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Climate change impacts on irrigated agriculture in the Guadiana river basin (Portugal)

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ABSTRACT

This study evaluates climate change potential impacts on irrigated agriculture in the Guadiana river basin, in the south of Portugal, by running long-term soil water balance simulations using the ISAREG model and taking into consideration the maximum potential yield. The ISAREG simulations were focused in a set of the most locally representative crops to assess the evolution of net and total water requirements, considering a monthly time step for two 30-year future periods, (2011–2040) and (2041–2070). Reference evapotranspiration was estimated using the temperature-based Hargreaves–Samani equation, and the simulations were performed using, as inputs, a combination of five climate change scenarios built using the Ensemble-Delta technique from CMIP3 climate projections datasets to set different alternative climate change bracketing conditions for rainfall and air temperature. Water balance outputs for different climate scenarios were combined with four agricultural scenarios allowing for the estimation of total irrigation requirements.

A general increase in crop irrigation requirements was estimated, mainly for those crops as maize, pasture, and orchards that are already big irrigation water consumers. Crops as olive groves and vineyards, well adapted to the Mediterranean conditions, show less sensitivity to climate change. The combined results of crop irrigation requirements for climate change and agricultural scenarios allow for the expectation of sustainability for the agricultural scenarios A and C, essentially defined by the complete use of the irrigation network and systems currently being constructed with the Alqueva project, but not for the ambitious irrigation area expanding scenario B.

1. Introduction

The Guadiana river basin, situated in southern Portugal, with a rich and diversified natural patrimony, presents important potential vulnerabilities in terms of physical and human desertification. In the Guadiana river basin region, socio-economic development has been, traditionally, highly dependent on the agricultural sector due to the lack of other valuable natural resources. Climate change and its related environmental local impacts are likely to be high, specifically in the agricultural and irrigation water availability domains.

Climate change has become universally recognized, based on scientific results backed by historically observed data, and also acknowledged by public perception in the last decades. Institutions like the Intergovernmental Panel on Climate Change (IPCC, 2014) and the European Environment Agency (EEA, 2012) have regularly reported works on observed and future climatic change and respective impacts and risks, and also mitigation and adaptation measures as policy requirements for a sustainable development. Climate change was already a strong concern in the Medalus project (Mairota et al., 1998). Within this project, Corte-Real et al. (1998) noted that "the Mediterranean is one of the areas where the impacts of climate change may be particularly severe" and that "a general decrease in rainfall for the western-central Mediterranean region in recent decades has been reported". The same authors observe that during the three decade period 1961–1990 rainfall has decreased sharply in March, reflecting in spring totals 23% less rainfall in the case of the Alentejo region, "with a detrimental effect on the growth of cereal crops".

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Within the same project Goodess et al. (1998) estimated future climates using GCM models with increasing CO_2 contents in the atmosphere, coupled with statistical models for sub-grid scale results, compensating for the large (300 km) grid elements typical to GCM models. These authors conclude that "effects on agriculture, for example, may be better described by looking at changes in the availability of water for crop growth". For the same authors, potential evapotranspiration (*ETo*) cannot be estimated from GCM. "Rather more confidence can be placed in GCM estimates of temperature, which can be related to *ETo* by an empirical formula. . .".

One of the remarkable aspects of climate change over the Mediterranean region is the increasing frequency of extreme climatic events as droughts. A recent example of a drought event occurrence was in the hydrological year of 2004/2005, one of the most severe and spatially extensive on record in Portugal (Botelho and Ganho, 2010). More recently, within the first 5 months of 2012, the Portuguese territory experienced a situation of severe drought due to low rainfall in the winter months, inspiring public and governmental concerns on climate change.

One of the most complete reports on climate change in Portugal, SIAM II (Santos and Miranda, 2006), underlines that the 6 warmest years in the period between 1931 and 2000 occurred in the last 12 years of the twentieth century. The SIAM II report also performed a thorough and relevant climate change characterization in Portugal, confirming the rising trends of mean air temperature and decreasing rainfall. Within the project SIAM II, Cunha et al. (2006), reporting on climate change impacts on water resources availability, concluded that "the tendency for reduction both on surface and groundwater is evident, especially in the centre and south regions of Portugal, with increasing non-symmetric distribution during the year, the rainfall concentrating in winter and reducing in spring, summer and fall. The same authors conclude that flow reduction in the rivers of south Portugal and Spain should deserve a particular attention on the strategy for adapting to climate change.

Other authors within the same project (Pinto et al., 2006) referring specifically to climate change impacts on Portuguese agriculture, used GCM (large scale) and regional (intermediate scale) climate change models and the FAO CERES models for crop yields. These authors conclude that drastic reduction on yields is predicted for crops like wheat and maize (up to 50% loss), and even more (up to 75%) for rice. Pasture and fodder crops are the only group of crops that may increase yields (up to 75%) on the future.

Within the present project, Valverde et al. (2014) analysing the CC impacts on crop yields over the Guadiana river basin during the historical period 1960–2010, observed similar in sense but less in absolute values tendencies for decreasing crop yields due to decreasing rainfall and increasing irregularity of precipitation and the values of temperature.

For the Guadalquivir basin in south Spain, next to the Guadiana basin, Rodríguez Díaz et al. (2007) in a study of climate change impacts on future crop irrigation requirements, stated that ". . . climate change threatens to exacerbate the current supply-demand imbalance" and modelled an increase in irrigation water requirements between 15 and 20% by the year 2050.

The consequences of global warming impacts on agriculture, water resources management and ecosystems pose particular concern in the Mediterranean climates in the transition zone between the arid climate of North Africa and the temperate climate of central Europe. The Mediterranean region, characterized by desert-climate transition features is potentially highly vulnerable to existing adverse trends of warming and rainfall reduction and will likely be the region within Europe to firstly experience severe economical and sociological consequences from climate change. Management and allocation of water are thus particularly sensitive issues in the local agricultural context.

The Alqueva dam is one of the biggest dams and the largest artificial lake (250 km^2) in West Europe, retaining water from the Guadiana river basin, with a total storage capacity of 4150 hm^3, of which 3150 hm^3 are usable during regular operation (EDIA, 2013). The Alqueva dam and its irrigation network was a project ambitioned for many decades and planned so as to counteract the poor water availability in the region. It has been, since its implementation in the first decade of this century, the major driving force for the development and expansion of irrigated agriculture in the region, providing a steady source of water supply and lessening the vulnerability of local farming, traditionally limited by water availability and the typical variability that characterizes the Mediterranean climate.

The intensification of irrigation is susceptible to a build-up of soil degradation processes, causing a reduction in overall soil water storage capacity and an increase in surface runoff, resulting in a significant loss of soil fertility. Irrigation management practices will therefore have to be planned to balance short-term economical returns with long-term sustainability, avoiding the effects contributing to the enhancement of the desertification processes.

Climate change, water availability and farming practices are indirectly interwoven with each other and many of the future challenges of a sustainable agricultural activity in the Guadiana river basin rely on both soil and water conservation practices to cope with the inevitable pressure of climate warming and rainfall reduction and irregularity.

Crop sensitivity to climate change is an important regional issue to be taken into account as adverse climate conditions can lead to considerable differences in overall basin-scale water consumption. Crop choices and irrigation management have a considerable effect in agriculture economic and environmental sustainability, and crop choice is frequently mentioned as one potential adaptation strategy to climate change. However, farmers often choose crops (woody perennial or herbaceous annual) based on a host of contextual factors such as crop revenue, water availability, soil conditions and government policies, disregarding climate change as a secondary concern.

Looking at this context, the main specific objectives of the present work can be described as to evaluate climate change for the Guadiana river basin and its impacts on the irrigation requirements of chosen crops within appropriate agricultural scenarios, as well as to evaluate the sustainability of such scenarios according to the water resources availability in the basin, holding policy decisions on water resources management integrating agricultural and other uses within the basin.

2. Materials and methods

2.1. Description of the study area and crop distribution

The study area is the Portuguese part of the Guadiana river basin, in southern Portugal. To allow an enhanced spatial resolution of climatic heterogeneities and, therefore, to provide a better assessment of the crop water use impacts, the Guadiana river basin was divided into six main units of analysis (UA) defined by the main sub-basins of the tributaries of the Guadiana river. This spatial definition was adopted from previous works carried out under a pilot project for the development of a Portuguese Drought Forecasting and Management System (Serralheiro et al., 2010; Vivas et al., 2010; Vivas and Maia, 2010). Two additional spatial units (7 and 8) were added to those referred, representing areas located outside the Guadiana river basin – one (7) in the Sado river basin (Alentejo region) and the other (8) in the eastern part (Sotavento) of the southern Ribeiras do Algarve river basin (Algarve region) – but irrigated with water abstracted from it, as shown in Fig. 1.

