole rootzone, with leaching fractions (LF) 0.05, 0.2 and 0.4

| Scen.* | Irrigation water | | | | | | | | | LF | Soil solution** | | |
|--------|--------------------|------|-------------------------------------|------------------|-----------------|----------------|-----------------|-------------------------------|-------------------------------|--------------------|-----------------|------|-------|
| | EC | SAR | Ca ²⁺ | Mg ²⁺ | Na ⁺ | K ⁺ | Cl ⁻ | HCO ₃ ⁻ | SO ₄ ²⁻ | | EC | SAR | Ca/Mg |
| | dS m ⁻¹ | | mmol ₍₊₎ L ⁻¹ | | | | | | | dS m ⁻¹ | | | |
| L-L | 0.44 | 0.89 | 1.60 | 1.40 | 1.09 | 0.12 | 0.80 | 2.68 | 0.73 | 0.05 | 1.57 | 2.20 | 0.90 |
| | | | | | | | | | | 0.20 | 0.95 | 1.41 | 1.11 |
| | | | | | | | | | | 0.40 | 0.68 | 1.16 | 1.14 |
| H-H | 2.08 | 4.48 | 6.98 | 5.55 | 10.28 | 0.13 | 13.98 | 4.44 | 4.52 | 0.05 | 9.77 | 9.94 | 0.83 |
| | | | | | | | | | | 0.20 | 5.18 | 6.95 | 0.96 |
| | | | | | | | | | | 0.40 | 3.71 | 5.56 | 1.12 |
| L-H | 0.73 | 3.69 | 1.50 | 1.07 | 4.18 | 0.10 | 3.94 | 2.39 | 0.52 | 0.05 | 3.31 | 9.10 | 1.14 |
| | | | | | | | | | | 0.20 | 1.75 | 5.77 | 1.39 |
| | | | | | | | | | | 0.40 | 1.21 | 4.82 | 1.40 |

* Scenarios: e.g. L-H, Low EC - High SAR; EC, electrical conductivity; SAR, sodium adsorption ratio; Case L-L and L-H from Alqueva dam, 26/01/2012 and 14/05/2012 (SNIRH 2017); case H-H from Roxo river, 03/11/2015 (ABR et al. 2016).

** Average values in the whole rootzone calculated by the Watsuit model; LF, leaching fraction.

In face of this recent diversification of the water origin for the Roxo dam, and also in face of future climate changes foreseen for the southern Portugal, we used the Watsuit model to test the effects of some water quality scenarios on soil salinity and sodicity. Three scenarios were considered based on some extreme values of real water analysis data, the first two from the Alqueva dam (SNIRH 2017) and the third one from the Roxo dam (ABR et al. 2016): (a) low EC and low SAR, (b) low EC and high SAR, (c) high EC and high SAR. A fourth scenario of high EC and low SAR was not considered because it was not possible to find a representative example in the available database records. As it would be expected, results obtained with the Watsuit model show an increase of the soil solution EC and SAR with the concomitant increase in the IW (Table 6). For each scenario, the EC and SAR of the soil solution is higher for lower LF. Additionally, lower LF also increases the risk of nutritional imbalance between Ca and Mg ($Ca/Mg < 1$).

4. Discussion

Comparing both maps obtained for the SSI (Figure 4), the strong reduction of the area with higher SSI stands out when this index is based on soil profile data (map B) compared to when it is based on the soil map, including the main soil characteristics and the delineations of the soil units (map A). Considering that the TWI component of the SSI is the same in A and B, the causes for this difference can be an overestimation of the area of the soil units with bad drainage (mostly the area mapped as Planosols, Figure 2) or an underestimation of the area predicted for soils of low DWF. Both explanations might hold some truth and can be expressed by more specific factors, namely, the equivalence between the soil drainage and the soil DWF classes, and the spatial prediction methodology used for each approach: expert delimitation of the mapping units vs. (geo)statistical inference. The validation with additional soil sampling and analysis was beyond the scope of this work, but it is critical to get a more accurate knowledge of

the susceptibility of the soils of the RIA to salinity, expressed in terms of its degree, extent and location. For the moment, the results obtained allow us to identify the northern and north-east parts of the RIA, abundant in poorly drained soils (mainly Planossolos, SROA 1970) as the most susceptible to soil salinity. Therefore, it is necessary that this area and these soils should be more carefully studied and monitored in regard to this type of soil degradation.

