SUSTAINABLE LAND MANAGEMENT IN AN INTENSIVELY IRRIGATED AGRICULTURE DOMAIN

Thesis report

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Illustration cover page: Rambla del Albujon

https://www.crcc.es/informacion-general/estructura-agraria/

PREFACE

This thesis is part of my graduation for the Mater study 'Civil Engineering and Management' with the specialization 'Integrated Water Management 'This finished thesis marks the end of my period at the University of Twente

The research preceding the thesis was carried out at the University of Twente. However, I had the privilege to be part of the CEBAS-CSI research centre in Murcia,Spain, where I developed the irrigation module for the hydrological model SPHY which allowed me to perform the computations for my research. I would like to thank Joris Eekhout who helped and guided me in understanding the PCraster phyton language throughout my staying in Murcia and till the end of the project. I highly appreciated your patience and comprehension. Furthermore, I would like to thank Joris de Vente and all the members of the CEBAS-CSI soil department for the way you welcomed me and for making me fell part of the amazing family you are.

From the University of Twente, I would like to thank Martijin Booiji and Joep Schyns. They both helped me in structuring and writing my thesis by providing me with useful and necessary feedback, thereby improving the quality of my thesis.

Last but certainly not least I would like to thank my family for supporting me in all my decisions. A massive thank goes out to all my friends who shape my life. To Viraj, Alan, Jay and Andre with whom I had the ultimate pleasure to spend my three years in the Netherlands. To all my friends from Torricella : Checco, Tarcio, Armando, Frischietto, 'Il Ciaccions', Passagallo, 'Il Dribla' and all the others ' Lesionati'. We achieved this goal together as will be for the next ones.

Thank you all for making me be the person I am.

I hope you enjoying reading my thesis

Kind Regards,

Luca Furii

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"Two thing defines you: Your patience when you have nothing and your attitude when you have everything"

George Bernard Shaw

SUMMARY

Global factors such as population growth and climate change continue to put increasing stress on the agricultural system and increase irrigation demands in regions suffering from water shortages. Hence, sustainable methods to optimize water use are gaining importance in arid and semi arid regions. Traditionally, agricultural research has prioritised on maximizing total production. In recent years focus has shifted to the limiting factors in production systems, notably the availability of water. Therefore, studies on water saving in intensively irrigated areas are of growing concern and Sustainable Land Management (SLM) techniques are increasingly promoted as an optimal approach to manage irrigation water supply. Therefore, the present study aims at implementing SLM techniques in a horticulture area domain suffering from water shortages to improve irrigation water use. The case study is the Rambla del Albujon catchment within the Campo de Cartagena, southern Spain, watershed one of the most important agriculture supply centre in Europe

Sustainable Land Management techniques are mainly employed in arid and semi-arid areas where the major need for development of intensive agriculture is to optimize water use and land health. Thus, the present study to improve irrigation water use, makes use of sustainable land management techniques as scheduling irrigation and crop rotation. Scheduling irrigation is the process to determine the current frequency and duration of water whilst crop rotation is the practise of growing successive cultivation of different crops in a specified order on the same fields. The SLM techniques are tested on Lettuce, Artichokes, Broccoli-Melon and Lettuce-Melon combinations which cover the entire horticulture area of the Rambla del Albujon. By analysing irrigation water use and yield as irrigation water productivity (yield / irrigation water use) and water productivity (yield/actual evapotranspiration) the effectiveness of SLM is assessed. To do so, the hydrological model SPHY is employed

As first step a baseline scenario is set to reflect the current situation within the study area in terms of irrigation water supply. Then, SLM strategies as deficit scheduling irrigation and crop rotation are implemented within the model. Two scheduling irrigation measures are evaluated both allowing a certain degree of stress to crops. The first one schedules irrigation by means of an evapotranspiration deficit. Irrigation is triggered by a difference bigger than zero between potential and actual evapotranspiration which means that not enough water is available for plant. On the contrary, the second approach rests on setting plant water stress allowance by means of a static crop water stress threshold during crop growing period beyond which irrigation is prompted Two sets of thresholds K_S1 and K_S2 are assessed to evaluate different crop response. Deficit scheduling irrigation techniques are tested with and without crop rotation. The crop rotation is simulated by changing soil organic matter and bulk density model input parameters. Organic matter content is increased of 20 percent whilst bulk density content is decreased of 5 percent.

Results show how the static crop water stress threshold approach with higher stress allowance ($K_s 2$) is the best solution to improve water use within the Rambla del Albujon. The approach results in up to 36 percent less irrigation water supply compared to the baseline scenario and a moderate reduction in production which have led to a rise in irrigation water productivity. In relation to the static crop water stress threshold approach with less stress experienced by crop, $K_s 1$, only lettuce-melon combination has reduced its yield. Nonetheless, yield losses can be offset by higher water savings which can be used to irrigate more land or for other activities. Furthermore, whether applied together with crop rotation the $K_s 2$ efficiency would increase even further. The two methods combined have led to the same production as for the baseline scenario with 36 percent less water supplied The evapotranspiration deficit turned out to be the best sustainable solution at a basin scale with an irrigation reduced up to 47 percent and just 18 percent less $\mathrm{ET_a}$rates. On the other hand, contrary to the static crop water stress approach plants experience a higher degree of stress which impairs cop quality. Furthermore, when simulated together with crop rotation the evapotranspiration deficit approach has not shown any improvement in terms of water use and yield as opposed to the static crop water stress threshold approaches. Crop rotation proved to be an effective method to improve water use in agriculture by increasing yields of crop combinations when simulated together with static crop water stress approaches. Crop rotation has shown how an improvement in soil properties positively affects irrigation water management. Thanks to SLM overirrigation has been reduced in the Rambla del Albujon. Irrigation water productivity has risen while water productivity has not changed. This highlights how without SLM too much water was delivered to crop since by reducing it the water productivity stayed the same.

CONTENTS

1. INTRODUCTION

1.1 Water use in agriculture

Water is a vital natural resource, which is becoming increasingly scarce owing to a surge in demand. Currently, the rapid growth of population along with the extension of irrigation agriculture, industrial development and climate change are stressing the quantity and the quality aspect of water (Chartzoulakis et al., 2015). The agriculture sector, production of energy, industrial uses, and human consumption are the main areas where the demand for water is high. Among the sectors enumerated agriculture is the highest intensive-user of freshwater worldwide (Hoekstra and Mekonnen, 2012) accounting for 70 percent of the total freshwater withdrawals, on average (Kogler & Soffker,2017). Water in agriculture is being used for irrigation, pesticide and fertilizer application. When agricultural water is applied effectively and safely, production and crop yield are positively affected and water losses reduced. When water is not managed accurately its misuse might lead to an increase in water application thereby reducing its availability.

As the population is growing at a rapid rate irrigation is being given an important role in increasing land use efficiency. Thus, irrigated farming is expected to expand rapidly in the future with subsequent increase of water use for irrigation (Chartzoulakis et al., 2015). The Food and Agriculture Organization(FAO,1988) estimated that almost two-thirds of the increase in crop production that is needed in developing countries in the upcoming decades must come from an increased yield per unit of water; one-fifth must come from increased arable land area and the remaining one-eighth from increased cropping intensity (Howell et al., 2001). To ensure that the expectations for food production and water use are met in a sustainable way, an effective management of water supplies is required since fresh water availability seriously limits the expansion of agricultural irrigation activities. Furthermore, continued or extended fresh water withdrawals by the agricultural sector impair seriously the sustainability of global freshwater resources (Kogler & Soffker,2017). To this end the study of water saving in irrigation is an essential requirement to increase global food supplies on a sustainable basis by means of a better management of natural resources such as water

Sustainable Land Management (SLM) can be defined as a system of technologies and or planning that aims at integrating ecological with socio-economic and political principles in the management of land for agricultural purposes (Hurni et al., 2000). SLM supports the prevention and reduction of land degradation, protects biodiversity, and includes established approaches such as conservation agriculture, cover crops, organic amendments, crop diversification, and water management (Sanz et al.,2017). The use of SLM practices is widely advocated by development organizations (World Bank and Food and Agriculture Organization) and bilateral programs (U.S. Agency for International Development) (Almagro et al., 2011) due to their capabilities to better exploit water resources for agricultural purposes as well as to increase irrigation water productivity for sustaining livelihoods. Furthermore, SLM practices may maintain or increase crop productivity while sustaining many ecosystem services such as carbon sequestration, climate change mitigation, biodiversity and resilience to natural and anthropogenic perturbation. SLM conservation practices such as reduction in tillage intensity or cover crops including leguminous species (i.e. green manure), lower energy consumption and corresponding carbon dioxide emissions (CO2) thereby increase soil organic matter

(SOM) and in turn water holding capacity. However, reduced tillage (RT) and green manure (GM) are not a common practice in semi- arid agroecosystems, because a fear of competition over water resource between green manure and the main crop (Almagro et al., 2011). Nonetheless, an improvement in soil properties can be achieved through crop rotation which refers to the cultivation of different crops on a particular piece of land over time. Crop rotation central idea is to have the crops themselves sustain soil health, rather than planting the same crop year in, year out, and then repairing soil health through fertilizers, pesticides and herbicides (Reza,2016). Keys advantages of crop rotation are increased soil organic matter, improved soil fertility and structure, increased yield and erosion control. Furthermore, it can be widely applied in semi-arid agroecosystems. Regarding SLM aiming at water management most attention has been given to Scheduling Irrigation (SI). Scheduling Irrigation is the decision-making process for determining when to irrigate the crops and how much water to apply. Irrigation timing is driven by crop's water requirement and soil water characteristics, whilst the adequacy of the irrigation method (i.e. drip, sprinkler or surface) determines the accuracy of how much water to apply. Deficit irrigation (DI) is an irrigation scheduling approach under which crops are allowed to sustain some degree of water stress whereby boosting water saving. Scheduling irrigation through deficit irrigation can be carried out by assessing soil water availability. This is the case of the static crop water stress threshold and the evapotranspiration deficit approaches. The static crop water stress threshold approach makes use of the crop water stress parameter, K_s, to proper manage plant response to water stress by setting thresholds expressing the maximum stress allowed to crops, beyond which watering is triggered. Differently, deficit scheduling irrigation through evapotranspiration deficit delivers irrigation when soil moisture stress is experienced by crops due to insufficient soil moisture content which manifest itself by means of an evapotranspiration deficit (potential ET- actual ET >0).

1.2 Current knowledge and research gap

SLM application is mainly employed in arid and semi-arid areas where the major need for development of intensive agriculture is to increase the ratio between crop yield and the amount of water involved in crop production. However, knowledge of SLM's effectiveness is mainly based on plot-scale and laboratory experiments demonstrating how SLM improves soil quality, and increase water use efficiency (Eekhout et al.,2018). Scheduling irrigation through deficit irrigation methods as the static crop water stress coefficient approach and the evapotranspiration deficit have been tested by researchers for reducing water use whilst reduction tillage, green manure and crop rotation mainly for preserving soil properties.