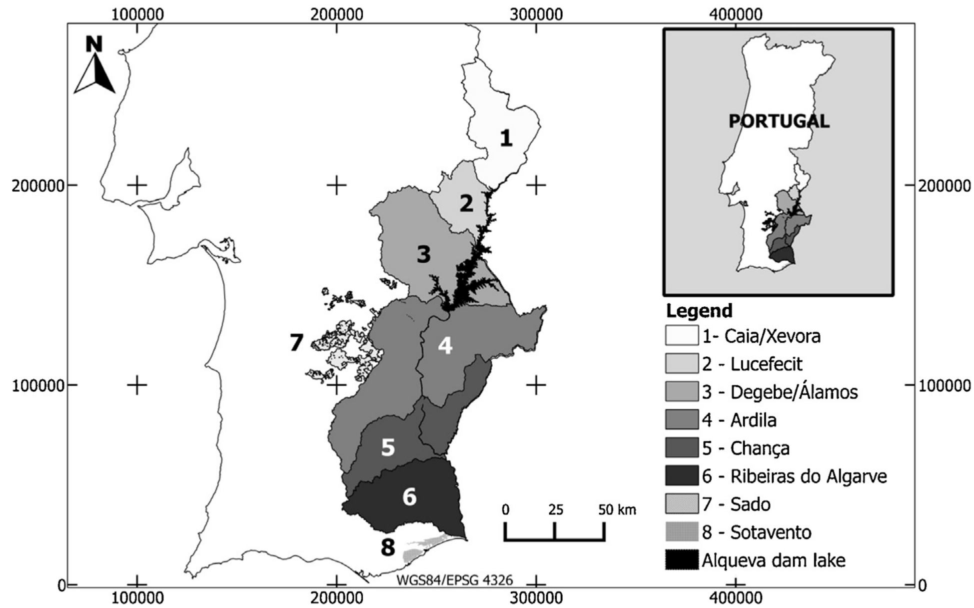

Fig. 1. Guadiana basin location and units of analysis (1–6) and additional ones (7 and 8). The Alqueva dam lake is seen adjacent to units of analysis 1–4.

The present situation regarding irrigated crop distribution areas, related irrigation methods and water sources was defined using information collected from the RA2009 (2009 national agricultural census) (INE, 2011), and irrigated areas reported by the public organizations in charge of reservoir distribution networks management.

Irrigated agriculture in the Guadiana basin – from now on in this paper, that corresponds to all the UA supplied with water abstracted in the Guadiana basin – was thereby divided into two groups: annual and permanent crops. The permanent crops considered in this study include permanent natural pastures and woody crops: orchards (except citrus), citrus olive and grapevine. The crop selected for modelling orchards other than citrus was the peach tree. The annual crop group comprises maize/spring grain cereals, wheat (winter grain cereals), pulse, spring fodder (maize/sorghum), winter fodder (barley), sunflower, and horticulture crops. The crops were chosen in order to gather the most representative in the region and, in some cases, each crop item encloses several individual species with similar water requirements so as to represent the mid-to-upper limits of non-stressing soil water contents for each crop group and, therefore, to achieve maximum yield. The golf course fields have been included in the analysis of water requirements because, while not being a crop or livestock by definition, these irrigated areas have an important role in the local economy of the Algarve region and have displayed a significant expansion in the last decade, competing and sharing water resources with the traditional agricultural crops.

2.2. Climate change scenarios (CCS)

Five climate change scenarios (CCS 1–5), aimed to describe the general characteristics of a future climate, were produced using the Global climate model output from the World Climate Research Programme's (WCRP's) Coupled Model Inter-comparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007), retrieved from www.engr.scu.edu/~ emaurer/global_data/. This dataset was downscaled as described by Maurer et al. (2009) using the bias-correction/spatial downscaling method (Wood et al., 2004) to a 0.5 degrees grid, based on the 1950–1999 gridded observations of Adam and Lettenmaier (2003). The CMIP3 climate simulations datasets used in this study include the outputs of 16 IPCC Models under 3 future emissions scenarios (A2, B1, A1B), resulting in a total of 48 different climate projections containing monthly records of both precipitation and temperature at a 0.5° spatial resolution for the period of 1950 to 2099. Each climate projection was extracted from the referred global climate archive (called "Globally Downscaled Climate Data") by clipping the data from the Guadiana basin's area coordinate's intervals (40.5° N to 37° N lat.; 1.5° W to 8.5° W long.). These bias-corrected and downscaled air temperature and rainfall projections, for the Guadiana river basin (Fig. 2), suggest that future climate will produce warmer and drier conditions.

The five CCS were defined to represent future possibilities and to bracket uncertainty. Four of the five CCS considered in this study (CCS 1, 2, 4 and 5) were defined in order to enclose different ranges/spread of projected air temperature and precipitation changes, with one middle scenario (CCS 3), representing the central tendency of projected changes of these climate variables (Bureau of Reclamation, 2009). Thus, it was necessary to establish a historical/reference period (1961–1990) as well as two different future periods (i) 2011–2040 (future 1) and 2041–2070 (future 2). The chosen climate change range of interest was defined as the intersection of the 25th to 75th percentile of changes in temperature and 25th to 75th percentile of changes in precipitation, while the central tendency correspond to the intersection of the median changes (50th percentile) in temperature and precipitation (Bureau of Reclamation, 2011). Table 1 summarizes, for each future period and CCS, the values obtained in terms of mean annual temperature and precipitation period-changes.

To inform each CCS, an ensemble of climate projections was chosen, accordingly with the ensemble-delta technique. The definition of CCS was conducted to support the development of climate inputs (the so-called climate-adjusted weather inputs) for the crop irrigation model (ISAREG) using the Ensemble Delta technique. This technique reflects changes in period monthly mean temperature and rainfall over the studied region, sampled from an ensemble of climate projections (Bureau of Reclamation, 2009). The ensemble-delta technique comprises the calculation of 12-month-specific change factors for both precipitation and air temperature, for each cell (of 0.5° resolution), and for each CCS (Ramos et al., 2014). Although, to run the crop model a higher resolution (0.125° resolution) is important. Thus, the change factors were interpolated using Inverse Distance Weighting technique, and then applied (for a

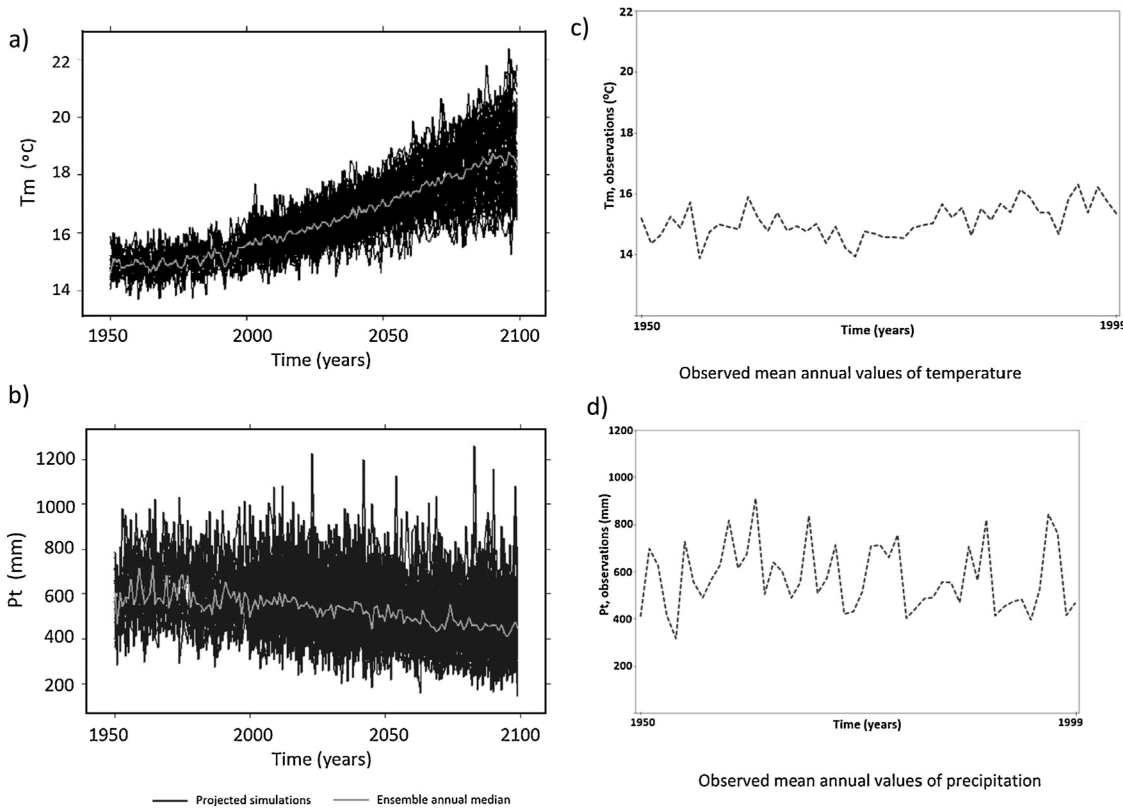

Fig. 2. Simulated (a) annual mean air temperature *Tm* (°C) and (b) total annual precipitation *Pt* (mm) for each of the 48 climate simulations, and the corresponding ensemble of annual values for the Guadiana river basin. In (c) and (d) the observed (1950–1999) annual mean air temperatures and precipitations respectively that constituted the basic series for the simulations.

given month and climate variable) uniformly to the 30 observed climate series of the historical period, obtaining the climate adjusted weather (CAW) series. This implies that the generated CAW series replicate, for future periods, the historic inter-annual variation pattern contained in the underlying base reference data (Ramos et al., 2014).