The reverse situation was found for soil sodicity in the RIA, i.e. higher abundance of sodic soils in the study IDRHa-DS (2003) than expressed by the soil map (SROA 1972) – which has no sodic soils. However, this difference does not seem to be strictly related to the irrigation history of the soils in the RIA because equivalent levels of sodicity can be found in soils in areas surrounding the RIA (IDRHa-DS 2003). Therefore, it is more likely due to natural causes and different soil taxonomic criteria.

Soils qualified as sodic in Table 1 and 2 are not equally under the same risk of soil degradation. Other soil properties are important besides sodium and magnesium levels (Table 3), namely, depth and thickness of the sodic horizons, its texture and clay mineralogy. Clay soils are more affected by sodicity, and especially those with more active clay minerals (e.g. smectite). Though clay mineralogy studies of the soils in the RIA are badly needed to understand better their behaviour with high levels of sodium and magnesium, data in Tables 2 and 3 also allow us to differentiate soils about their risk for sodicity. For instance, profile 127N has a relatively high clay content below 40 cm but its low cation exchange capacity suggests the dominance of lower charged clays (e.g. kaolinite) rendering it less affected by sodicity than would be expected just by its texture. The high level of rock fragments in this soil can also attenuate the permeability reduction due to sodicity.

Soil sodicity in the RIA seems a matter of greater concern than salinity, mainly because: (i) the small analytical database available has a strong presence of soils with the qualifier sodic according to the WRB 2014, justifying the need for more studies about the properties and true representation of these soils, (ii) sodicity has a negative impact in other soil properties due to

clay dispersion, decreasing porosity and drainage, hence, increasing the risks of soil salinity and productivity loss, (iii) soil sodicity is harder to manage and remediate than soil salinity, and (iv) in irrigated areas, the future behaviour of these soils will be also very dependent on the water quality applied.

The irrigation water from the Roxo dam, though slight to moderate saline, most commonly has shown an adequate salinity level to prevent the dispersion of soil colloids and the consequent reduction of soil infiltration and soil drainage (Ayers and Westcot 1985). However, to fulfil the same conditions for soils with greater ESP, and especially for sodic soils ($ESP > 6$), the water would need to be increasingly saline ($EC > 1.2$ dS/m for $SAR = 3-6$, and $EC > 1.9$ dS/m for $SAR = 6-12$).

Among the scenarios considered for the IW, and presented in Table 6, the first one (L-L: Low EC, Low SAR) is representative of wet years, and is based on the analytical data of water of good quality sampled from the Alqueva dam in 26/01/2012 (SNIRH 2017). Estimates of the Watsuit model (Table 6) show that with this type of water even the lowest LF considered (0.05) would give a medium EC and SAR soil solution ($EC 1.57$ dS m^{-1} and $SAR 2.20$). On the contrary, if a high LF is adopted (0.4 or greater) this IW may cause infiltration problems for soils with high ESP on the topsoil or drainage problems for soils with high ESP in the subsoil. Based on the historical records of the water quality of both dams, Roxo and Alqueva, (SNIRH 2017) we can expect a salinity reduction of the blended water in the Roxo dam. The EC reduction in the water of the Roxo dam observed during the first four months with water blending from the Alqueva dam (June to September 2016, months 30-33 in Figure 5) gave support to that expectation. This EC reduction of the blended water would represent less salinity risk, but can increase the risk of waterlogging problems in sodic soils of the RIA.