Fereres (2007) in his research highlights the benefits of applying deficit irrigation in water scarce area over full irrigation, where no stress is experienced by crops and their growth is fully supported by applying water. Fereres (2007) states how thanks to deficit irrigation deep percolation and transport of fertilizers and agro-chemicals out of the root-zone is controlled, optimum soil condition for plant growth is created, owing to plant roots development, and increase in water productivity is observed. Water productivity (WP) represents the relationship between crop produced and the amount of water involved in crop production (Ali et al., 2008). However, one consequence of reducing irrigation water use by deficit irrigation is the greater risk of increased soil salinity due to reduced leaching (Fereres 2007). Scheduling irrigation through deficit irrigation rest on crop water stress. Crop water stress is a deficiency in water supply detected as a reduction in soil water content or from the physiological responses of the plant to water deficit(Ali et al., 2008). Plant indicators commonly used to determine crop water status are leaf water potential and stomatal conductance, but their measurements are either destructive, labor- intensive or unsuitable for automation, which make it difficult for irrigators to adopt (Ihuoma & Madramootoo, 2017). Thus, techniques for monitoring crop water status that would provide non-destructive, rapid, and reliable estimates of plant water status are needed. Ahmadi et al (2014) carried out a study on potato field in Iran by comparing a static crop water stress approach to a dynamic one. When potatoes were allowed to experience the same amount of stress all through their growing period, static coefficient approach, a 28% increase in water productivity compared to full irrigation was observed associated with a 25 % water saving. However, when the dynamic approach was involved, both water productivity and water saving increased of 34 and 28 percent respectively. Yield losses were relatively low for the two approaches with a 10 percent reduction for the dynamic and 7 percent for the static approach. Ahmadi et al., (2014) findings were in line with Geerts (2009) in his research on horticulture crops as quinoa and wheat underscores how irrigation only needs to be scheduled during the most drought- sensitive stages, i.e plant establishment, flowering and early grain filling. Furthermore, he stressed how maximizing WP may be economically more profitable for the farmer than maximizing yields since water saved can be used to irrigate more land thereby, compensating for the economic loss due to yield reduction. However, although the deficit irrigation by means of the crop water stress parameter thresholds can be applied as a tactical measure to reduce irrigation water when supplies are limited by droughts or other factors, it is imperative to investigate the sustainability of the approach via long-term experiments and modelling efforts to determine to what extent it can contribute to the permanent reduction of irrigation water use (Kogler & Soffket 2017). Geerts(2009) underscores the need to combine field research with thoroughly calibrated and validated crop water productivity models to further improve promising deficit irrigation scheduling by means of the crop water stress parameter Ks.

Scheduling Irrigation by means of the evapotranspiration deficit approach has been tested by Batjes(2012) and Wehling (2014) for ten different crops in wester Romania. Thanks to remote sensing (RS) an accurate analysis of moisture stress experienced by crops owing to insufficient soil moisture content was obtained. Irrigation was delivered when potential Evapotranspiration (ETp) was bigger than actual Evapotranspiration (ETa). However, if on the one hand RS empowers researchers to gather information over an entire area, on the other hand RS lacks temporal resolution since satellites circumnavigate the earth and cannot be used for continuous observation (Karats et al.,2009). Moreover, satellites at some elevation are stationary to the rotation of the earth hence, it is possible to focus on one area and a several satellites are needed to know what is going on globally (Vuolo et al.,2015). Therefore, more studies on the evapotranspiration approach based just on ground data information are required to cover the time period and land over which no satellite images are available. Osroosh et al (2016) in his study on drip irrigated apple tress analyzed. scheduling through the evapotranspiration deficit by means of the Hargreaves (Hargreaves and Samani,1985) equation He stated how the approach led to a reduction in water supply compared to the crop water stress approach with dynamic threshold. Furthermore, he stressed how thanks to the evapotranspiration deficit approach was able to predict how changes in weather parameters affected plant water status

As water can be saved in agriculture by delivering it in time and by applying the right amount, saving can be achieved by means of crop rotation as well. Crop rotation's effectiveness in agriculture is mainly related to an increase in soil organic matter (SOM) (European Commission, 2010). Increased soil organic matter improves soil infiltration and water holding capacity, which enables water to be absorbed into the soil (Reza,2016). Wei et al (2020) applied four crop rotation patterns: lentil-wheat- pea, wheat-potato-lentil, wheat-maize-potato and wheat-flax-pea showing an increased in soil water content related to an almost 20 % build up in SOM owing to the rotation of legumes and two cash crops. The study was in line with Blair and Crocker (2000) who examined the effect of different rotations, including legumes, on soil structural stability, unsaturated hydraulic conductivity and the concentration of different carbon fractions and found how the carbon fraction increased compared to the monoculture scenario. The impact of crop rotation on soil quality is related to a reduction in bulk density (BD) as well. Bulk density is an indicator of soil compaction and increases with soil depth since subsurface layers have reduced SOM, aggregation and root penetration which in turn reduce soil pore space thereby porosity decreases. A high bulk density is detrimental to soil functions, because it reduces gas and liquid flow, root growth and water infiltration (European Commission, 2010). Karlen et al (1994) and Reevers (1997) stated that any practise that improves soil structure leads to a reduction in bulk density. Liu (2003) in a five years cultivation under wheat-soyabean rotation reported a development of soil organic matter along with a decrement of 5 % in bulk density content.

1.3 Problem statement & research objective

SLM methods have been tested and have proven to contribute significantly to improve soil quality and to reduce water use in intensively irrigated land. Nevertheless, more researches in the field are required to see their impact in reducing water consumption in the long run since very few studies assessed the performance of sustainable land management to improve water use in agriculture. Besides, studies comparing the efficiency of SLM scenarios to advance water productivity in intensively irrigated agriculture are yet to be carried out. Therefore, the goal of this research is:

To evaluate the effectiveness, in terms of water use and production, of deficit irrigation scheduling and crop rotation in intensively irrigated agriculture to reduce irrigation water supply

The efficiency of the sustainable land management techniques is appraised in the semi -arid catchment of the Rambla del Albujon within the Campo de Cartagena watershed in the region of Murcia, southern Spain. The Rambla del Albujon overlaps almost entirely with the basin of the Campo de Cartagena which despite the adverse conditions, one of the driest in Europe (Europe Environment Agency, 2016), is one of the most important agricultural supply centers in Europe (Castejon-Porcel et al., 2018) Measures to withstand intensive irrigated agriculture to keep up with the surge in food demand are of growing concerns. Therefore, the objective of this study is to implement SLM techniques as deficit irrigation scheduling and crop rotation to decrease water use in the catchment of the Ramble del Albujon. The effectiveness of the SLM techniques is evaluated on four crop combinations. The sustainable land management measures are assessed through the hydrological model SPHY. The SPHY model, thanks to its capability of producing spatially distributed maps of root water content and evapotranspiration deficit enables both the identification of locations where irrigation is required and a quantitative assessment of crop water stress.

1.4 Research questions

To achieve the research objective, four research questions need to be answered:

1) *To which extend does the baseline scenario reflect the current situation within the Ramble del Albujon in response to irrigation supply?*

The first research question aims at creating the baseline scenario for the project. A realistic simulation of the current situation of the study area is paramount to assess the effectiveness of each SLM scenario. The accuracy of the baseline scenario is appraised by comparing the model output with available data upon the irrigation delivered to the horticulture area and yield within the Rambla del Albujon.

2) *How has the evapotranspiration deficit technique affected irrigation water use and yield compared to the baseline scenario?*

Deficit scheduling irrigation by means of the evapotranspiration deficit techniques is assessed with regards to the baseline scenario. A comparison between the two irrigation techniques is carried out in terms of irrigation water supply and yield. Furthermore, time series are shown to give insights into irrigation frequency and plant stress

3) *How have irrigation water use and production changed compare to the baseline scenario when the static crop water stress threshold approach is employed?*

As for the previous research question, irrigation water supply and production owing to a deficit scheduling irrigation method are assessed with regards to the baseline scenario. The research question focuses on the crop stress approach with a static threshold technique. Irrigation frequency is assessed by means of time series.

4) *To which extend has crop rotation contributed to reduce irrigation water use and yield within the Rambla del Albujon?*

A crop rotation simulation is carried out by changing soil parameters within the hydrological model. The degree of variation is assessed by means of literature study and a sensitivity analysis. The crop rotation impact on water use and production within the study area is evaluated along with the scheduling irrigation deficit techniques.

5) *How crop combinations responded to SLM implementation in terms of water use and yield?*

The effectiveness of sustainable land management techniques is assessed for each crop combination in respect of water use and production. The response of each crop combination is analyzed and the efficiency of each sustainable land management measures evaluated. All comparisons are with regard to the baseline scenario water use and production.

1.5 Report outline

The report opens with a description of the study area and the main crop cultivated within. Secondly, the hydrological model SPHY is described. Here, insights on model relevant formula for the sustainable land management calculation are shown. Once the model has been explained the report makes clear the methods and data employed all through the project. Then, results are displayed followed by a discussion chapter where limitations, comparison with other projects and hurdles due to SLM practical implementation are argued. The report signs off with conclusions and recommendations for further studies

2. STUDY AREA

2.1 Rambla del Albujon

La Rambla del Albujon is located in the Mar Menor coastal lagoon in the region of Murcia, Spain and constitutes the drainage network of the Campo de Cartagena. The Albujon wadi is the major watercourse in the catchment and drains, together with several smaller, so called tramblas (ephemeral water courses with non- continuous flow), into the Mar Menor (Stefanova et al., 2015). The wadi is born in the surrounding mountains of Sierra de Carrascoy, Sierra del Algarrobo, Sierra de las Victorias, Sierra de Los Gomes (Marin & Castillo, 2016). The catchment of Albujon comprises 17 sub-catchments with size ranging from 38 and 55 km^2 while the all surface area is of 782 km^2. Geomorphologically, the catchment is characterized by moderate elevations averaging from 0.4% next to the mouth to 5.8 % close to the mountains. The morphology follows the Campo de Cartagena, mainly covered by agriculture crops with also scattered areas of wooded in the mountains where coniferous and scrubs formation can be found (Marin & Castillo,2016). Figure 1 gives an overview on the heterogenous land use distribution in Rambla del Albujon catchment. Furthermore, the picture displays the Rambla del Albujon location within the Campo de Cartagena catchment. It is covered by a compound mosaic cover class which integrates an irregular pattern of different land use classes among which rainfed and irrigated intensive agriculture have the biggest share. The climate is semi-arid Mediterranean, characterized by dry and hot summers and mild winters. The mean annual temperature is about 18 °C, and the mean annual precipitation about 300 mm, mostly occurring during short episodic storm events in autumn and spring. The estimated potential evapotranspiration is about three times higher than the mean annual precipitation and ranges between 800 mm/y and 1200 mm/y (Stefanova et al., 2015)

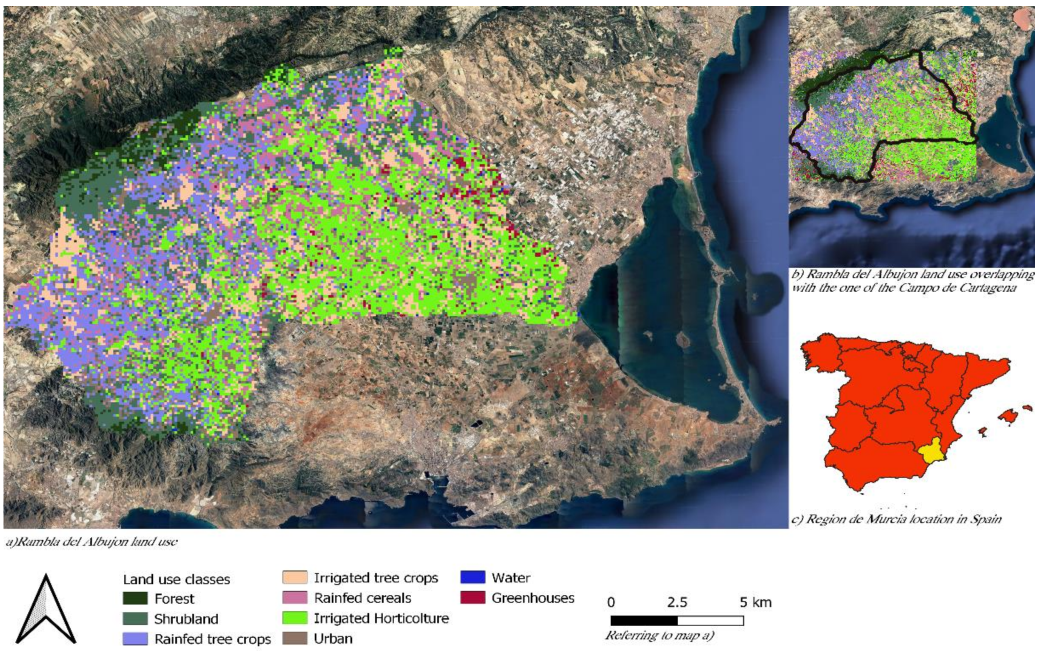

Figure 1. Overview land use Rambla del Albujon. In the Campo de Cartagena(Cdc) Figure a) displays the Rabla del Albujon land use, while Figure b) displays the Rambla del Albujon land use share along with the one of the CdC. FIgure c) gives information about the geographical location of the Region de Murcia in Spain