Fig. 3 depicts the CAW air temperatures (°C) series generated for the central tendency scenario (CCS 3) considering the spatial average of the UA considered in the Portuguese part of the Guadiana river basin. For both (a) future period 1 (2011–2040) and (b) future period 2 (2041–2070) the minimum, maximum and mean air temperatures (*Tmin*, *Tmax*, *Tm*) describe a rising tendency, with *Tm* reaching a maximum of 27.4 °C for future period 1 and 28.4 °C for future period 2. Within both future periods 1 and 2, the model predicts that *Tmin* will rise faster than *Tmax*, resulting in a decreasing thermal amplitude (*Tmax* – *Tmin*), as shown in Fig. 3a and b by a negative slope. Comparing the monthly averages of both 30-year future periods 1 and 2, the model predicts that minimum air temperatures will rise at a faster rate (21.8–23.2 °C) than the maximum temperatures (33.4–34.4 °C), resulting in an overall time-decreasing thermal amplitude. For the remaining CAW series, albeit built with different thresholds resulting in lower absolute values of the temperatures for CCS (1,2) and higher temperatures for CCS (4,5), the outputs display similar evolution tendencies, exhibiting a rising tendency of *Tmin*, *Tmax* and *Tm* and slightly decreasing thermal amplitude (*Tmax* – *Tmin*).

2.3. Agricultural scenarios (AGS)

To address the future outcomes of irrigated crop area occupation in the Guadiana river basin and associated irrigation-dependent areas, four basin-scale agricultural scenarios (AGS) were defined: Present, A, B and C, in order to address realistic evolution patterns of farmland given the current status and tendencies.

This section contains a description of three future scenarios of irrigated agriculture – called scenarios A, B, and C – referring

Table 1
Definition of the climate change scenarios (CCS) and the corresponding spread and central tendency shown as percentile (pctl) for mean annual temperature *T* (°C) and precipitation *P* (mm).

Period	CCS	*T* (°C)		*P* (mm)	
Future 1 (2011–2040)	1 – warm and mildly dry	0.99	(25pctl)	−4.89	(75pctl)
	2 – warm and much dry	0.99	(25pctl)	−10.70	(25pctl)
	3 – hot and dry (central tendency)	1.23	(50pctl)	−8.76	(50pctl)
	4 – hotter and mildly dry	1.39	(75pctl)	−4.89	(75pctl)
	5 – hotter and much dry	1.39	(75pctl)	−10.70	(25pctl)
Future 2 (2041–2070)	1 – warm and mildly dry	1.73	(25pctl)	−9.80	(75pctl)
	2 – warm and much dry	1.73	(25pctl)	−21.79	(25pctl)
	3 – hot and dry (central tendency)	2.31	(50pctl)	−15.20	(50pctl)
	4 – hotter and mildly dry	2.61	(75pctl)	−9.80	(75pctl)
	5 – hotter and much dry	2.61	(75pctl)	−21.79	(25pctl)

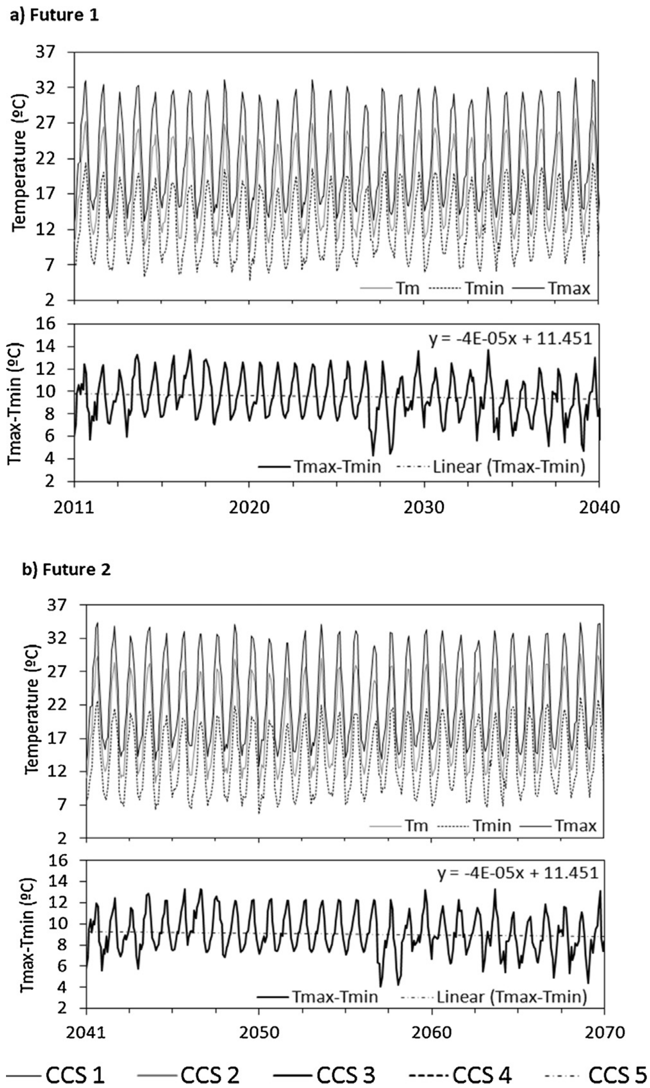

Fig. 3. Monthly average CAW air temperatures series (°C) for (a) future period 1 (2011–2040); and (b) future period 2 (2041–2070), representing maximum (*Tmax*), minimum (*Tmin*), mean (*Tm*) and thermal amplitude (*Tmax* – *Tmin*) generated for CCS 3.

to the areas that may be occupied in the units of analysis in the Guadiana river basin by the main irrigated crops. It should be noted that, although just the irrigated crops are considered herein, each irrigation scenario corresponds to an agricultural scenario including the areas of rainfed crops, because irrigation and rainfed cropping are always inter-dependent and complimentary systems. Therefore, the agricultural scenarios also aim to address the possible area-management exchange outcomes between irrigated and rain-fed crops as a response to climate change and future water availability contexts. The total cultivated area remaining constant, each increase in irrigated area is compensated by an equal decrease in rainfed area. On the other hand, scenarios A, B, and C represent different developments with reference to the Present situation, which is described first.

Present situation was defined on the basis of the 2009 agricultural inquiry (INE, 2011), which contains data on total irrigated areas and its distribution by the main irrigated crops. Water sources for agriculture in the Guadiana basin include mainly public water storage structures (medium to large public dams such as Alqueva), but also water extraction from small private dams and groundwater sources (private water sources). As the irrigated areas in the public sector (irrigation districts) are well known from official reports, the "private irrigated areas" could be deducted. Moreover, as total irrigated area is modifying fast in the Guadiana basin with the implementation of the Alqueva project, it was updated to 2011 by adding the new irrigation blocks meanwhile converted from rainfed to irrigated agriculture. On the other hand, the new irrigated areas were attributed the proportions of the 2009 inquiry for distribution of the irrigated areas by the crops. The Present scenario is numerically characterized in Table 2.

Scenario A was defined as the situation of irrigated agriculture that may be expected for 2020, assuming that the Alqueva project will be complete and completely used at that time. In the region of Alentejo, which encloses most of the Guadiana Basin area, the total area of irrigated land increased between 1999 and 2009 (INE, 2011) by around 17%, or 20,086 ha. Much of this increase is attributed to the new irrigation network-equipped areas made available by the Alqueva dam (EDIA, 2013), but it is clear that there was also a significant investment in this type of agricultural intensification relying on private sources of water. Therefore, for each of the UA in the Guadiana basin, an identical growth of 17% in the irrigated areas was considered, for both public and private water sources.