The scenario H-H for the IW is intended to reflect the climate change predictions for the Mediterranean region, namely, increasing heat extremes and risk of droughts, decrease in precipitation and in the river flow (EEA 2017). It represents also the possibility of reuse of drainage water for irrigation downstream. For this scenario it was

used the analytical data of a water sample from the Roxo river, collected in 03/11/2015 (Table 6), which registered one of the highest EC and SAR measured (ABR et al. 2016). Even for the highest LF considered ($LF = 0.40$) this scenario will create severe saline conditions for crop growth in the soil rootzone ($EC > 3.0$ dS m^{-1}), and almost sodic conditions ($EC 3.71$ dS m^{-1} and $SAR 5.56$). However, soil infiltration and soil drainage can be controlled as long as the IW salinity is kept high enough. For the example given this means to have LFs about 0.30 or greater, not only to prevent excessive salinity and sodicity in the rootzone, but also to reduce the risk of nutritional Ca-Mg imbalances, i.e. $Ca/Mg < 1$ (Table 6). Therefore, a conflicting situation may arise in this scenario, the need to spend more water during the irrigation season in years with greater water shortage.

Theoretically, the scenario L-H represents a worst case scenario. Although it reflects a rare situation, it is based on the analytical data of a water sample from the Alqueva dam collected in 14/05/2012 (SNIRH 2017). As shown in Table 6, for every LF the soil solution has high values of SAR and relatively low values of EC, which does not create short term salinity problems for crop growth, but can cause infiltration and/or drainage problems in medium and finer textured soils, and especially in sodic soils or even soils with medium ESP values. In the short term, this scenario is most prone to cause soil waterlogging and all its negative consequences on land productivity. In the long run it can lead also to an increase in soil salinity, especially wherever high water demanding crops are at stake.

For all three scenarios considered, medium and fine textured soils with high ESP, especially sodic soils, are among the most sensible to degradation, either by salinization, sodification or both. Colloids in these soils tend to disperse with low EC water (e.g. rain water), reducing soil drainage and the capacity of the rain to leach the salts accumulated during the previous irrigation season. With the reduction of the annual precipitation foreseen in most climate change scenarios, natural salt leaching by rain will decrease in all soils, but sodic soils have the conditions to become among the first affected by strong salinity and could be used as an indicator for other soils in the region. Additionally, the IW scenarios

with high SAR (H-H and L-H), will tend to expand the area of sodic soils and to difficult the management of already high ESP soils. A better and more detailed soil spatial characterization of the sodic soil in the RIA would be a basic tool for soil protection against the risk of waterlogging, salinization and sodification in this area.

The traditional paradigm of irrigation is changing rapidly in the RIA and in other irrigation areas in southern Portugal. Both annual and permanent crops diversity is increasing, opportunities for blending waters of different origins are emerging and the adoption of more efficient irrigation technologies is expanding and allowing more land to be irrigated. Conversely, uncertainty about the annual precipitation and the seasonal rain patterns is increasing as climate change unfolds, and also the risk of soil and environment degradation, especially as marginal soils are converted to irrigation and submitted to agricultural technologies aiming very high productivities. All these factors stress the need for better irrigation management tools, both at the irrigation infrastructure scale and at the field scale. These tools should be supported on a deeper knowledge of the soil resources and its spatial distribution, and integrate at least regular weather, water quality, soil and crop basic monitoring.

5. Conclusions

Soil salinity was not a significant problem in the last soil survey covering the RIA, but it was found higher abundance of sodic soils than suggested by the soil units mapped in the 1960s. A qualitative soil salinity index applied to the RIA suggests that soils most susceptible to salinity occur to a much smaller extent when it is obtained from soil profile data (approach B) than when it is based on information of the soil map (approach A).

Both the water of the Roxo dam and of the Roxo river, monitored during two periods from Jun/2014 to Jan/2017, were classified as slight to moderate saline for crop growth and with no

restrictions for soil infiltration, though the river water more than doubled the EC and almost doubled the SAR. The Roxo dam received water from the Alqueva dam for the first time between June and September 2016, and a small, though regular, decrease of the water EC (0.99 to 0.76 dS m⁻¹) was observed during the same period.

Three scenarios of irrigation water, identified by Low/High EC-SAR (L-L, H-H, L-H) were simulated with the Watsuit model. Low EC water (L-L and L-H) represent wet years and show no risk of soil salinity in the rootzone, allowing smaller LF and less water consumption. However, the risk of waterlogging increases in soils with high ESP, especially for water with high SAR (L-H). High EC water (H-H), which represents dryer years and the reuse of drainage water, originates severe saline conditions in the rootzone, even for the highest LF simulated (0.40), increasing the need to spend more water during the irrigation season. In all three scenarios, prosodic and sodic soils are most sensible to degradation by salinization, sodification or both.