2.2 Agricolture in the Rambla del Albujon

The agriculture sector within Rambla del Albujon reflects the Campo de Cartagena activities. Despite the adverse climatic conditions, the region is one of the main producers of agricultural products nationally and internationally (Castejon-Porcel et al., 2018, Aparicio et al., 2017). The insolation and quality of its soil have contributed to the generation of intensive agriculture activity with high productivity which has made the Campo de Cartagena one of the most important agricultural supply centres in Europe (Castejon-Porcel et al., 2018). Irrigated farmland comprises an area of approximately 300 km^2 with 128.1 km^2 of annual row crops, 34.1 km^2 of perennial vegetables, and 136.8 km^2 of fruit trees. Drip Irrigation is the primary irrigation method due to water scarcity and requirement of water conservation, deployed in 95 % of the area. (Alcon et al.,2011). Within the irrigated area the predominant crops, in order of importance, are vegetables (lettuce, melon, artichoke and broccoli), citrus (lemon, orange and mandarin) and greenhouses crops (pepper) (Estructura Agraria,2011; Jimenez- Martinex et al., 2009; Castejon–Porcel et al., 2018; Contreas et al., 2014; Soto-Garcia et al., 2013). Lettuce has become a horticultural species to which a large area of land is dedicated and given its short cycle, between 45 and 90 days, two consecutive plantations are usually made. It is usually planted from September, to keep the markets supplied. Broccoli is another crop incorporated in recent years, suitable for industrialization. It is planted from September to be harvested in December and can be planted again in January and collected in March. Melon, which is still a traditional species in the area, is planted from mid-March, in plastic mulch and also in a tunnel, and its cultivation remains until July. Artichoke is transplanted in summer, in July - August, and its cultivation is maintained for two seasons (Estructura Agraria,2011). In plots dominated by row crops, rotation of autumn-winter (e.g. lettuce, artichokes and broccoli) and spring summer (e.g. melon) crop is a common practice (Jimenez-Martinez et al., 2011).

3. SPHY

The Spatial Processes in HYdrology (SPHY) model (Terink et al., 2015) is a spatially distributed leaky bucket type of model, and is applied on a cell-by-cell basis. The hydrological model simulates the most relevant hydrological processes, such as interception, evapotranspiration, dynamic evolution of vegetation cover, including seasonal patterns and response to climate change, surface runoff, and lateral and vertical soil moisture flow. Hydrological processes are described in a conceptual way so that changes in storages and fluxes can be assessed adequately over time and space. SPHY is written in the Python programming language using the PCRaster dynamic modelling framework (Terink, et al., 2015). SPHY is grid based and represents averages over a cell. The SPHY soil column structure consists of two upper soil storages, rootzone and subzone, and a third ground-water storage, see Appendix A1. One of the characteristics of SPHY is to enable the user to turn on/off modules (processes) that are relevant/ irrelevant for the area of interest. All modules can run independently of each other, except for the glacier module (Terkin et al., 2015). Table 1 shows all modules present in SPHY and the ones deployed throughout the project. Soil hydraulic properties are computed by the model using textures (sand, silt, clay) and organic matter as input, which are obtained from SoilGrids (Hengl et al.,2017). Then are combined with the most up to date pedo-transfer function to compute the soil hydraulic properties. The pedo-transfer functions are obtained from Saxton and Rawls (2006)

Table 1.SPHY modules

SPHY modules	Switched on
Glacier	
Snow	X
Routing	X
Lakes	
Reservoirs	
Dynamic vegetation	
Groundwater	X
Sediment (calculates sediment yield)	
Sediment transport (Indicates sediment will be routed through the channel network)	
Irrigation	X

The SPHY model does not feature any irrigation module. In the present project the Irrigation module has been implemented within the model in order to represent the current situation within the Campo de Cartagena and to assess SLM techniques. In previous studies the model turned out to be a suitable tool for application in agricultural water management by facilitating easy integration of remote sensing data whereby all relevant soil water fluxes correspond to crop development stages all through the growing season (Terink et al., 2015). However, the current project does not make use of remote sensing data and the amount of water to be supplied will be evaluated by means of the single crop coefficient (kc) (Brouwer and Heibloem

,1986) and the soil water stress conditions (Allen et al., 1998). The model runs on a daily basis and irrigation in the first day of the model run has been set to zero. Then the amount of water supplied, based on the approach chosen, is added as input for the following day.

3.1 Root water balance

The Root Water Balance (RWB) gives information on the amount of water depleted in the rootzone and on the volume of water supplied. Following a rain or irrigation event water takes few hours in case of a sandy soil whilst, up to two or three days in case of clay soil before it becomes available for crop growth (Brouwer et al., 1986). After drainage from the saturation zone has finished the large soil pores are filled with both air and water while the smaller pores are still full of water. At this stage, which is considered to be ideal for crop growth, the soil is said to be at field capacity(FC). Little by little the water stored in the soil is taken up by plants roots or evaporated from the topsoil into the atmosphere. The dryer the soil becomes, the more tightly the remaining water is retained and the more difficult it is for plant roots to extract water. At a certain stage, the uptake of water is not sufficient to meet the plant's need. The plant therefore loses freshness and wilts, leaves change colour from green to yellow and finally the plant dies. The soil water content where the plant dies is called permanent wilting point (PWP). The difference between FC and PWP, is the Total Available Water (TAW). TAW is the amount of water that a crop can extract from its root zone and its magnitude depends on the type of soil and the rooting depth (Z_r) .However, although water is theoretically available until wilting point, crop water uptakes is reduced well before wilting point is reached. The fraction of TAW that a crop can extract from the root zone without suffering water stress is referred to as the Readily Available Water (RAW). The RAW is the product of TAW and the depletion fraction (d). Figure 2 gives information about the root zone content and displays TAW and RAW

$$TAW = (\theta_{FC} - \theta_{PWP}) * Z_r \qquad [mm] \tag{1}$$

Where θ_{FC} is the soil water content at field capacity (-) ,θ_{PWP} is the soil water content at wilting point (-) and Z_r the crop root depth (mm)

$$RAW = d * TAW \qquad [mm] \tag{2}$$

Where the depletion fraction *d* is equals to :

$$d = d_{tabular} + 0.04(5 - ET_{pot}) \tag{3}$$

Where $d_{tabular}$ is a land use specific tabular value of the depletion fraction (-) and ET_{pot} is the potential evapotranspiration (mm). Values for the land use specific tabular value of the depletion fraction can be obtained from Table 22 in Allen et al (1998)

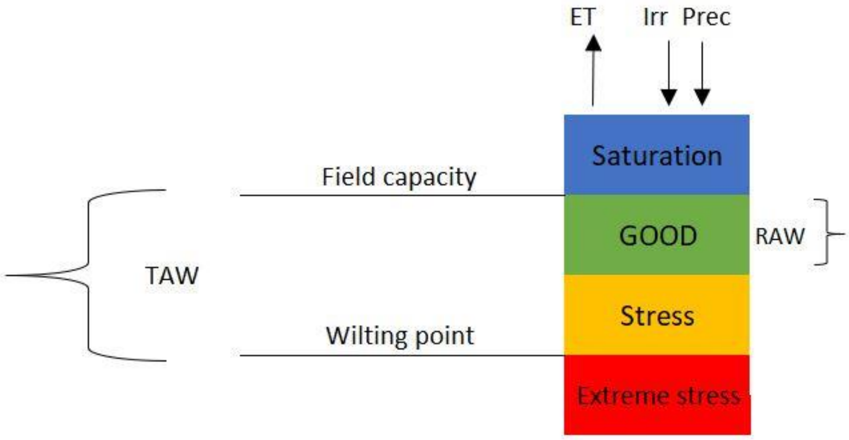

Figure 2. Root zone content. RAW and TAW concept displayed

3.2 Potential and actual evapotranspiration

SPHY is a water-balance model it only accounts for stresses related to water shortage or water excess (Terink et al.,2015). To this end, to estimate Actual Evapotranspiration, it makes use of two reduction parameters. $ETred_{wet}$ the water excess parameter with a value equal to 0 if the soil is saturated otherwise 1 and $ETred_{dry}$, the water shortage reduction parameter. In the current version of SPHY the water shortage reduction parameter has been changed using the method proposed by Allen et al (1998) (Eekhout et al 2018). It ranges from 1 optimal plant condition and 0 no root water uptake at all. The computation works as follow

$$ETred_{dry} = \frac{TAW - D_r}{(1-d)TAW} \quad (4)$$

Where $ETred_{dry}$ is the reduction parameter for water shortage [-], TAW is the total available water in the root zone (mm) in equation 1, D_r is the root-zone depletion (mm) and *d* is the depletion fraction. The root-zone depletion D_r is defined as

$$D_r = \theta_{FC} - \theta \quad (5)$$

Where θ is the current soil water content (mm)

The $ETred_{dry}$ is then used to compute the Actual Evapotranspiration which works as follow

$$ET_a = ET_p * ETred_{wet} * ETred_{dry} \text{ [mm]} \quad (6)$$

Where ET_p

$$ET_p = K_c * ET_{ref} \text{ [mm]} \quad (7)$$

ET_{ref} is defined by the Hargreaves equation (Hargreavs and Samani 1985) and represents the evapotranspiration rate from a large area, covered by grass, 8 to 15 cm tall, which grows actively, completely shades the ground and which is not short of water (Allen et al.,1998)

The SPHY model computes the crop water stress coefficient ,K_s. The latter gives information onto plant response to water shortage and is calculated in the same way as the $ETred_{dry}$. The way of computing the coefficient is the same shown in equation 4 with the difference that K_s values ranges between 0 optimal plant water condition and 1 fully stressed. Therefore:

$$K_s = (1 - ETred_{dry}) \quad (8)$$

4. METHODS AND DATA

This chapter elaborates on the methods and data used to achieve the objective and answer the research questions. Firstly, insights are given into the crops used throughout the project ,by showing their growing period and land coverage . Secondly, the baseline scenario is discussed in paragraph 4.2.Thirdly, the SLM techniques, deficit scheduling irrigation and crop rotation are argued in section 4.3. Finally, the performance parameters employed to assess the effectiveness of the SLM methods are described

4.1 Crop combinations

Based on the data retrieved four main irrigated crops (Broccoli, Lettuce, Artichokes and Melon) are used as case study in this project. Lettuce, Broccoli, Melon and Artichokes growing periods and their relative crop coefficient (Kc) are assessed. The crop coefficient incorporates crop characteristics and averaged effects of evaporation from the soil (Allen et al., 1998). A growing season is the period of the year when crops grow successfully. The total growing period (in days) is the period from sowing or transplanting to the last day of the harvest. The type of crop and variety, the climate, and planting date are the factors mainly influencing the growing period. Once the total growing period is known, the duration (in days) of the various growth stages has to be determined. The total growing season of a crop can be divided into four growth stages (Brouwer et al., 1989). Growth stages are shown in Figure 3. The four growth stages are:

The Initial stage: this is the period from sowing or transplanting until the crop covers about 20% of the ground

The Crop development stage: this period commences at the end of the initial stage and lasts until the full ground cover has been reached (ground cover 70- 80%); it does not necessarily mean crop is at its maximum height

The Mid-season stage: It begins at the end of the crop development stage and lasts until maturity; it includes flowering and grain- setting

The Late-season stage: this phase starts at the end of the mid-season stage and finishes when harvesting; it includes ripening

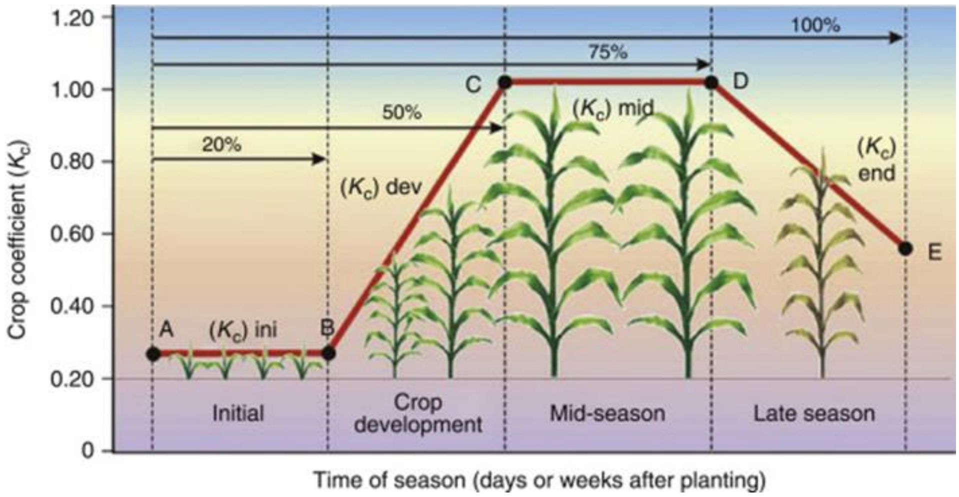

Figure 3.Crop growth stages.