Private irrigation systems were considered to increase maintaining the current proportions to the public irrigated sector, reflecting the observed regional interest on irrigated agriculture. In what concerns the distribution of the irrigated crops in the irrigation area, present proportions were considered with some modifications that look realistic on the basis of current data and tendencies. Therefore, the areas with olive groves and vineyards were considered to increase at the rhythms observed for the former decade between the agricultural inquiries of 1999 and 2009 (INE, 2011). The increase in irrigated areas was done with equivalent reduction in rainfed areas, mainly winter cereals and fodder crops. In this scenario it is assumed that irrigation water will maintain a relatively low price as the present status, with water subsidized by the government as part of irrigation expansion incentive policy. In Table 3 these criteria were applied to the numerical characterization of agricultural scenario A.

Scenario B was thought to exist by the years 2030 and 2040, if the current interest in irrigated agriculture is maintained. Therefore, this scenario is the most optimistic assuming high availability and thus low price of water, which consequently translates to the highest expansion of irrigation areas. For this case, a 45% area increase was considered upon scenario A, corresponding to an increase of 50,000 ha in the area served by the Alqueva system. This hypothesis is being considered and planned by the Alqueva authorities, irrigators associations and other regional stakeholders. If it reveals sustainable, the increase in irrigated area will be compensated by an equivalent decrease in rainfed area with winter cereals and fodder crops, the irrigated area being distributed by crop groups maintaining the proportions in scenario A. For this scenario B to be sustainable, it requires enormous efforts from the agricultural sector to improve technology, mainly for soil, water, and energy conservation. Scenario B is numerically characterized in Table 4.

Scenario C is defined as a conservative alternative to the intensive water use scenario B, and will be characterized by a high awareness of farmers to sustainable agricultural practices due to high water prices in a scarcity context. Scenario C was thought as to exist by the years 2030 and 2040, as alternative opposing to scenario B. For scenario C the costs of water, energy, other production factors, soil and water conservation and other technological applications were considered more relevant, reducing the interest in irrigation, and therefore the irrigated areas. In this context, the irrigated areas of scenario A were considered for scenario C, along with some redistribution of irrigated areas by the crop groups, looking for the reduction of water requirements, of energy and other costs

Table 2
Summary of areas in the Present agricultural scenario for each unit of analysis in the Guadiana river basin and external irrigation dependent areas: Sado and Sotavento, Algarve (abbreviated as Sot.); total irrigated crop areas (public and private water sources) – *T* (ha), and areas irrigated with private sources of water (small dams and groundwater) – *P* (ha).

Crops	Agricultural scenario present – units of analysis																	
	1		2		3		4		5		6		Sado		Sot		Total	
	T	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*
Maize/spring grain cereals	1200	51	650	203	1767	239	183	183	11	11	15	15	939	0	0	0	4765	702
Wheat/winter grain cereals	2029	518	417	328	1991	1094	1459	1459	121	121	6	6	751	0	0	0	6774	3526
Grain legumes	206	62	145	5	17	12	38	38	4	4	6	6	87	0	0	0	503	127
Spring fodder	247	228	92	29	586	354	145	145	7	7	12	12	94	0	0	0	1183	775
Winter fodder	393	238	160	143	1329	626	589	589	149	149	5	5	263	0	0	0	2888	1750
Sunflower/oleaginous	296	103	12	11	367	79	992	992	97	97	0	0	145	0	0	0	1909	1282
Horticulture	1709	489	302	255	787	344	514	514	63	63	102	71	523	0	156	0	4156	1736
Pastures	277	107	57	15	627	50	526	526	49	49	205	205	237	0	0	0	1978	952
Fruit orchards (except citrus)	630	223	285	266	138	96	147	147	191	191	239	220	146	0	138	0	1914	1143
Citrus	96	22	34	32	110	76	222	222	43	43	1366	1274	61	0	1431	0	3363	1669
Olive groves	3804	1511	612	441	5480	2253	18407	18407	2411	2411	47	47	1710	0	0	0	32471	25070
Grapevine	405	340	1135	989	5623	3549	2463	2463	137	137	63	54	689	0	66	0	10581	7532
Golf course fields	0	0	0	0	0	0	0	0	0	0	34	0	0	0	126	0	160	0
Total	11292	3892	3901	2715	18822	8772	25684	25684	3283	3283	2100	1915	5645	0	1917	0	72644	46261

Table 3
Summary of areas in agricultural scenario A for each unit of analysis in the Guadiana river basin and external irrigation dependent areas: Sado and Sotavento, Algarve (abbreviated as Sot.); total irrigated crop areas (public and private water sources) – *T* (ha), and areas irrigated with private sources of water (small dams and groundwater) – *P* (ha).

Crops	Agricultural scenario A – units of analysis																	
	1		2		3		4		5		6		Sado		Sot		Total	
	T	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*
Maize/spring grain cereals	1209	60	685	238	1808	280	11230	214	14	14	18	18	7411	0	0	0	22375	824
Wheat/winter grain cereals	2117	606	473	383	2177	1280	10514	1707	141	141	7	7	5925	0	0	0	21354	4124
Grain legumes	217	73	146	6	19	14	1062	44	5	5	7	7	684	0	0	0	2140	149
Spring fodder	286	267	97	33	646	414	1277	169	8	8	14	14	745	0	0	0	3073	905
Winter fodder	434	279	184	168	1435	733	3772	689	174	174	6	6	2074	0	0	0	8079	2049
Sunflower/oleaginous	314	121	14	12	380	93	2858	1160	113	113	0	0	1143	0	0	0	4822	1499
Horticulture	1792	572	345	298	845	402	6744	602	73	73	114	83	4132	0	400	0	14445	2030
Pastures	295	125	60	18	635	58	3397	616	57	57	240	240	1872	0	0	0	6556	1114
Fruit orchards (except citrus)	668	261	330	311	154	113	1890	172	224	224	276	257	1156	0	354	0	5052	1338
Citrus	100	25	40	38	123	89	972	260	51	51	1583	1491	480	0	3669	0	7018	1954
Olive groves	4091	1798	696	525	5908	2681	41972	21904	2870	2870	56	56	13501	0	0	0	69094	29834
Grapevine	538	472	1521	1374	7007	4934	11513	3423	191	191	85	76	5442	0	169	0	26466	10470
Golf course fields	0	0	0	0	0	0	0	0	0	0	34	0	0	0	323	0	357	0
Total	12059	4659	4589	3403	21139	11090	97202	30961	3921	3921	2439	2254	44564	0	4915	0	190828	56288

Table 4
Summary of areas in agricultural scenario B for each unit of analysis in the Guadiana river basin and external irrigation dependent areas: Sado and Sotavento, Algarve (abbreviated as Sot.); total irrigated crop areas (public and private water sources) – *T* (ha), and areas irrigated with private sources of water (small dams and groundwater) – *P* (ha).

Crops	Agricultural scenario B – units of analysis																	
	1		2		3		4		5		6		Sado		Sot		Total	
	T	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*
Maize/spring grain cereals	1753	87	993	344	2621	405	16283	310	20	20	25	25	11159	0	0	0	32854	1191
Wheat/winter grain cereals	3070	879	685	556	3157	1856	15245	2476	205	205	11	11	8922	0	0	0	31295	5983
Grain legumes	314	105	212	9	28	21	1540	64	7	7	10	10	1031	0	0	0	3142	216
Spring fodder	414	387	140	48	937	601	1852	246	12	12	20	20	1122	0	0	0	4497	1314
Winter fodder	629	404	267	243	2081	1062	5469	999	252	252	9	9	3123	0	0	0	11830	2969
Sunflower/oleaginous	455	176	20	18	552	135	4145	1682	164	164	0	0	1721	0	0	0	7057	2175
Horticulture	2599	829	501	432	1226	583	9778	872	106	106	165	120	6222	0	808	0	21405	2942
Pastures	428	182	86	26	921	85	4926	893	83	83	347	347	2818	0	0	0	9609	1616
Fruit orchards (except citrus)	968	378	479	450	224	163	2741	249	324	324	400	373	1741	0	715	0	7592	1937
Citrus	145	37	57	55	178	128	1410	377	74	74	2295	2161	722	0	7413	0	12294	2832
Olive groves	5932	2608	1009	761	8567	3887	60860	31761	4161	4161	81	81	20330	0	0	0	100940	43259
Grapevine	779	685	2205	1992	10161	7154	16694	4964	276	276	123	110	8195	0	342	0	38775	15181
Golf course fields	0	0	0	0	0	0	0	0	0	0	49	0	0	0	653	0	702	0
Total	17485	6756	6654	4935	30652	16080	140943	44893	5685	5685	3536	3268	67106	0	9931	0	281992	81617

of irrigation production factors. In this context, the following steps were taken for building scenario C upon scenario A:

The area with maize in scenario A was reduced in 65% that was converted to irrigated winter cereals and fodder crops;
The areas with olive groves and vineyards in Scenario A will maintain in scenario C;
Some areas with irrigated herbaceous crops were redistributed to irrigated woody perennial crops, mainly orchards but also traditional rainfed forest species on limited quality soils;
The areas with herbaceous irrigated crops were finally arranged for each UA in order to be 2/3 with winter crops (less water demanding) and 1/3 with spring and summer crops.