In face of the limited soil data in the RIA, more fundamental soil studies are essential to deepen our knowledge about their behaviour under irrigation in a climate change context. Better tools to integrate soil, water quality, weather and crops monitoring, and make predictions well supported on soil spatial data are also fundamental for sustainable soil management in the RIA, as well as in other irrigated areas of southern Portugal.

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REFERENCES

- ABR, IPB, UE. 2016. QARSC – Qualidade da água da albufeira do Roxo na dinâmica dos solos e das culturas agrícolas [Internet]. Associação dos Beneficiários do Roxo, Instituto Politécnico de Beja, Universidade de Évora. Aljustrel. [cited 2017 Jan 27]. Available from: <http://qarsc-abroxo.opendata.arcgis.com/?mapSize=map-normal>.
- Abrol IP, Yadav JSP, Massoud FI. 1988. Salt-Affected Soils and their Management. FAO Soils Bulletin 39. Rome: FAO.
- APHA. 1998. Standard Methods for the Examination of Water and Wastewater, 20th edition. Washington, D.C.: American Public Health Association.
- Ayers RS, Westcot DW. 1985. Water quality for agriculture. FAO Irrigation and Drainage Paper 29 Rev. 1, (Reprinted 1989, 1994). Rome: FAO.
- Boehner J, Selige T. 2006. Spatial prediction of soil attributes using terrain analysis and climate regionalisation. In: Boehner J, McCloy KR, Strobl J, editors. SAGA - Analysis and Modelling Applications. Goettingen: Goettinger Geographische Abhandlungen. p. 13-28.
- CEC. 2006. Thematic Strategy for Soil Protection [Internet]. Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions. Commission of the European Communities. COM(2006)231 Final, Brussels, 22.9.2006. [cited 2017 Feb 24]. Available from: <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52006DC0231&from=EN>.
- Conrad O, Bechtel B, Bock M, Dietrich H, Fischer E, Gerlitz L, Wehberg J, Wichmann V, Böhrner J. 2015. System for Automated Geoscientific Analyses (SAGA) v. 2.1.4. Geosci Model Dev. 8:1991-2007. (doi:10.5194/gmd-8-1991-2015).
- DGADR. 2014. Estratégia para o Regadio Público 2014-2020. Direção Geral de Agricultura e Desenvolvimento Rural. Ministério da Agricultura e do Mar. 58 p.
- EDIA. 2017. O que é o Alqueva [Internet]. Sistema Global de Rega. Empresa de Desenvolvimento e Infraestruturas do Alqueva, S.A. [cited 2017 Feb 24]. Available from: <http://sigims.edia.pt/indicadoresgeograficos/indexevo.html>.
- EEA. 2017. Climate change, impacts and vulnerability in Europe 2016. An indicator-based report [Internet]. European Environment Agency. EEA Report No 1/2017. [cited 2017 Feb 14]. Available from: <http://www.eea.europa.eu/publications/climate-change-impacts-and-vulnerability-2016> (doi:10.2800/534806).
- FAO. 2011. The state of the world's land and water resources for food and agriculture (SOLAW) – Managing systems at risk [Internet]. Rome and Earthscan, London: Food and Agriculture Organization of the United Nations. 285 p. [cited 2017 Mar 06]. Available from: <http://www.fao.org/docrep/017/i1688e/i1688e00.htm>.
- FAO. 2017. Voluntary Guidelines for Sustainable Soil Management [Internet]. Rome: Food and Agriculture Organization of the United Nations. 16 p. [cited 2017 Feb 14]. Available from: <http://www.fao.org/3/a-bl813e.pdf>.
- FAO, ITPS. 2015. Status of the World's Soil Resources (SWSR) - Main Report [Internet]. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome. [cited 2017 Feb 14]. Available from: www.fao.org/3/a-i5126e.pdf.
- Fuglie K. 2008. Is a slowdown in agricultural productivity growth contributing to the rise in commodity prices? Agricultural Economics 39:431-441.
- IDRHa-DS. 2003. Estudo de caracterização dos solos e esboço de aptidão das terras para o regadio à escala 1:25.000 na área a beneficiar com o Empreendimento de Fins Múltiplos de Alqueva. Lisboa: Instituto de Desenvolvimento Rural e Hidráulica – Divisão de Solos, MADRP.
- IUSS Working Group WRB. 2015. World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps [Internet]. World Soil Resources Reports No. 106. Rome: FAO.
- Marques CMP. 2016. Caracterização do aproveitamento hidroagrícola do Roxo [Internet]. In: Associação dos Beneficiários do Roxo, Instituto Politécnico de Beja, Universidade de Évora, editors. QARSC – Qualidade da água da albufeira do Roxo na dinâmica dos solos e das culturas agrícolas. Projecto Proder 50370. Aljustrel. p. 6-24. [cited 2017 Jan 27]. Available from: <http://abroxo.infoagir.pt/qarsc/livro.pdf>.
- Marques CMP. 2017. Personal communication.
- Moore ID, Grayson RB, Ladson AR. 1991. Digital terrain modeling: a review of hydrological, geomorphological and biological applications. Hydrological Processes 5:3-30.
- Pansu M, Gautheryrou J. 2003. Handbook of Soil Analysis. Mineralogical, Organic and Inorganic Methods. Berlin, New York: Springer-Verlag. 995 p.
- Pebesma EJ. 2016. Package 'gstat'. Spatial and spatio-temporal geostatistical modelling, prediction and simulation [Internet]. [cited 2017 Jan 27]. Available from: <https://r-forge.r-project.org/projects/gstat/>.
- QGIS Development Team. 2016. QGIS Geographic Information System. Open Source Geospatial Foundation Project. [cited 2017 Jan 27]. Available from: <http://www.qgis.org/>.
- R Development Core Team. 2017. The R Project for Statistical Computing [Internet]. R Foundation. Vienna, Austria [cited 2017 Jan 25]. Available from: <http://www.r-project.org>.