According to Estructura Agraria (2011) and Martin-Gorriz et al (2014) Lettuce, Melon, Broccoli and Artichokes cover the biggest share of the irrigated land in the Campo de Cartagena catchment. Data on the Rambla del Albujon were not available hence, data on crop cover in the Campo de Cartagena were clipped to the study area by means of QGIS. Computation is described in the Appendix A2. To better assess the baseline and SLM scenarios the four crops have been divided in four different crop combinations with the aim of representing the current situation within the study area. One with a double cycle of lettuce, one with artichokes and the other two with Broccoli-Melon and Lettuce-Melon. The growing period length for each combination is displayed in Figure 4 and 5 while each crop growth stage length and crop coefficients for each stage are shown in Table 2. Table 3 holds crop combination surface area while Figure 6 shows their location within the study area. Crop coefficients for Lettuce, Melon, Artichokes and Broccoli come from Brouwer (1986).When no crops are on the field a Kc for a bare soil of 0.15 has been employed (Pocas et al., 2015)

Table 2. Crop growth stages length and relative crop coefficient for the four combinations. L_in corresponds to the initial stage, L_dev to the development stage, L_mid to the mid-season stage and L_late to late season stage. For each growth stage there is the respective Kc.

CROP	***L_ in***	***L_dev***	***L_mid***	***L_late***	***Tatal (days)***	***Kc_in***	***Kc_dev***	***Kc_mid***	***Kc_late***
Lettuce	20	30	15	10	**75**	0.45	0.6	1	0.9
Broccoli	20	20	40	10	**90**	0.45	0.75	1.05	0.9
Melon	30	30	50	30	**140**	0.45	0.75	1	0.75
Artichokes	20	20	200	30	**270**	0.5	0.7	1	0.95

Table 3. Crop combinations surface area

Crop combination	Surface area (km^2)
Lettuce	4324
Artichokes	6360
Broccoli-Melon	9104
Lettuce-Melon	2312

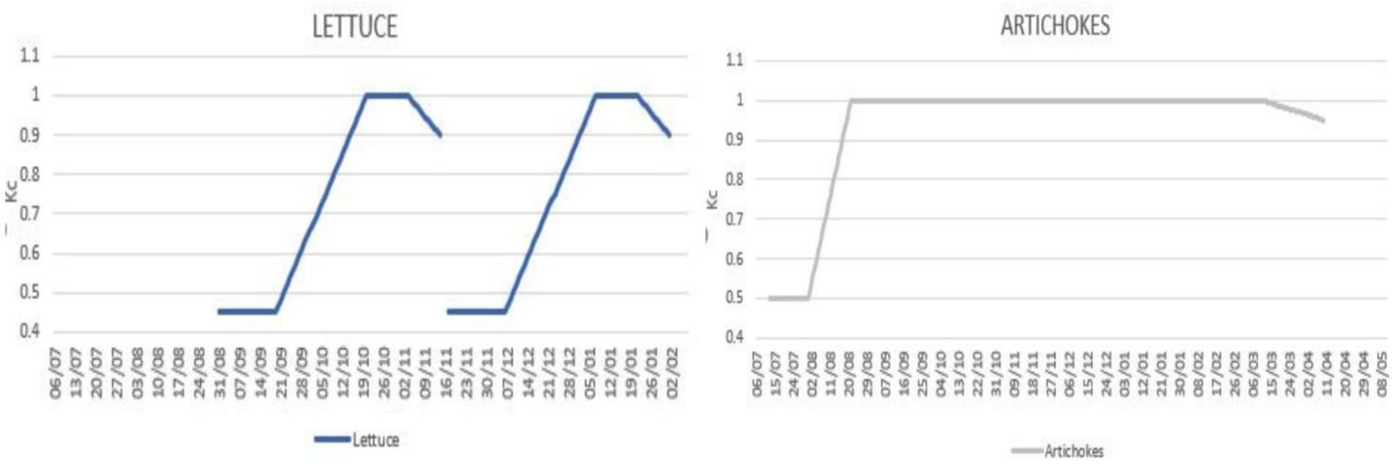

Figure 4.Lettuce (a) and Artichokes(b) growing period length.

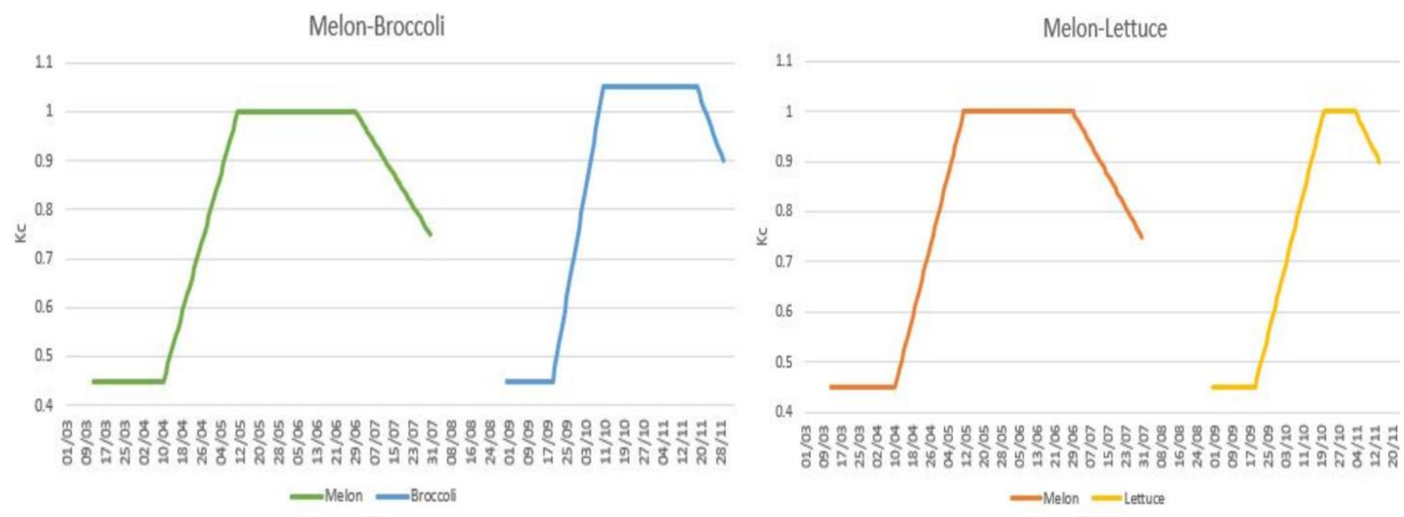

Figure 5.Melon-Broccoli (a) and Melon-Lettuce (b) growing period length

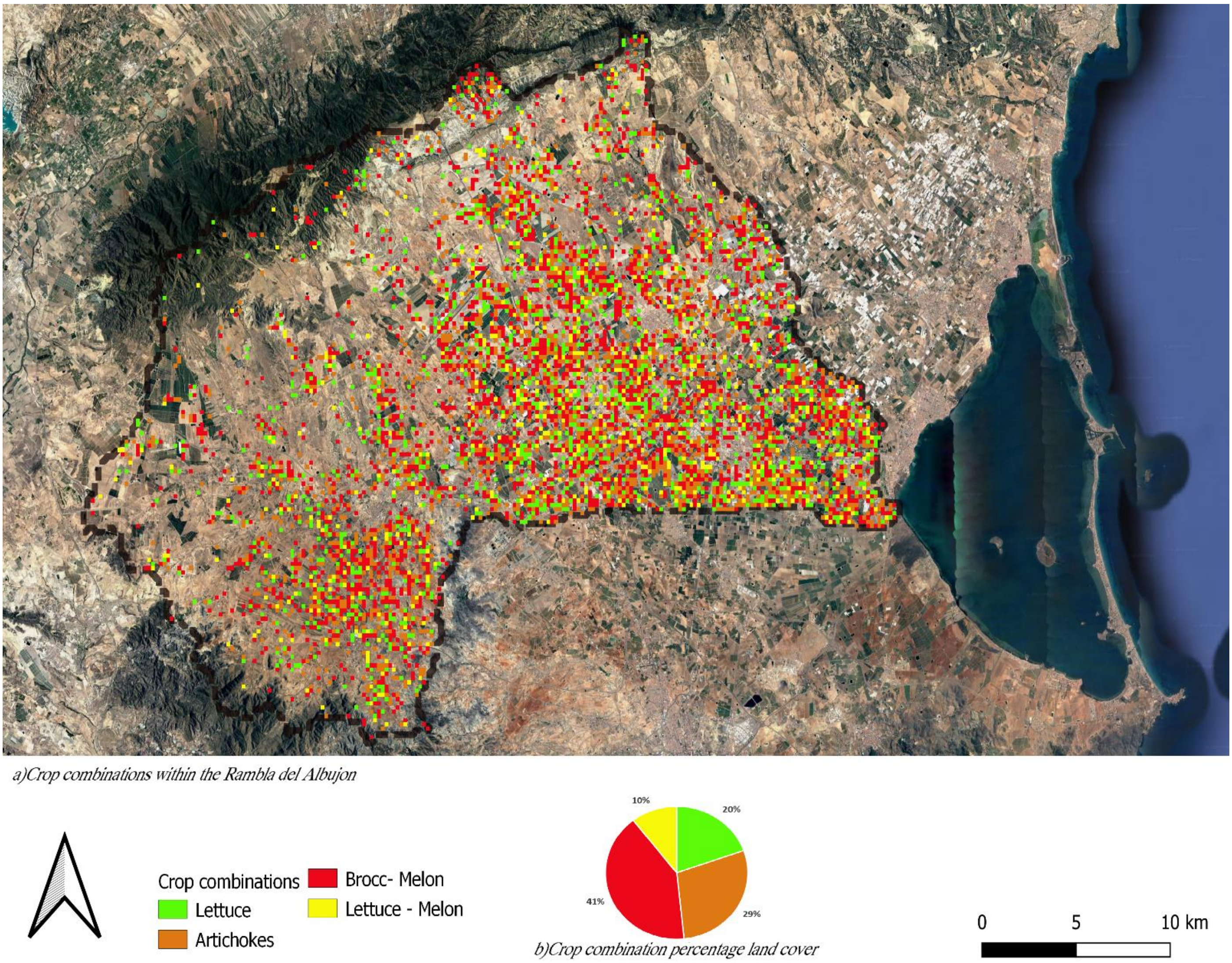

Figure 6. (a)Crop combination within the Rambla del Albujon. (b) crop combinations percentage land cover