Table 5 contains the numerical characterization of scenario C.

The Sado and Sotavento are irrigation areas outside the Guadiana basin, but still dependent on the Alqueva dam irrigation system and so these areas were accounted for as part of the public-sourced water consumption share of the studied basin.

Irrigation efficiency was determined as specific to each irrigation method, improving in future scenarios according to the technological constraints, specially the costs of the irrigation water. On the other hand, the RA 2009 (INE, 2011) contains information on the irrigation methods used for each crop group. Therefore, assuming that irrigation methods will likely remain proportional in the future, irrigation efficiency could be calculated for each scenario. Most crops are served by one or two irrigation methods, woody crops (olive and grapevine) rely heavily on drip irrigation while grain cereals are mostly irrigated with sprinklers. There are still traces of gravity irrigation in the Guadiana river basin, but supported by modern management (piped gravity irrigation), allowing relatively high irrigation efficiencies, comparable to sprinkler irrigation. Considering the existence of little future potential for improvement, the average irrigation efficiencies were assumed as 0.85 for drip irrigation, and 0.75 for both sprinkler and gravity irrigation.

The proportion between water consumption from private water sources (small private dams and groundwater extraction) and public water sources (large dams) has been established (as of 2009) from combined information from the agricultural census 2009 (INE, 2011) and public dam management reports. Groundwater is currently not a heavily explored water source for agricultural purposes in the region, being usually deprecated in favour of surface water sources, although it has considerable importance in smaller farms not served by publicly managed irrigation networks. In this study it was assumed, for the future scenarios, that water used in irrigation from private water sources will maintain its current distribution ratio between surface and groundwater origins for each crop and UA.

2.4. Crop net irrigation requirements

Crop net irrigation requirements were determined by way of the ISAREG water balance model, developed at the *Instituto Superior de Agronomia* (ISA) by Teixeira and Pereira (1992). The model estimates crop net irrigation needs implementing a soil water balance algorithm, based on the FAO methodology (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979), later enhanced by Allen et al. (1998) in which the soil is considered a reservoir, giving in or receiving water at any period of time, depending on the balance between the inputs (precipitation, irrigation) and outputs (crop evapotranspiration, drainage, deep percolation) (Teixeira and Pereira, 1992). In this study the inputs to the model were the effective precipitation (*Pef*), reference evapotranspiration (*ETo*), soil water data (depth of soil horizon, upper and lower limits of available water, i.e. field capacity and wilting point), and the characteristics of crop growth

Table 5
Summary of areas in agricultural scenario C for each unit of analysis in the Guadiana river basin and external irrigation dependent areas: Sado and Sotavento, Algarve (abbreviated. as Sot.); total irrigated crop areas (public and private water sources) – *T* (ha), and areas irrigated with private sources of water (small dams and groundwater) – *P* (ha).

Crops	Agricultural scenario C – units of analysis																	
	1		2		3		4		5		6		Sado		Sot		Total	
	T	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*
Maize/spring grain cereals	421	21	236	82	626	97	3907	74	4	4	6	6	2812	0	0	0	8012	284
Wheat/winter grain cereals	2754	788	781	633	2855	1679	15792	2565	114	114	13	13	9360	0	0	0	31669	5792
Grain legumes	215	72	144	6	19	14	1055	44	4	4	7	7	753	0	0	0	2197	147
Spring fodder	284	265	95	33	640	410	1270	168	6	6	14	14	814	0	0	0	3123	896
Winter fodder	564	363	304	277	1883	961	5665	1035	140	140	12	12	3290	0	0	0	11858	2788
Sunflower/oleaginous	312	120	14	12	377	92	2841	1153	89	89	0	0	1230	0	0	0	4863	1466
Horticulture	1782	569	340	293	837	398	6704	598	57	57	114	83	4433	0	200	0	14467	1998
Pastures	294	124	59	17	629	58	3377	612	45	45	240	240	2024	0	0	0	6668	1096
Fruit orchards (except citrus)	704	275	361	339	236	172	2132	193	350	350	276	257	1397	0	554	0	6010	1586
Citrus	100	25	40	38	123	89	972	260	51	51	1583	1491	498	0	3669	0	7036	1954
Olive groves	4091	1798	696	525	5908	2681	41972	21904	2870	2870	56	56	14020	0	0	0	69613	29834
Grapevine	538	472	1521	1374	7007	4934	11513	3423	191	191	85	76	5652	0	169	0	26676	10470
Golf course fields	0	0	0	0	0	0	0	0	0	0	34	0	0	0	323	0	357	0
Total	12059	4894	4589	3630	21139	11584	97202	32031	3921	3921	2439	2254	46281	0	4915	0	192545	58314

throughout the crop cycle (root depth, lower limit of available soil water for maximum yield, duration of the crop growth stages, crop coefficients). In the present work, a simplified model of soil profile was used for annual herbaceous crops, with a unique horizon of 60 cm depth and 100 mm available water capacity. The model was set to simulate irrigation to achieve maximum yield, where irrigation is applied to reach soil water field capacity whenever soil moisture reaches the limit of the readily available soil water in the root zone.

Effective precipitation, *Pef* is the fraction of the total rainfall contributing to both soil water storage in the crop root zone and deep drainage. The methodologies available to determine *Pef* from total precipitation data (*Pt*) account for the loss of soil water intake due to the effects on runoff from local topography, soil texture and leaf interception by vegetation. In this study, the effective precipitation (*Pef*) used as input in the ISAREG model was determined, for each unit of analysis, using the method defined in (Eq. (1)), originating from the USDA Soil Conservation Service (USDA-SCS) (Clarke, 1998), where *Pt* is the total precipitation (mm), estimated as the area-weighted average precipitation in each unit of analysis within the Guadiana basin.

$$Pef = \begin{cases} \dfrac{Pt(125 - 0.2Pt)}{125} & ;(Pt < 250\,\text{mm}) \\ 125 + 0.1Pt & ;(Pt \geq 250\,\text{mm}) \end{cases} \quad (1)$$

Reference evapotranspiration (*ETo*) estimates are widely used to define crop water requirements. The Modified Penman-Monteith (FAO-56 PM), presented by FAO Irrigation & Drainage Paper No.56 (Allen et al., 1998) is currently the standard method to estimate *ETo*, but is relatively high data demanding, making it suitable for computing evapotranspiration with data from automatic weather stations, but impracticable to use with global climate datasets which often provide a limited set of climate variables. Santos and Maia (2005) have studied datasets from the COTR – SAGRA automatic weather station network located in the Alentejo region, partially enclosing the Guadiana river basin, and found that for nine different weather stations, the linear regression results of the Hargreaves–Samani (HS) equation (Hargreaves and Samani, 1985) versus the standard FAO-56 PM in the Guadiana river basin returned an average determination coefficient of 0.9. Other studies also found that the HS equation, despite its simplicity, returns results comparable to the more accurate FAO-56 PM equation (Droogers and Allen, 2002; Shahidian et al., 2012). The reference evapotranspiration (*ETo*) was estimated for the 8 units of analysis and climate scenarios (CCS) using the HS equation for semi-arid regions (Eq. (2)) where *Ra* is the average extra-terrestrial radiation (mm day^{-1}) and *Tmax*, *Tmin* and *Tmed*, are respectively the maximum, minimum and average air temperatures (°C).

$$ETo = 0.0023Ra(T\max - T\min)^{0.5}(Tmed + 17.8) \quad (2)$$

Table 6 lists the crop coefficients and ground cover reduction coefficients used in the ISAREG model to estimate monthly net irrigation requirements for main growth stages of each representative crop under non-limiting water supply conditions, given the effective rainfall (*Pef*) and *ETo* estimated for each of the climate scenarios (CCS1-5) and future periods considered in this study. The average crop coefficients (*Kc*) used were based on those proposed by FAO (Allen et al., 1998) for the Mediterranean conditions, although introducing adjustments to reflect the local crop development stages namely planting and harvest timeframes, management conditions, and considering, where applicable, the appropriate *Kc* for the established crop densities.

The golf fields, while not being directly related to agriculture, were introduced in this study because of their increasing importance to the economy, especially in the Sotavento region of the

Table 6
Crop coefficients, ground cover, and growth stages duration considered in the ISAREG model.