- Ramos TB, Gonçalves MC, Castanheira NL, Martins JC, Santos F, Prazeres A, Fernandes M. 2009. Effect of sodium and nitrogen on yield function of irrigated maize in southern Portugal. *Agricultural Water Management* 96(4):585-594. (doi:10.1016/j.agwat.2008.09.023).
- Ramos TB, Šimůnek J, Gonçalves MC, Martins JC, Prazeres A, Castanheira NL, Pereira LS. 2011. Field evaluation of a multicomponent solute transport model in soils irrigated with saline waters. *J of Hydrology* 407(1-4):129-144. (doi:10.1016/j.jhydrol.2011.07.016).
- Rhoades JD, Kandiah A, Mashali AM. 1992. The use of saline waters for crop production. FAO irrigation and drainage paper 48. Rome [cited 2018 Feb 22]. Available from: <https://www.ars.usda.gov/pacific-west-area/riverside-ca/us-salinity-laboratory/docs/watsuit-model/>.
- Richards LA, editor. 1954. *Diagnosis and Improvement of Saline and Alkali Soils*. Agriculture Handbook No. 60. United States Salinity Laboratory Staff. Washington, D.C.: USDA.
- Schermerhorn L J G, Stanton W I, Strauss G, Abreu F, Matze K, Zbyszewski G, Ferreira O V, Freire de Andrade R. 1984. Carta Geológica de Portugal na escala 1:50 000, Folha 42-D (Aljustrel). Serviços Geológicos de Portugal. Direcção Geral de Geologia e Minas.
- SNIRH. 2017. Sistema Nacional de Informação de Recursos Hídricos [Internet]. Agência Portuguesa do Ambiente, I.P. [cited 2017 Jan 25]. Available from: <http://snirh.pt/>.
- SROA. 1970. Carta dos Solos de Portugal. 6ª Ed. Vol. I: Classificação e caracterização morfológica dos solos. Lisboa: Serv. de Reconhecimento e de Ordenamento Agrário, Sec. de Estado da Agricultura.
- SROA. 1972. Carta de Capacidade de Uso do Solo. Bases e normas adoptadas na sua elaboração. 6ª ed. Boletim de Solos nº 12. Lisboa: Serviço de Reconhecimento e de Ordenamento Agrário, Sec. Estado da Agricultura. Ministério da Economia.