4.2 Baseline scenario

In order to represent the current situation within the Rambla del Albujon the soil water balance (SWB) approach has been used (Allen et al., 1998). The approach reflects the full irrigation methods according to which no stress is experienced by crops during their growing period because the soil moisture in the root zone is allowed to fluctuate between an upper limit approximating field capacity and the lower limit of the RAW, referred to as the threshold, above which crop begins to experience water stress (Ket et al.,2018) Irrigation is required when rainfall is insufficient to compensate for the water lost by evapotranspiration. Therefore, the primary objective of irrigation is to apply water. at the right time period and in the right amount by calculating the soil water balance of the rootzone on a daily basis (Allen et al.,1998). The study area suffers from water scarcity hence, it was inferred that the amount of water delivered to crops occurred when the root zone was below its field capacity. Thus, the RAW content has been depleted till a certain percentage of its volume and then refilled. Four RAW depletion thresholds and two replenishment rates have been tested to see which one suited the case study for the baseline scenario the best. Irrigation was prompted every time the RAW content reached the depletion threshold. The depletion thresholds have been set to 90, 80,70 and 60 percent of the RAW depletion content. Then, once beyond the threshold the RAW has been refilled to 10 and 30 percent of its volume. The small replenishment rates are meant to reflect drip irrigation standards according to which water has to be delivered in small amounts but frequently. Furthermore, crops in the field feature shallow roots hence little water can be stored in the rootzone and frequent but small irrigation applications are needed (Brouwer et al., 1989). The irrigation water supply, regarding the RAW depletion rate, is diverted before crops would experience stress. When two crops are into the field the mean is taken for depletion factor (d). A standard, rooting depth (Z_r) of 500 mm has been used for all four rotations. Allen (1998) reports that the maximum crops root depth for each single crop considered in this analysis swings between 0.4 and 0.8 (m) hence, the predefined (Z_r) has not been changed. Soil water balance approach computations within the model SPHY is shown in the Appendix A1-SPHY, Figure 20

4.3 Evapotranspiration deficit

The evapotranspiration deficit approach rests on delivering water to the field all the time not enough water is available for crops. The water shortage is expressed through evapotranspiration deficit. When the difference between potential and actual evapotranspiration is bigger than zero means that there is water shortage hence, not enough water is available for crops. The amount of irrigation is equal to the difference expressed by the Evapotranspiration deficit. The ET_a and ET_p computations is provided in equation 6 and 7. For normal irrigation planning and management purposes, for the development of basic schedules, and for most hydrological water balance studies, average crop coefficients are relevant and more convenient than the K_c computed on a daily time step using a separate crop and soil coefficient (Allen et al., 1998). For the present study the K_c values for each crop have been previously shown in Table 2. When two crops are present as in the case of Lettuce-Melon and Broccoli-Melon crop combinations, K_c values of both crops are considered in the same year without any overlapping as shown in Figure 4 & 5 . As for the baseline scenario evapotranspiration deficit calculation in the model SPHY are shown in Figure 21 and 22 - Appendix A1.

4.4 Static crop water stress threshold

Scheduling Irrigation by means of a static crop water stress threshold approach entails a static amount of stress to the crops throughout their growing period. Studies have highlighted how crops react differently to water stress in different growth stages by suggesting distinct crop water stress coefficients ($\mathrm{K_s}$) throughout the growing period. However, the project makes use of a single crop water stress coefficient ($\mathrm{K_s}$) for each crop combinations during the different crop growth stages. $\mathrm{K_s}$ thresholds choice has been done by following researches according to which not too much leeway was allowed in terms of water stress to vegetables featuring shallow roots as lettuce, and broccoli as well as to perennial crops as artichokes. Allen (1998) ranks vegetables as highly sensitive crops to water shortages. The only crop which sensitivity is rated as medium-high is melon (Allen et al., 1998). Furthermore, low values of $\mathrm{K_s}$ might lead to a higher water saving to the detriment of a valuable yield. $\mathrm{K_s}$ values for each rotation are shown in Table 4. Two sets of $\mathrm{K_s}$ values were tested to appraise crop's behaviour to different stress conditions and how it would impact their yield and productivity. A replenishment rate of 10% of the RAW has been employed. The refilling rate has been set based on the one selected for the baseline scenario. Further details about previous studies on the crop's sensitivity employed in this study and their thresholds can be found in Appendix A3 while the approach computations in the model SPHY are shown in Figure 21 and 22 , Appendix A1

Table 4. Static crop water stress thresholds

Land Use	***Ks1***	***Ks2***
Lettuce	*0,15*	*0,3*
Artichokes	*0,15*	*0,3*
Broccoli-Melon	*0,25*	*0,4*
Lettuce- Melon	*0,25*	*0,4*

4.5 Crop rotation

The model SPHY is not suitable for assessing the development of soil health over time, since such carry-over effects are not included in the model. Nevertheless, soil input map parameters as organic matter and bulk density can be modified to simulate a crop rotation. A sensitivity analysis has been carried out to see model sensitivity to a variation in organic matter and bulk density, on irrigation amount and actual evapotranspiration. The sensitivity analysis has been tested on the baseline scenario and the two deficit irrigation scheduling approaches. A one at the time approach has been used where one parameter has been changed while the others have been kept constant. The soil organic matter and bulk density maps have been changed with ± 20, 40 ,60 percent of their initial content. Broad ranges have been selected by dealing with a sensitivity analysis and not with an assessment of effects of real measures. The sensitivity analysis, which results are held in Appendix A6, illustrates a model sensitivity to only a ± 20 percent variation in organic matter while better response is observed to a bulk density variation. The sensitivity analysis outcomes along with the aforementioned literature study researches upon crop rotation impact on soil organic matter (Wei et al., 2020) and bulk density (Liu et al., 2013) have led to a change of + 20 percent of soil organic matter content and – 5 percent of bulk density content. The crop rotation simulation has been applied to the two deficit irrigation scheduling techniques

4.6 Performance indicators

The effectiveness of each SLM techniques is evaluated by means of the water productivity. Water productivity (WP) is a useful indicator for quantifying the impact of irrigation scheduling decisions with regard to water management. In a crop production system WP is often considered along with the irrigation water productivity (IWP). Irrigation water productivity is used to define the relationship between crop produced and the amount of water delivered to crops (Ali et al.,2008). Irrigation water productivity computation works as follow:

$$IWP = \frac{Yield\ [Ton/ha]}{Irrigation\ water\ application\ [m^3\ ha^{-1}]} \tag{9}$$

While water productivity is expressed as the ratio between the yield and the actual evapotranspiration:

$$WP = \frac{Yield\ [Ton\ /ha]}{actual\ evapotranspiration\ \ [m^3\ ha^{-1}]} \tag{10}$$

Yield computation is not featured in the model SPHY therefore, an external equation has been used to estimate the earnings from each crop combination . The equation rests on the yield response factor K_y. K_y is a factor that describes the reduction in relative yield according to the reduction in evapotranspiration caused by soil water shortage (Doorenbos and Kassam 1979). Specifically, the yield response to ET is expressed as:

$$(1 - \frac{Y_a}{Y_m}) = K_y(1 - \frac{ET_a}{ET_m}) \quad (11)$$

Where:

Y_a = actual yield [Kg/ha]

Y_a= maximum yield [Kg/ha]. The maximum yield is defined here as the harvested yield under conditions where water, nutrients, pests, and diseases do not limit the crop growth (Doorenbos and Kassam 1979)

K_y = yield response factor [-]. The Ky values are crop specific and vary over the growing season according to growth stages. A K_y >1 means crop response is very sensitive to water deficit while a

K_y<1 crop is more tolerant to water deficit and recovers partially from stress and K_y =1 means yield reduction is directly proportional to reduced water used (Doorenbos and Kassam 1979). K_y values for each land use class are shown in Table 5

ET_a = actual evapotranspiration [mm]

ET_m = represents the maximum evapotranspiration(mm) when crop water requirements are fully met namely (ET_p) (Doorenbos and Kassam 1979)

Table 5. Ky values for each crop combination

Crop combinations	Ky	Reference
Lettuce	1.07	*Effect of deficit irrigation on curly lettuce grown under semiarid conditions (Kuslu et al., 2008)*
Artichokes	1.04	*Determination of the yield response to water for two different artichokes cultivars (Yilmaz et al., 20016)*
Broccoli – Melon	0.97	*Irrigation depth and yield response factor in the productive phase of yellow melon (De azevedo et al.,2016) , Deficit Irrigation effects on broccoli yield (Ayas et al., 2011)*
Lettuce – Melon	0.99	*Irrigation depth and yield response factor in the productive phase of yellow melon (De azevedo et al.,2016). Effect of deficit irrigation on curly lettuce grown under semiarid conditions (Kuslu et al., 2008)*

As it occurs all through the project when two crops are in the field, the mean of each crop value has taken into account. According to literature for Broccoli and Melon K_y equals to 1.04 and 0.91 respectively. The computation of yield not only gives a better insight into how each scenario contributes to reduce water use in the study area but allows the calculation of the water productivity for each scenario

5. RESULTS

The section encompasses model results to the irrigation methods implemented. The model SPHY has run for thirty years starting on January 1 1985 and ending on December 31 2015. The first-year model run has been skipped as spin up year.

5.1 Baseline scenario

In order to choose the best scenario for the case study the irrigation output of the 8 combinations has been compared to the reference irrigation supply of 4800 $\mathrm{m}^3/\ \mathrm{ha}/\ \mathrm{y}$ Table 6 displays irrigation amount of each depletion threshold for the two refilling rates. It stands out how an increase in replenishment rate is associated to a rise in irrigation. This is due to the fact that the root zone reaches earlier the 60 percent depletion than 90 percent thereby the watering is higher for a smaller depletion rate. In other words, irrigation intervals are more frequent for a lower depletion rate than for a higher depletion rate. For a 10 percent RAW refilling rate, a 90-depletion scenario delivers 4450 $\mathrm{m}^3/\ \mathrm{ha}/\ \mathrm{y}$ of water contrary to 5050 $\mathrm{m}^3/\ \mathrm{ha}/\ \mathrm{y}$ by 60 %. The wettest scenario is the RAW 60% depletion with a replenishment rate of 30 % where the 70 % of the root- zone capacity is reached. The 70 percent scenario with a 10 % replenishment shows a 4750 $\mathrm{m}^3/\ \mathrm{ha}/\ \mathrm{y}$ water addressed to the root zone while 5600 $\mathrm{m}^3/\ \mathrm{ha}/\ \mathrm{y}$ for a 30% replenishment rate with an increase in 18% in water delivered. Considering the reference of 4800 $\mathrm{m}^3/\ \mathrm{ha}/\ \mathrm{y}$ among the 8 combinations, the one represented the baseline scenario the best is the RAW 70 % depletion with a replenishment rate of 10 %. The scenario is then used as reference to assess the effectiveness of SLM techniques.

Table 6 RAW depletion and refilling rate scenarios at comparison for each crop combination. Data in $\boldsymbol{m}^3$/ha

	RAW 90% depleted		**RAW 80% depleted**		**RAW 70% depleted**		**RAW 60% depleted**	
RAW refilled by	10%	30%	10%	30%	10%	30%	10%	30%
Lettuce	*1000*	*1300*	*1010*	*1340*	*1050*	*1350*	*1100*	*1370*
Artichokes	*1000*	*1100*	*1070*	*1140*	*1120*	*1100*	*1150*	*1230*
Broc-Melon	*1900*	*2260*	*1960*	*2320*	*2010*	*2400*	*2200*	*2450*
Lett - Melon	*550*	*700*	*560*	*700*	*570*	*750*	*600*	*750*
Total	*4450*	*5400*	*4600*	*5500*	***4750***	*5600*	*5050*	*5800*

To appraise model behaviour in relation to precipitation, irrigation and $\mathrm{ET_a}$ frequency time series have been analysed for the RAW 70% depletion with a 10 % recharge scenario. The model behaved homogeneously throughout the thirty years model run therefore, four years have been displayed to make the time series more visible and understandable whilst the remaining years are held in the Appendix A7. The SPHY model responded well to the inputs given, as crop expressed no stress. Figure 7 shows how $\mathrm{ET_p}$ and $\mathrm{ET_a}$ values overlap all during the crops growing period this is due to the fact that $\mathrm{ETred}_{\mathrm{dry}}$ was 1 or very close to one meaning optimal conditions for plant to grow. No irrigation has occurred after precipitation events since rainfall has contributed to refill the RAW which depleted to 70 percent of its content days later thereby delaying irrigation application. This is confirmed by Figure 8 which shows how part of the precipitation has run off. However, the root zone was never saturated. $\mathrm{ETred}_{\mathrm{wet}}$ kept a constant value of 1. It has never reached 0 as no flat trend for ET arisen. This might be explained by the fact that run off occurred due to infiltration excess surface runoff after that heavy rainfall has exceeded the soil infiltration capacity.