Crop	Ground cover (%)	Kc/crop stage			Start date	Crop stage length			
		Initial	Mid	Final		Initial	Mid	Final	Late
Maize/spring grain cereals	–	0.30	1.20	0.35	1-May	30	50	60	40
Wheat/winter grain cereals	–	0.30	1.15	0.25	15-November	30	140	40	30
Grain legumes	–	0.50	1.15	0.30	01-December	40	35	35	25
Winter fodder	–	0.30	1.15	0.25	15-November	30	140	40	30
Spring fodder	–	0.30	1.20	0.35	1-May	25	37	30	34
Horticulture	–	0.60	1.15	0.90	15-April	30	40	45	30
Sunflower	–	0.35	1.15	0.35	15-March	25	35	45	25
Pastures	–	0.30	0.75	0.75	01-October	140	60	120	24
Fruit Orchards (peaches)	70	0.55	0.90	0.65	1-March	92	30	61	30
Citrus	70	0.70	0.65	0.70	1-March	150	64	50	38
Olive groves	59	0.65	0.50	0.50	1-March	30	90	60	90
Grapevine	50	0.30	0.70	0.00	1-March	30	120	32	56
Golf fields	–	0.30	0.75	0.75	01-October	140	60	120	24

Algarve, in the Guadiana river basin. With the expansion of the Alqueva irrigation network providing a steady source of water, golf fields are seen as an economic opportunity for local development and can become a competitor with agriculture for water. From the water use standpoint, golf courses are diverse landscapes, usually with vast permanent diverse species grass areas (with diverse water requirements) and sparse shrubs and trees to provide sun coverage and habitat for wildlife. For the purposes of this study the irrigation requirements of golf fields were considered analogous to well irrigated permanent pastures, with an "initial" relatively long (140 days) stage coincident with low strengthening fall and winter periods.

3. Results and discussion

3.1. Climate trends and generated climate scenarios

Each CCS was defined through the combination of rainfall and air temperature changes relative to the historical period (1961–1990) as shown in Table 1. Annual rainfall shows a decreasing trend for both future periods. Future period 1 annual rainfall projected averages are between 515 mm (CCS 2 and 5) and 552 mm (CCS 4) and, under the more adverse conditions of future period 2, the rainfall averages are lower, falling within 438 for CCS 2 to 517 mm (CCS 4).

The average daily *ETo* was determined using the temperature-based HS equation (2), resulting from each CCS, returning a higher atmospheric demand in future 2 (2041–2070), with an average *ETo* ranging from 3.29 to 3.40 mm day^{-1}, while future 1 (2011–2040) outputs an average *ETo* range between 3.23 and 3.27 mm day^{-1}. Although the overall mean temperature *Tmed*, and the maximum *Tmax* and minimum *Tmin* temperatures increase over time in both future periods (Figs. 2a and 3), the *ETo* determined by the HS method did not return a significant *ETo* temporal trend. This may be due to the fact that, in the simulated CCS scenarios, *Tmin* grows faster than *Tmax*, thereby decreasing (although slightly), over the years, both the thermal difference used in the Hargreaves–Samani equation (Eq. (2)) and the *ETo* values calculated with this equation, reducing its reliability in simulating *ETo* trends for distant future periods, whilst using the CCS as primary data sources.

3.2. Net irrigation requirements

Crop choice is one of the possible adaptation strategies to cope with climate changes and water availability. Depending on whether rainfall increase or decrease, farmers will tend to shift towards either drought tolerant or water demanding crops respectively, in order to maximize economic return. The different combinations of rainfall and air temperature variations considered in each CCS affect the irrigation requirements of each crop differently. Therefore, despite the previously mentioned erratic behaviour of the *ETo* trends when calculated with the Hargreaves–Samani equation (Eq. (2)), it is important to address the effects of each CCS in the average net irrigation requirements. Table 7 lists the average annual net irrigation requirements estimated by the ISAREG model, given the 30-year historic reference period (1961–1990) climate and considering the representative crops selected.

Table 7 also summarizes, for each crop type, the net irrigation requirements determined by the ISAREG model using as inputs the climate data (*ETo* and *Pef*) generated from each CCS, aggregating the average results from the eight spatial units of analysis irrigated areas supplied by water abstractions in the Guadiana river basin.

Maize, horticulture, and fruit trees, as well as permanent irrigated crops such as pasture, are some of the most water demanding crops, exhibiting higher irrigation demands. The crops' response to different climate change scenarios is particularly important to the overall irrigation water demand. The impacts of each CCS on crop irrigation requirements are different, as crops respond differently to each threshold of rainfall and temperature variations. The maximum net irrigation requirements occur within CCS-3–CCS-5, which is coherent with their definitions (Table 1), corresponding to climate conditions of higher air temperatures and lower annual rainfall. However, the underlying monthly distribution of climate variables also has an important effect on how each crop will respond to a given CCS, as some crops are more sensitive to changes occurring in certain months, in accordance with its specific crop cycle. The results show that high rainfall decrease will have a more noticeable effect on the winter crops' irrigation needs, while a temperature increase will tend to increase water demand more noticeably on permanent crops with crop cycles occurring in spring and summer months. The range of irrigation demand variation between CCS for each crop and its corresponding standard deviation can be used as an indicator of the crop response to different climate change thresholds.

Grain legumes are short-cycle winter crops with typically low irrigation requirements, which consequently show very small variation response in irrigation demand for different CCS, exhibiting the lowest range of variation and standard deviation within the selected crops for both future periods.

The crops which are the most adapted to Mediterranean conditions such as olive and grapevine show a similarly small range of annual variation between CCS: 73 and 79 m^3 ha^{-1} for future period 1 and 198 and 186 m^3 ha^{-1} for future period 2. The modest standard deviations of olive and grapevine relative to other crops also confirms that the irrigation demands of these crops have a smaller

Table 7
Annual average net irrigation requirements (m^3 ha^{-1} $year^{-1}$) for the representative crops in the Guadiana river basin estimated for the historic period (1960–1990) and for each CCS and descriptive climate-induced variations (variation range; standard deviation, SD; and coefficient of variation, CV) between CCS outputs.

Crop	Historic period	CCS -1	CCS -2	CCS -3	CCS -4	CCS -5	Range	SD	CV
Future 1 (2011–2040)									
Maize/Spring grain cereals	5663	5919	5970	6056	6081	6071	162	71.4	1.2
Wheat/Winter grain cereals	1654	1796	1930	1932	1904	1891	136	55.4	2.9
Grain legumes	244	275	303	307	266	275	41	18.5	6.5
Spring fodder	3797	4001	4025	4039	4033	4066	65	23.5	0.6
Winter fodder	1654	1796	1930	1932	1904	1891	136	55.4	2.9
Sunflower/oleaginous	3349	3577	3650	3671	3663	3676	99	40.6	1.1
Horticulture	5647	5935	5980	6017	6049	6043	114	47.6	0.8
Pastures	4978	5301	5418	5454	5460	5451	159	66.8	1.2
Fruit orchards (except citrus)	5128	5402	5528	5576	5589	5583	186	78.3	1.4
Citrus	4225	4415	4556	4625	4616	4628	213	90.4	2.0
Olive groves	1441	1587	1628	1644	1658	1660	73	29.9	1.8
Grapevine	2916	3122	3156	3186	3193	3201	79	32.5	1.0
Other: golf courses	4978	5301	5418	5454	5460	5451	159	66.8	1.2
Future 2 (2041–2070)									
Maize/spring grain cereals	5663	6173	6161	6385	6455	6451	295	147.0	2.3
Wheat/winter grain cereals	1654	1935	2090	2134	2146	2196	261	99.8	4.8
Grain legumes	244	294	338	317	290	357	66	28.4	8.9
Spring fodder	3797	4143	4092	4297	4349	4344	257	119.3	2.8
Winter fodder	1654	1935	2090	2134	2146	2196	261	99.8	4.8
Sunflower/oleaginous	3349	3739	3800	3924	3983	3966	244	107.5	2.8
Horticulture	5647	6168	6142	6381	6452	6436	309	149.2	2.4
Pastures	4978	5543	5673	5849	5903	5948	405	170.1	2.9
Fruit orchards (except citrus)	5128	5685	5761	5928	6011	6016	331	150.1	2.6
Citrus	4225	4731	4927	5060	5094	5114	383	159.9	3.2
Olive groves	1441	1690	1741	1861	1880	1888	198	90.2	5.0
Grapevine	2916	3279	3279	3422	3465	3458	186	93.9	2.8
Other: golf courses	4978	5543	5673	5849	5903	5948	405	170.1	2.9

spread from the median values within each of the 30 year periods considered.

The most irrigation demanding crops such as maize, citrus, fruit orchards and permanent pasture showed a higher range of variation in irrigation requirements between CCS as a response to progressively adverse climate change. In future period 1 (2011–2040), citrus, fruit orchards and maize have the highest variation range of annual irrigation requirements, with, respectively, 213, 186 and 162 m^3 ha^{-1} outlining the high dependency of these crops on irrigation. In future period 2 (2041–2070), these water demanding crops maintained a higher irrigation requirements range between CCS, despite the pasture having the highest variation range (405 m^3 ha^{-1}). These results show that the permanent crops, due to requiring irrigation during most of their crop cycle in order to meet their maximum potential yield, can respond with a more steeply increase in irrigation requirements under decreasing rainfall and warmer conditions in comparison with crops with higher demands but with shorter crop cycles such as maize.

Crops such as wheat, sunflower, and winter/spring fodder displayed a more mild behaviour as their irrigation requirements variation pattern lie between crops well adapted to the Mediterranean climate and crops heavily dependent on irrigation.

Fig. 4 depicts the net irrigation requirements variation for each crop type between the climate conditions generated for future 1 (2011–2040) and future 2 (2041–2070) under the influence of different thresholds of warming and rainfall decrease described for each CCS. These results imply that crop irrigation demand variations can respond very differently within crops when given identical variations of the climate variables.

Olive groves and grapevines have the lowest variation between the two future periods analysed, but also have smaller differences between CCS confirming their good adaptation to Mediterranean climate conditions. These crops can be maintained even under harsher conditions resulting from the CCS thresholds considered. Permanent pasture, citrus and fruit orchards can experience an annual variation above 400 m^3 ha^{-1} in net irrigation requirements between the two 30 year future periods, thereby revealing that climate change has a considerable impact in maintaining these crops at their maximum potential yield conditions.

3.3. *Gross irrigation requirements*

Gross irrigation requirements were estimated in order to mingle the different effects of climate change combinations integrated in the CCS thresholds of progressive rainfall decrease and temperature increase and a set of the most probable alternative irrigated crop area distributions defined as agricultural scenarios.

The total irrigation requirements outputs are shown in Fig. 5 for each combination of CCS and AGS during the two considered future periods (futures 1 and 2). The shape of the output graphics is similar between the agricultural scenarios shown in Fig. 5 (a) AGS-Present, (b) AGS-A, (c) AGS-B and (d) AGS-C, as irrigation requirements for each CCS are driven by common time-based *ETo* and rainfall data, while the represented irrigation volumes are more closely dependent on the crop distribution and the different irrigated areas defined for each AGS.

Extreme values, averages and range of total irrigation requirements (difference between the maximum and minimum values) are very important, at basin scale, in setting up dam and irrigation network systems management and control. Table 8 summarizes the total irrigation requirements estimated for the Guadiana river basin, outlining the outputs for each combination of future period, climate change scenario and agricultural scenarios.

The agricultural scenario A, representing the complete implementation of the Alqueva irrigation network's projected areas, resulted in total irrigation requirements estimated, for the most representative crops, to be nearly three times higher than the historical agricultural situation for each CCS, reaching a maximum of 875 hm^3 $year^{-1}$ for the 30-year period (2011–2040) and

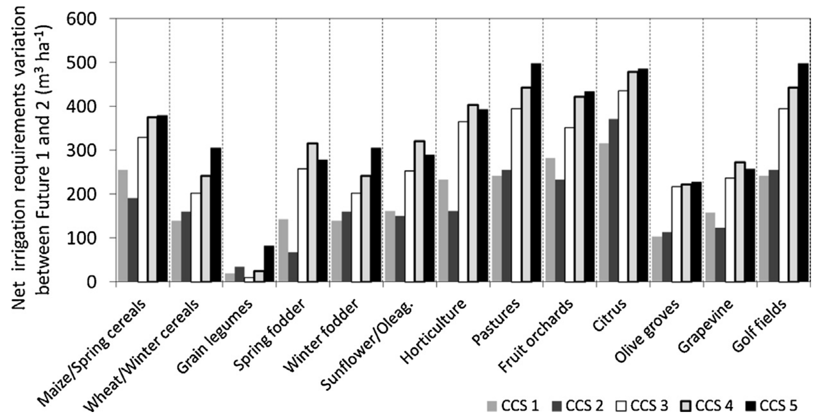

Fig. 4. Net irrigation requirements ($m^3\ ha^{-1}$) variation between future 1 (2011–2040) and future 2 (2041–2070) for each climate change scenario (CCS).

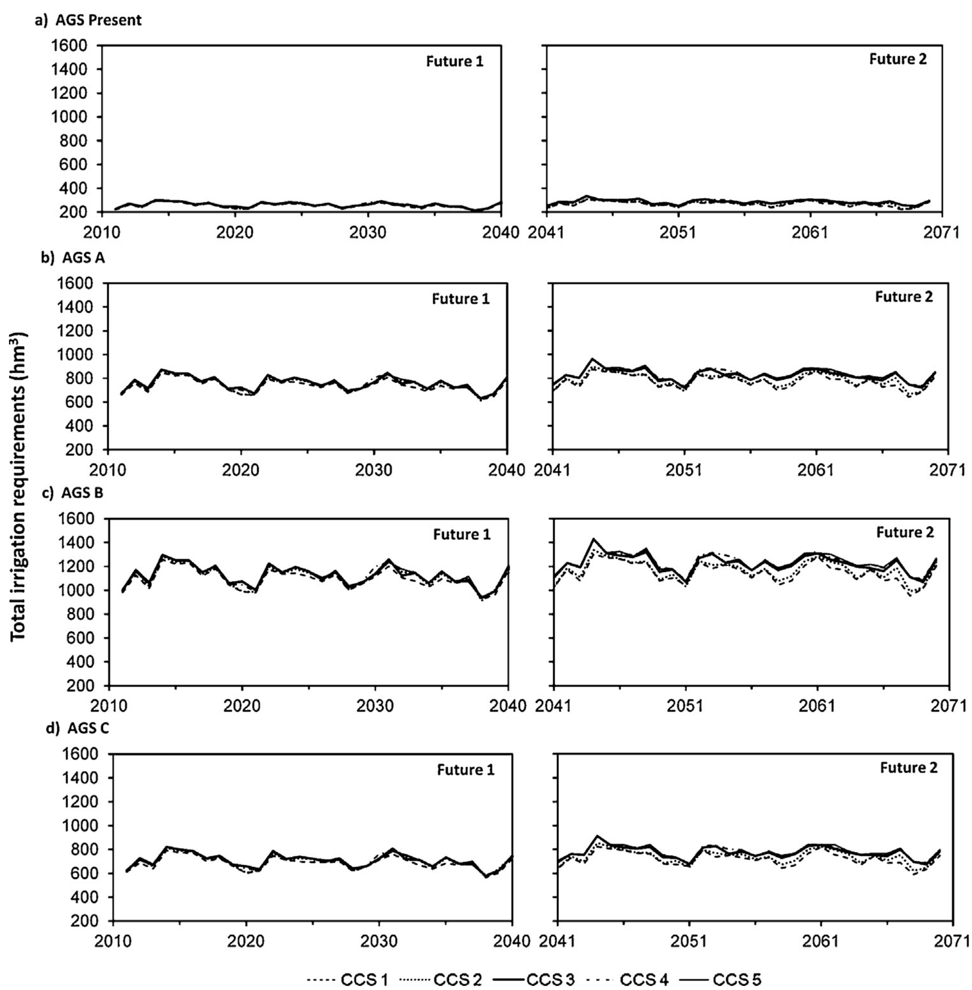

Fig. 5. Total irrigation requirements (hm^3) for the ensemble of representative irrigated crops in the Guadiana basin for each combination of climate change scenario (CCS) and agricultural scenario (AGS).

966.8 $hm^3\ year^{-1}$ for future period 2 (2041–2070), both under the most adverse climate change scenario (CCS-5).

For agricultural scenario B, considering the hypothesis that the irrigated area will be increased in 45% with reference to the new irrigation districts within the Alqueva project, the estimates of total irrigation requirements show a steep increase in comparison with the historical conditions. In this agricultural scenario, and under the CCS-5 climate change thresholds, the total irrigation requirements can reach an estimated maximum of 1300.4 $hm^3\ year^{-1}$ for the period 2011–2040, and 1434.3 $hm^3\ year^{-1}$ for the period 2041–2070. The variation between minimum and maximum (annual range) of annual irrigation total requirements for AGS-B is estimated to be almost as high as the present situation's total maximum requirements, resulting therefore in considerable challenges to management and control of dam water levels and associated irrigation networks.

Under agricultural scenario C, the crop distribution was established under the hypothesis that farmers in the future will favour

Table 8
Gross irrigation requirements for the representative crops in the Guadiana river basin (hm^3 year^{-1}) for each combination of CCS, AGS and future period F1 (2011–2040) and F2 (2041–2070); max, maximum annual irrigation requirements; range, difference between annual max and minimum gross irrigation requirements; SD, standard deviation; av. variation, average variation between total irrigation requirements between future periods 1 and 2; slope, overall slope of linear regression of annual gross irrigation requirements for future periods F1 and F2.