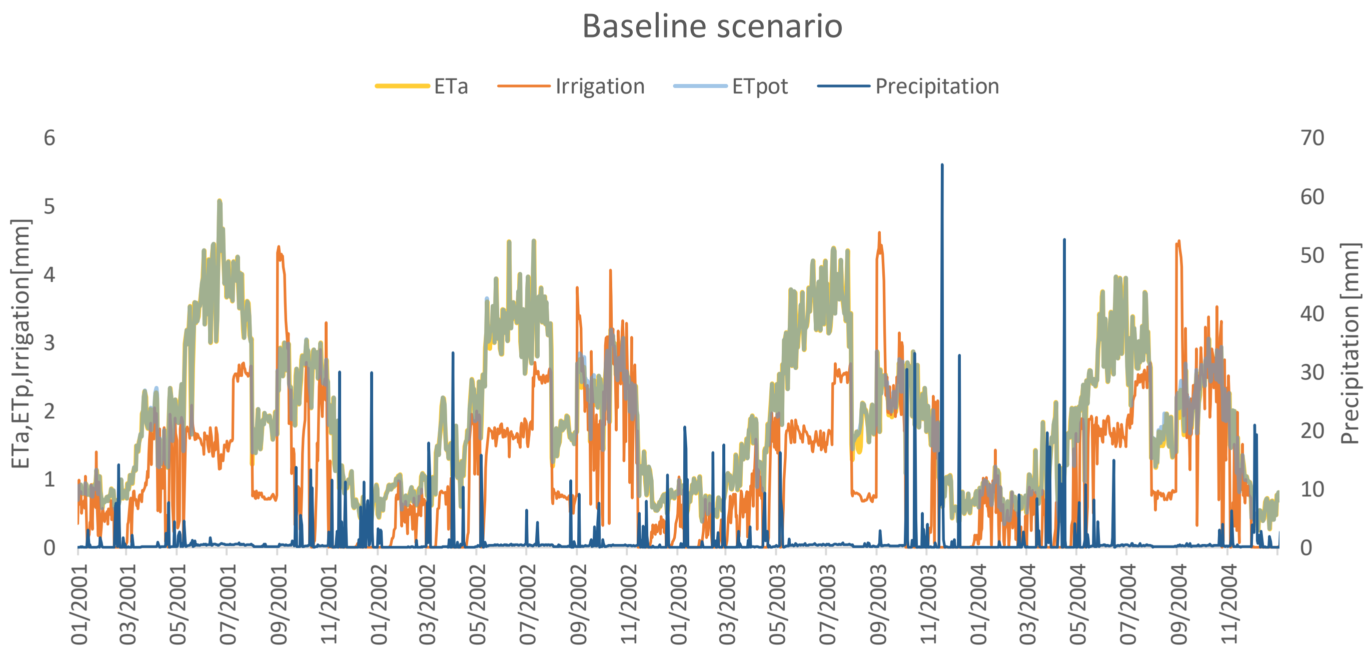

Figure 7 Baseline scenario ETa, irrigation, ETpot, and precipitation time series (2001-2004)

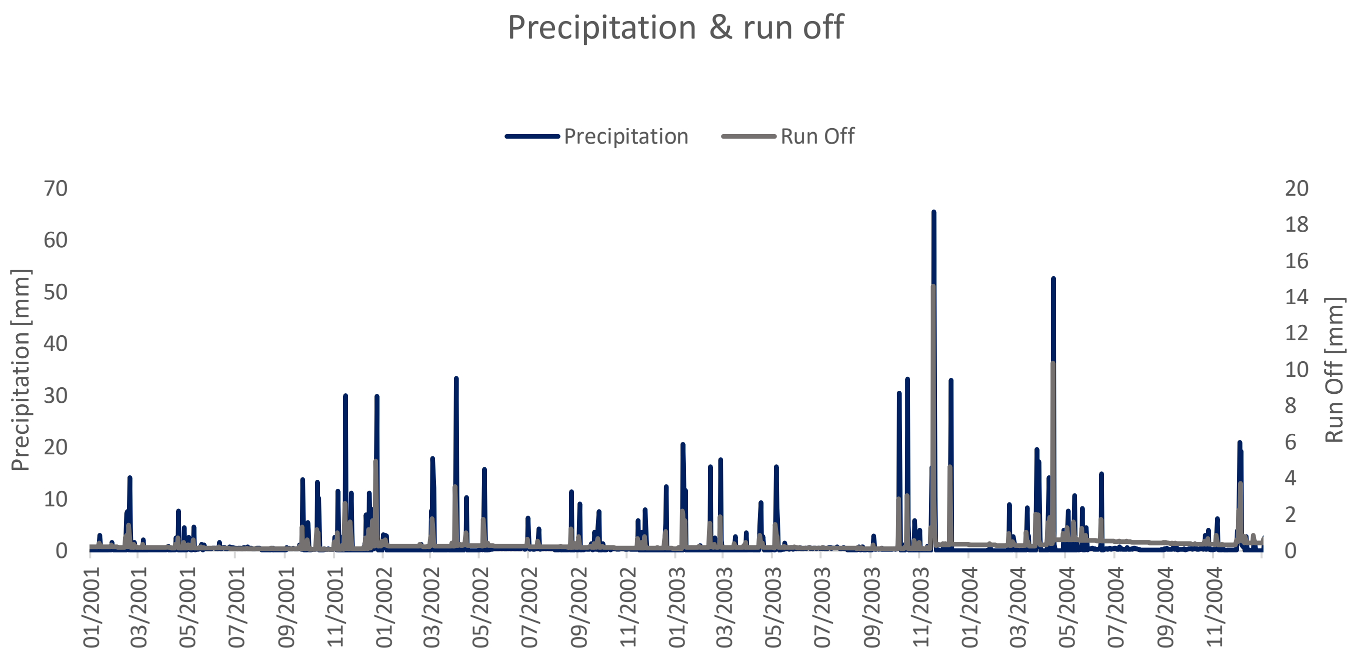

Figure 8. Baseline scenario precipitation &run off time series years 2001-2004

5.2 Evapotranspiration deficit

The time series shows how crops have experienced stress throughout their growing period as highlighted by the gap between potential and actual evapotranspiration. Stress and consequently irrigation have mainly occurred between the half of April and the beginning of October. Temperatures get higher in summer months and the potential evapotranspiration goes up. On the other hand, the evapotranspiration deficit increases as well since there is less water available for evapotranspiration hence, actual evapotranspiration goes down. The deficit irrigation scheduling by means of the evapotranspiration deficit approach showed a remarkable reduction in the amount of irrigation water supplied corresponding to a decrease up to 47% compared to the baseline scenario. Irrigation went from 4750 to 2500 $m^3/ ha/ y$. However, the decrement in irrigation water has not affected the actual evapotranspiration rates which have slightly gone down in relation to the baseline scenario as displayed in Figure 10. This is owing to the rise in percolation rates. Percolation rates have contributed to an increase in soil water content which in turn has increased $ETred_{dry}$by leading to high ET_a values. High ET_a values affected positively yield and in turn irrigation water productivity (IWP) and water productivity (WP) of each crop. All crops acted well in response to almost half of irrigation applied with regards to the baseline scenario. Lettuce went from 20 baseline to 15 ton/ha/y with ET deficit, Lettuce-Melon from 20 to 15 ton/ha/y while Broccoli-Melon from 18 to 15 ton/ha/y Table 7. Artichokes turned out to responded best to the evapotranspiration deficit approach with the same production as for the baseline scenario. IWP has increased for all crop combinations except for lettuce. Lettuce- Melon combination has increased its IWP up to 35 % compared to the baseline scenario. However, WP has not changed from full irrigation. This means that when adopting the evapotranspiration deficit more water remains into the root zone which can be used for irrigating more land or for other activities by making the approach sustainable at a basin scale. Information on ET deficit and percolation time series for the remaining years can be found in the Appendix A8

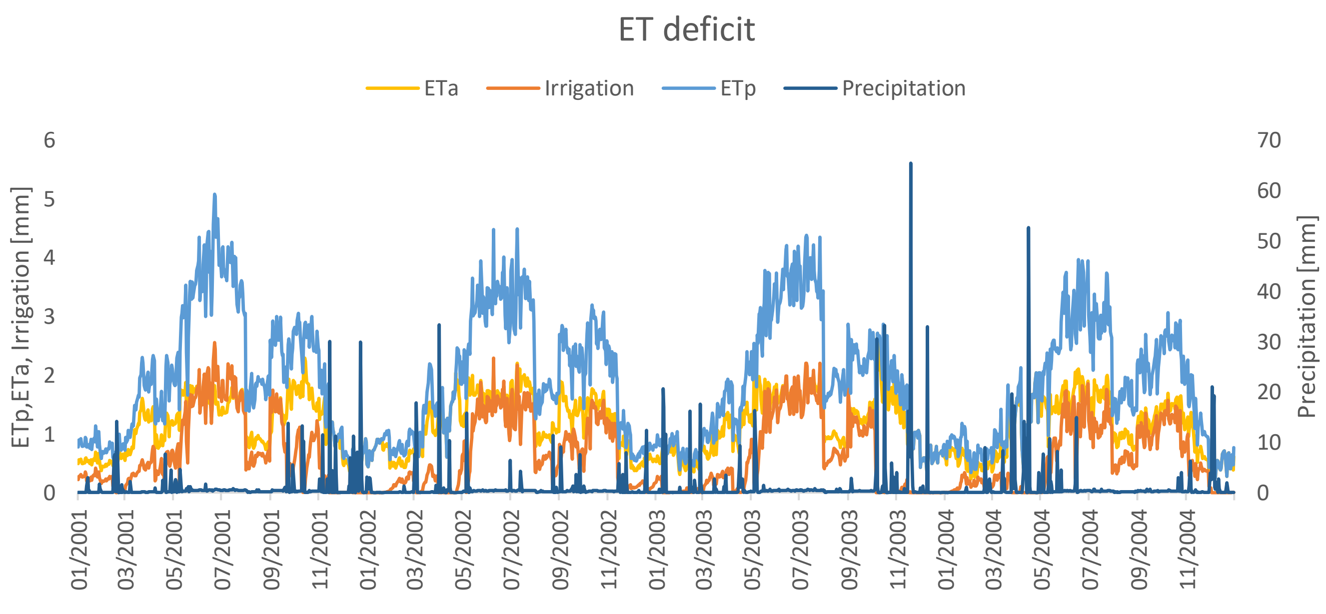

Figure 9 ETa, Irrigation, ETpot, Precipitation rates for the ET deficit scenario (2001-2004)

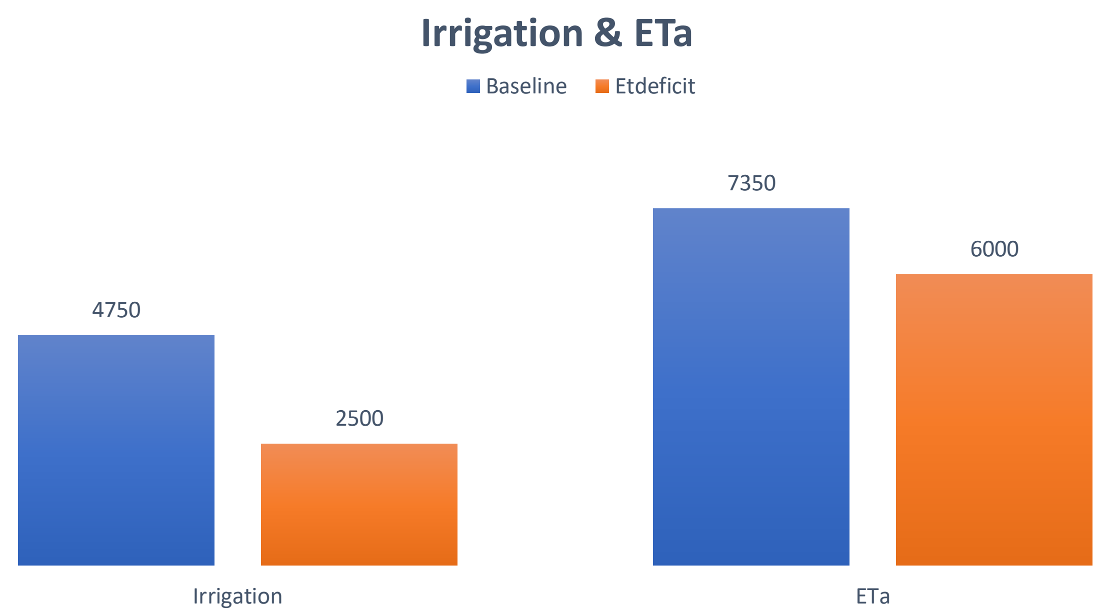

Figure 10 Irrigation and ETa comparison between Baseline and ET deficit. Data in $\mathbf{m^3 / ha / y}$.

Table 7 Crops response to ET deficit approach. Irrigation, ETa, Yield , IWP(irrigation water productivity) and WP(water productivity)

	Irrigation $[\mathrm{m^3/ha/y}]$		**ETa** $[\mathrm{m^3/ha/y}]$		**Yield [Ton/ha/y]**		**IWP** $[\mathrm{Kg/m^3/y}]$		**WP** $[\mathrm{Kg/m^3/y}]$	
	Baseline	ETdeficit	Baseline	ETdeficit	Baseline	ETdeficit	Baseline	ETdeficit	Baseline	ETdeficit
Lettuce	1050	610	1500	1100	20	15	20	20	10	10
Artichokes	1120	500	1950	1720	10	10	10	20	5	5
Brocc-Mel	2010	1060	3050	2550	18	15	10	15	5	5
Let-Mel	570	330	850	630	20	15	35	50	25	25

5.3 Static crop water stress threshold

The static crop water stress threshold method tolerates stress to the plants during their growing period. However, contrary to the ET deficit approach the user is able to better monitor the plant water stress by deciding how much stress is allowed to plant. This can be achieved by setting thresholds to the crop water stress coefficient (K_s), Equation 8. In the project two sets of K_s values(K_s1, K_s2)for each combination have been chosen based on each crop tolerance to water stress, Table 5. The K_s1 and K_s2 referr to as the static crop water stress approach. A comparison of actual evapotranspiration rates between the baseline scenario and the two crop water stress thresholds, K_s1 and K_s2 is given in Figure 11 whereas Figure 12 displays irrigation. For the time series of the remaining years see Appendix A9. From Figure 12 stands out the similarity between the baseline and the K_s2 scenarios irrigation frequency. Low irrigation intervals occurred for the K_s2 scenario while higher irrigation amount was supplied for the K_s1 scenario. This might be explained by different stress conditions experienced by crops all through their growing period. From the K_s2 trend it seems that the four rotations reached the thresholds mostly at the same time in contrast to Ks1 where irrigation frequency was lower meaning that not all the crops experienced stress together. K_s1 contrary to both the baseline and the K_s2 scenario has delivered irrigation when precipitation took place. Figure 11 shows a similar trend in ET_a between the two static crop water stress thresholds which in turn display lower ET_a values than the baseline scenario owing to stress allowed to crops. In relation to the baseline scenario the deficit irrigation approach led to a 21 % and a 36 % reduction in irrigation application for K_s1 and K_s2 scenario respectively. K_s1 delivered 3750 m^3/ha /y of water whilst K_s2 3050 m^3/ha /y., Figure 13 A decrement in irrigation between the two scenario is due to the fact that allowing less stress to the crop entails an earlier water application thereby more water is supplied when less stress is experienced by the crops. However, a reduction in irrigation has not severely affected actual evapotranspiration values. ET_a has gone from 7350 to 6800 m^3/ha /y for the K_s1 scenario whereas from 7350 to 6200 m^3/ha /y for K_s2.

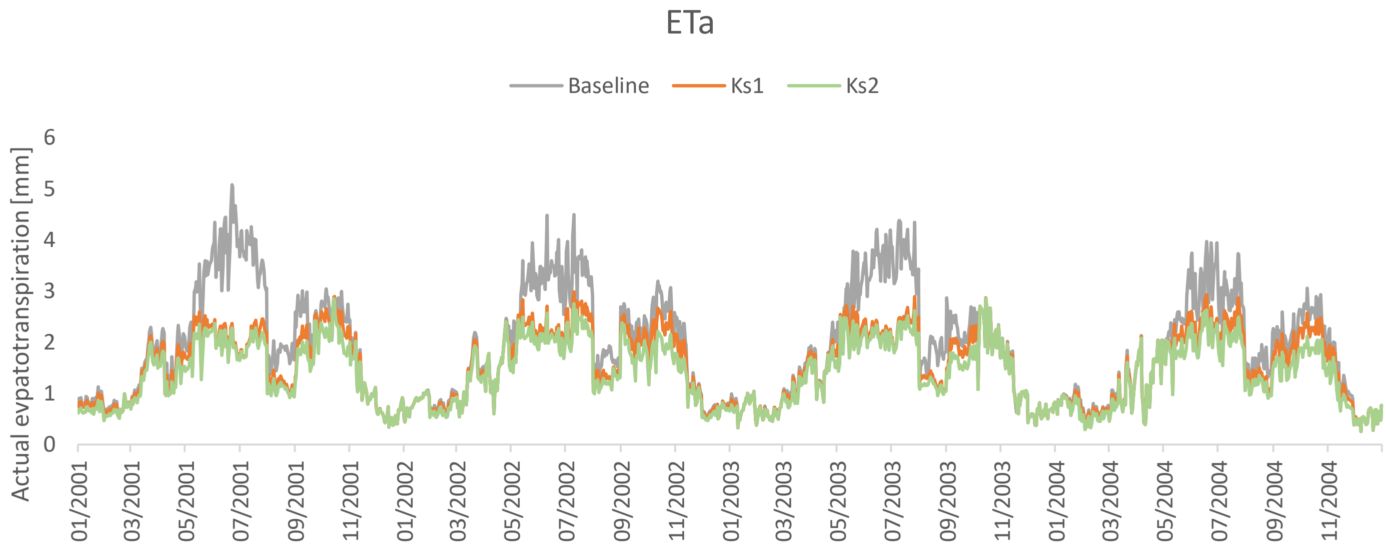

Figure 11. ETa comparison between the baseline and the two static crop water stress thresholds, Ks1 and Ks2. Period 2001-2004

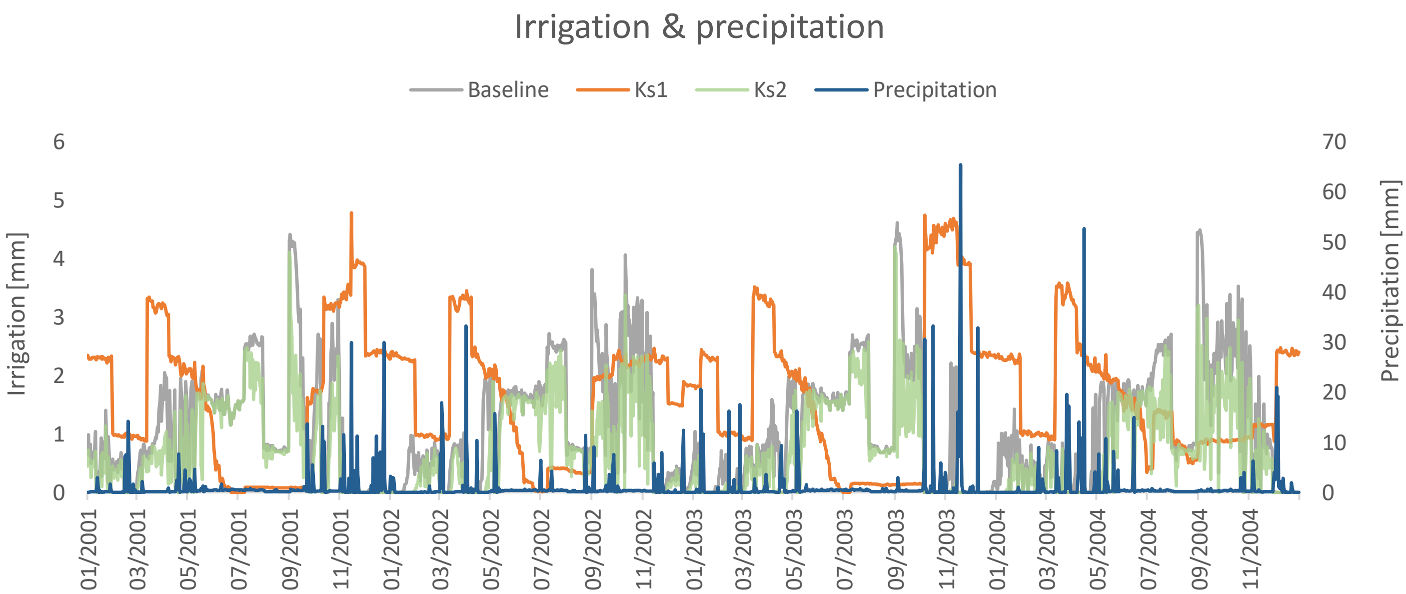

Figure 12 Irrigation amount comparison between the baseline and the two static crop water stress thresholds, Ks1 and Ks2. Period 2001-2004

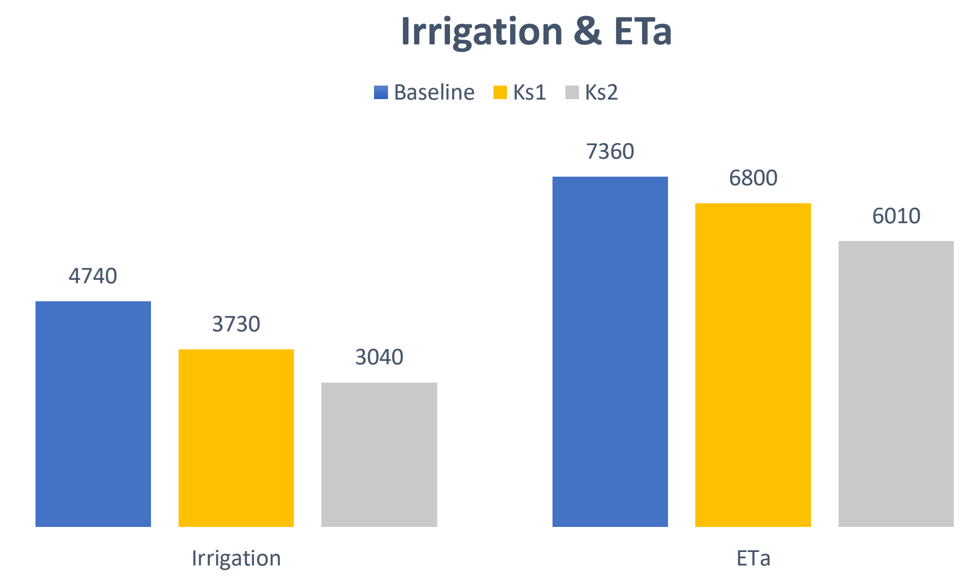

Figure 13. Irrigation and ETa rates comparison between baseline and Ks1 & Ks2. Data in $\boldsymbol{m^3/ha/y}$.