AGS	Period	Total irrigation requirements	CCS-1	CCS-2	CCS-3	CCS-4	CCS-5
Present	F1	Max	293.5	297.3	298.9	299.6	300.8
	2011–2040	Range	84.4	91.5	85.8	86.7	88.0
		Average	253.4	258.1	260.7	261.6	261.0
		SD	21.6	23.2	22.1	22.3	22.0
	F2	Max	303.1	309.3	333.9	335.0	335.5
	2041–2070	Range	83.9	84.7	86.4	82.9	83.0
		Average	266.7	271.6	285.5	288.2	288.3
		SD	22.1	22.3	19.6	19.7	19.8
	F2 – F1	**Av. variation**	**13.3**	**13.5**	**24.9**	**26.5**	**27.4**
	2011–2070	**Slope**	**0.2**	**0.2**	**0.5**	**0.5**	**0.5**
A	2011–2040	Max	846.4	863.8	872.8	868.2	875.2
		Range	225.0	249.9	240.5	235.7	247.5
		Average	736.4	750.4	758.1	759.3	758.4
		SD	57.2	62.1	60.2	59.9	59.7
	2041–2070	Max	876.0	900.5	962.6	965.6	966.8
		Range	234.0	234.1	242.6	237.3	243.5
		Average	773.9	787.8	823.9	834.1	833.5
		SD	59.7	59.9	53.8	53.8	55.0
	F2 – F1	**Av. variation**	**37.5**	**37.5**	**65.8**	**74.8**	**75.0**
	2011–2070	**Slope**	**0.5**	**0.6**	**1.2**	**1.5**	**1.5**
B	2011–2040	Max	1255.2	1283.5	1297.0	1290.1	1300.4
		Range	332.3	371.1	357.9	350.5	368.2
		Average	1093.1	1113.8	1125.2	1127.1	1125.8
		SD	84.6	92.0	89.2	88.6	88.4
	2041–2070	Max	1301.6	1337.7	1428.4	1432.6	1434.3
		Range	348.0	348.1	359.9	350.5	359.5
		Average	1148.6	1169.4	1222.7	1237.9	1237.1
		SD	88.5	88.8	79.8	79.6	81.2
	F2 – F1	**Av. variation**	**55.6**	**55.6**	**97.5**	**110.8**	**111.3**
	2011–2070	**Slope**	**0.7**	**0.9**	**1.8**	**2.2**	**2.2**
C	2011–2040	Max	791.8	813.9	820.8	813.0	823.1
		Range	227.6	247.3	240.6	232.5	250.8
		Average	684.0	700.8	707.3	707.7	706.7
		SD	55.9	61.4	59.6	58.7	59.0
	2041–2070	Max	823.1	854.1	912.6	916.1	916.8
		Range	232.7	232.3	237.6	234.9	236.7
		Average	720.5	739.4	773.4	782.4	782.8
		SD	59.2	59.2	53.4	52.7	54.4
	F2 – F1	**Av. variation**	**36.5**	**38.6**	**66.1**	**74.7**	**76.1**
	2011–2070	**Slope**	**0.5**	**0.7**	**1.3**	**1.5**	**1.6**

the growing of crops well adapted to Mediterranean climate such as olive groves, and endorse the substitution of high water demanding herbaceous crops such as maize for traditionally rainfed herbaceous and woody crops, in order to increase the productivity of the irrigation water. Agricultural scenario C also aims to promote soil and water conservation and to reap benefits from the most efficient irrigation methodologies associated with woody crops (drip irrigation versus sprinkler irrigation), assuming future increasing environmental strengthens reflected on water prices. Although assuming a total irrigated area similar to AGS-A, under the most adverse CCS, the results for AGS-C show an estimated maximum total annual irrigation requirements of 823.1 hm^3 year^{-1} and 916.8 hm^3 year^{-1}, respectively for future periods 1 and 2. No significant changes were found in the annual ranges of total irrigation requirements between AGS-A and AGS-C as well as in their standard deviations and trends between the two future periods.

The results of AGS-C were partially hampered, because swapping large areas of herbaceous crops for woody crops may not provide significant benefits in minimizing water consumption, as citrus and fruit orchards have shown to respond to climate change with strong increases in water usage (Table 7). This fact limits the potential advantages of replacing typical sprinkler irrigated crops with drip irrigated crops.

The outputs of all future agricultural scenarios (AGS A, B and C) show that total irrigation water demand will likely be significantly displaced towards the public sub-sector after the completion of the Alqueva irrigation network, resulting in a relative increase of water demand in the public sub-sector between 30% and 32.5% when compared with the Present scenario. It also looks reasonable to admit that the usage of groundwater resources for irrigation in the Guadiana basin will maintain a complementary but important role in irrigated agriculture, mainly in smaller farms.

4. Conclusions

Climate change will cause substantial impacts on water requirements for irrigated agriculture in the Guadiana river basin. Future water and irrigation management decisions can depend on the correct identification of such potential climate change consequences on irrigation requirements. Although no general tendency for variation of *ETo* was identified in the present study, a general increase in net irrigation requirements of the main representative crops was identified for the five different climate change scenarios studied (CCS 1–5) and future periods 1 (2011–2040) and 2 (2041–2070).

Each crop responded in a different way, depending on the relationships, modelled by the ISAREG programme, of each growing stage and respective water requirements interacting with varying temperatures (and *ETo*) and decreasing rainfall. The crops which are well adapted to the Mediterranean climate, such as olive trees and grapevine, showed less variation in irrigation requirements under adverse climate change, indicating that the induced changes in the rainfall and air temperature do not produce significant changes in these crops estimated irrigation requirements. High water demand crops such as maize and fruit trees (citrus and others) were the crops most prone to significant increases in irrigation demands. The results also showed that herbaceous permanent crops, such as pasture and golf lawn, tended to respond more steeply under adverse climate change conditions, increasing their irrigation requirements and resulting in a higher annual variation than other short-cycle crops.

Gross annual irrigation requirement for agricultural scenario A (AGS A) is 875.2 hm^3 $year^{-1}$ for the period 2011–2040 and 966.8 hm^3 $year^{-1}$ for the period 2041–2070, under the most adverse climate scenario (CCS 5).

The results for agricultural scenario B (AGS B) indicate a steep increase of total irrigation requirements, and, under the most adverse climate change scenario (CCS-5), the total estimated irrigation requirements totalled 1300.4 hm^3 $year^{-1}$ in the period 2011–2040, and 1434.3 hm^3 $year^{-1}$ in the period 2041–2070. The inter-annual variations in total irrigation requirements for AGS-B can reach 368.2 hm^3 $year^{-1}$ for CCS-5 in the 2011–2040 period, which is higher than the historical total irrigation requirements for the Guadiana basin.

Agricultural scenario C (AGS C) showed similar results to scenario A, as the irrigated areas considered for both scenarios are equal. In fact, the swapping of herbaceous crops such as maize and fodder by woody crops did not cause a significant reduction in the overall crop water demand estimates. The substitution of maize and other spring cereals for wheat and other winter cereals with complimentary irrigation may be more effective in saving irrigation water, holding cereal yields on the years with drought and abnormally dry periods. Although olive trees showed a relatively modest increase in water use under climate change, fruit trees (citrus and other fruit orchards) have shown higher values due to its intrinsically unfavourable response to climate change.

The agricultural scenarios elaborated in this study demonstrate that crop area distribution and crop choice can be the most important factor in water use in irrigated agriculture. If properly managed, that choice of area and factors is an important means of promoting conservative and sustainable water use at the basin-scale. Therefore, it should deserve the maximum attention from planners and managers, who should take into account the present results when managing water resources in the Alentejo region, in particular the Guadiana basin. More specifically, gross irrigation requirements shown in Table 8, coupled with estimated urban and industrial uses (mainly power generation) allow for the conclusion that AGS A and C have high possibility to be sustainable, at the pace that AGS B strongly risks to be unsustainable, mainly in drought years which, on the other hand, show an increasing frequency in the future.

These conclusions may apply to all irrigated agriculture subsystems: public, private with surface reservoirs, private pumping from aquifers. However, some constraints referred to AGS B are more likely to occur in the public irrigation sector, because public large reservoirs support, cumulatively with delivering water for irrigation, urban and industrial consumption, as well as water delivery for power generation.

This study provided a quantitative approach for estimating and quantifying the possible water demand outcomes of irrigated agriculture in the Guadiana river basin. However, it is important to underline that future outcomes are also dependent on management practices and soil quality preservation (as considered in AGS-C). The intensification of irrigation will always demand a more conscientious soil management in order to prevent erosion and salinization and to maintain nutrient balance.

Although this study is focused solely on the irrigated agriculture, recognized as the most water-demanding economical sector of the Guadiana river basin, it is important to bear in mind that climate change consequences on water demand in a future water scarcity scenario go well beyond agriculture, requiring a multidisciplinary team for addressing all aspects of planning, management policy development, monitoring and evaluation enforcement, in order to accomplish an equitable allocation of water resources between all-consuming sectors, including the domestic uses, energy generation and ecological management.

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