Table 8 and 9 highlight crop response to the static crop water stress threshold approach for the two scenarios. What sticks out is that the water productivity does not vary regardless a reduction in $\mathrm{ET_a}$ rates. The reduction was not so significant thereby not affecting the final WP. However, yield has gone down due to the linear relationships with $\mathrm{ET_a}$ and a change in WP would have been expected. Irrigation water productivity has not changed for crops when low stress was experienced. Only Lettuce-Melon combination has slightly increased its water productivity going from 35, baseline, to 35 $\mathrm{Kg}\ /\mathrm{m}^3$/y. On the other hand, $\mathrm{K_s}2$ scenario has shown an increase in IWP for all combination except for the one with Broccoli and Melon in the same field. IWP has risen of 28 % for Lettuce – Melon combination moving from 35 to 45 $\mathrm{Kg}\ /\mathrm{m}^3$/y whereas of 50 % for the Artichokes going from 10 to 15 $\mathrm{Kg}\ /\mathrm{m}^3$/y. The increment in IWP is owing to the reduction in irrigation water supplied to the crops. Artichokes, is the only one has not reduced its yield for both $\mathrm{K_s}1$ and $\mathrm{K_s}2$ application. Remarkable is the lettuce and melon combination response to the static crop water stress approach by being the only combination to increase irrigation water productivity for both crop water stress thresholds. This is due to their sensitivity to water stress. A $\mathrm{K_y}$ <1 ($\mathrm{K_y}$ Lettuce-Melon combinations = 0.99) has curbed yield reduction by leading to an increase in IWP owing to reduction in irrigation water supply

Table 8.Crop combinations at comparison.for the Ks1 scenario where IWP is the irrigation water productivity and WP the water productivity

	Irrigation $[m^3/ha/y]$		**ETa** $[m^3/ha/y]$		**Yield** **[Ton/ha/y]**		**IWP** $[Kg/m^3/y]$		**WP** $[Kg/m^3/y]$	
	Baseline	K_s1	Baseline	K_s1	Baseline	K_s1	Baseline	K_s1	Baseline	K_s1
Lettuce Ks =0.15	1050	870	1500	1450	20	18	20	20	10	10
Artichokes Ks=0.15	1120	900	1950	1830	10	10	10	10	5	5
Brocc-Mel Ks=0.25	2010	1530	3050	2770	18	15	10	10	5	5
Let-Mel Ks=0.25	570	450	850	750	20	20	35	40	25	25

Table 9. Crop combinations at comparison. For the Ks1 scenario where IWP is the irrigation water productivity and WP the water productivity

	Irrigation $[m^3/ha/y]$		**ETa** $[m^3/ha/y]$		**Yield** **[Ton/ha/y]**		**IWP** $[Kg/m^3/y]$		**WP** $[Kg/m^3/y]$	
	Baseline	K_s2	Baseline	K_s2	Baseline	K_s2	Baseline	K_s2	Baseline	K_s2
Lettuce Ks=0.3	1050	730	1500	1350	20	18	20	25	10	10
Artichokes Ks=0.3	1120	710	1950	1680	10	10	10	15	5	5
Brocc-Mel Ks=0.4	2010	1240	3050	2500	18	15	10	10	5	5
Let-Mel Ks=0.4	570	370	850	670	20	17	35	45	25	25

5.4 Crop rotation simulation

The crop rotation simulation has been carried out by changing the organic matter and bulk density of + 20 percent and – 5 percent of their content respectively. The simulation resulted in a light reduction in irrigation water for the $\mathrm{K_s}1$ scenario contrary to the evapotranspiration deficit and $\mathrm{K_s}2$ scenarios. Here no changed occurred when crop rotation was employed, Figure 14. On the other hand, all deficit irrigation approaches have shown a reduction in actual evapotranspiration when crop rotation was simulated, Figure 15. Applying crop rotation together with the static crop water stress approach turned out to be more effective than with the evapotranspiration deficit for almost all crop combinations, Tables 10,11,12. Same IWP and WP values were observed when crop rotation was applied with the static crop water stress threshold approach , both $\mathrm{K_s}1$ and $\mathrm{K_s}2$, whilst reduction in IWP was experienced for Artichokes and Broccoli-Melon combination when crop rotation was simulated along with the evapotranspiration deficit approach. However, when ks1 scenario was coupled with crop rotation IWP for lettuce and lettuce – melon combinations has gone from 20 to 25 kg/m^3 /y and from 40 to 50 kg/m^3 /y while WP from 10 to 15 kg/m^3 /y and from 25 to 30 kg/m^3 /y , Table 11. The ratio was the same when $\mathrm{K_s}2$ scenario was tested with the crop rotation simulation. However, the scenario has led to an increment in IWP for Broccoli-Melon combination as well. The latter has increased from 10 to 15 kg/m^3 /y, Table 12. Furthermore, Broccoli -Melon along with Lettuce have seen their yield increase when $\mathrm{K_s}2$ scenario was applied with crop rotation. Lettuce yield has increased up to 10 % whilst Broccoli-Melon up to 20%. Artichokes yield, IWP and WP have shown no variation between scheduling irrigation techniques with and without crop rotation.

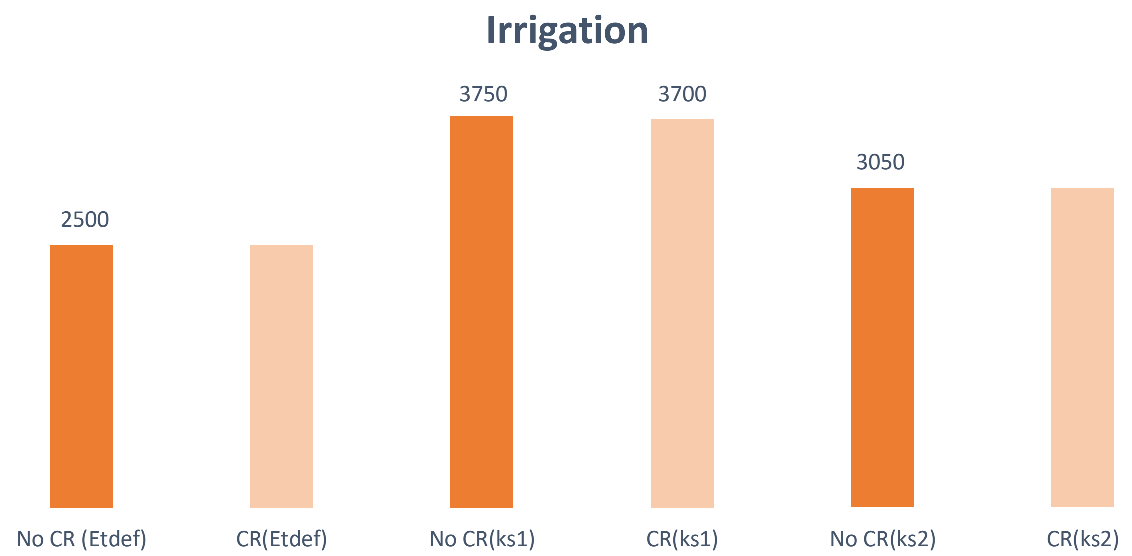

Figure 14.Irrigation rates at comparison among the deficit scheduling irrigation techniques with and without crop rotation. Data in $\boldsymbol{m^3/ha/y}$

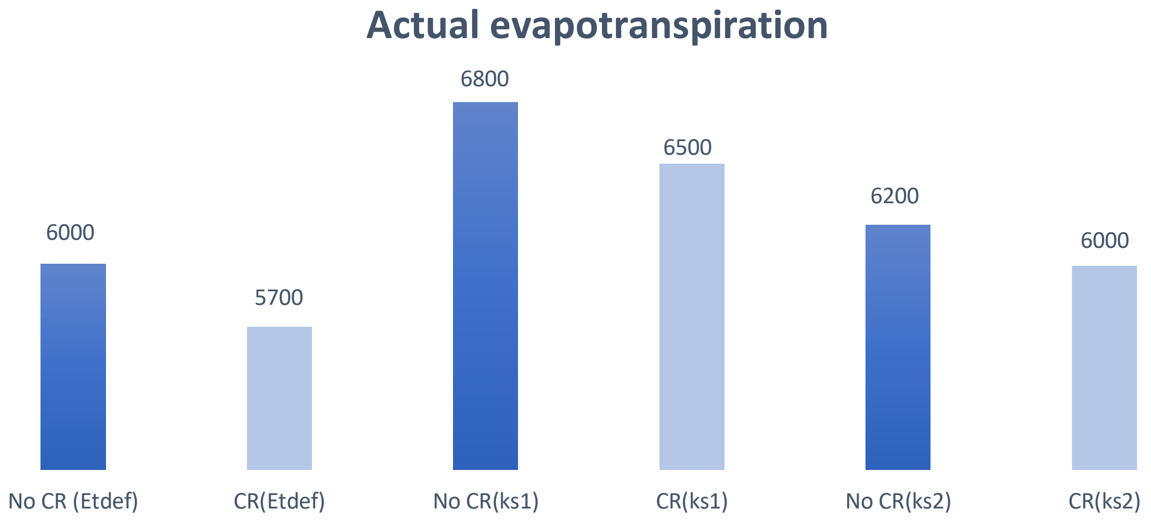

Figure 15 Actual evapotranspiration rates at comparison among the deficit scheduling irrigation techniques with and without crop rotation Data in $m^3/\ ha/\ y$.

Table 10 **Crops Yield, IWP and WP response to ET deficit approach with and without crop rotation**

ET deficit	Yield [Ton/ha]		IWP $[kg\ /m^3\ /y]$		WP$[kg\ /m^3\ /y]$	
	No CR	CR	No CR	CR	No CR	CR
Lettuce	15	15	20	25	10	10
Artichokes	10	8	20	15	5	5
Broc-Mel	15	15	15	10	5	5
Lett-Mel	20	15	50	50	25	25

Table 11 Crops Yield, IWP and WP response to Ks1 static crop water stress threshold approach with and without crop rotation.

$K_s 1$	Yield [Ton/ha]		IWP $[kg\ /m^3\ /y]$		WP$[kg\ /m^3\ /y]$	
	No CR	CR	No CR	CR	No CR	CR
Lettuce	18	20	20	25	10	15
Artichokes	10	10	10	10	5	5
Broc-Mel	15	18	10	10	5	5
Lett-Mel	20	20	40	50	25	30

Table 12 Crops Yield, IWP and WP response to Ks2 static crop water stress threshold approach with and without crop rotation.

$K_s 2$	Yield [Ton/ha]		IWP $[kg\ /m^3\ /y]$		WP$[kg\ /m^3\ /y]$	
	No CR	CR	No CR	CR	No CR	CR
Lettuce	18	20	20	30	10	15
Artichokes	10	10	15	15	5	5
Broc-Mel	15	18	10	15	5	5
Lett-Mel	17	20	45	55	25	30

5.5 Crop response to SLM techniques

Figure16,17,18 display crops response in relation to irrigation and yield for the scheduling evapotranspiration deficit approach and for the K_s1 and $K_s2$static crop water stress thresholds, respectively. Each deficit scheduling irrigation technique is appraised with and without crop rotation. Axes values are scaled to the baseline scenario to better assess irrigation and yield variation of each crop owing to SLM.

The crop that turned out to react the best to a reduction in water supply for the three scenarios was Artichokes. Regardless of the water supplied its production has not changed when both deficit scheduling irrigation scenarios were assessed. Same pattern when deficit scheduling irrigation techniques were simulated with the crop rotation despite a reduction in irrigation water. The Artichoke proved to resist well to water shortages when ET deficit irrigation was applied along with crop rotation. Its production was up to 15 percent down in relation to about 57 % less water application. Artichoke's behaviour is due to the crop growing period and environmental influence. The reliance of the basin on irrigation inputs is especially relevant during winter period in coincidence with the artichoke's mid development stage. Here, precipitation event occurs which provide water to the crop during flowering and grain setting. Yield does not change compare to the baseline scenario since when $ET_p$are met the production does not increase any further with additional water supply.

Broccoli-Melon combination has shown a good response to all the SLM techniques. When half of the irrigation was supplied for the ET deficit approach its production has decreased up to 15 percent in relation to the baseline scenario and kept at the same rate for both the static crop water stress thresholds approaches. This was in line with the K_y values which is less than 1. When K_s1 approach was simulated together with the crop rotation it has shown a slight increase in yield with the same amount of water supplied, Figure 17. Furthermore, when more stress was experienced (K_s2 approach) along with crop rotation simulation the yield has not changed compare to the baseline scenario regardless of up to 40 % reduction in irrigation water supplied, Figure 18. On the contrary, Lettuce-Melon combination resulted to be more sensitive to water reduction. Yield has dropped when less water was supplied for the evapotranspiration deficit as well as for the K_s2 static crop water stress threshold approach. However, Lettuce-Melon yield has increased when crop rotation was simulated, Figure 18.

Lettuce yield has risen when crop rotation was employed in all three deficit scheduling irrigation approaches. However, as for the lettuce-melon combinations its yield has dropped to 15 percent less than the baseline scenario when the evapotranspiration deficit approach was simulated. On the other hand, its yield has decreased up to 10 percent when both static crop water stress approaches were used despite of the reduction in irrigation. The K_s1 methods delivered to lettuce up to the 17 percent in relation to the baseline scenario whilst almost up to 30 percent less for the K_s2 scenario. Lettuce proved to be sensitive to water stress as shown by a K_y bigger than one (1.07)

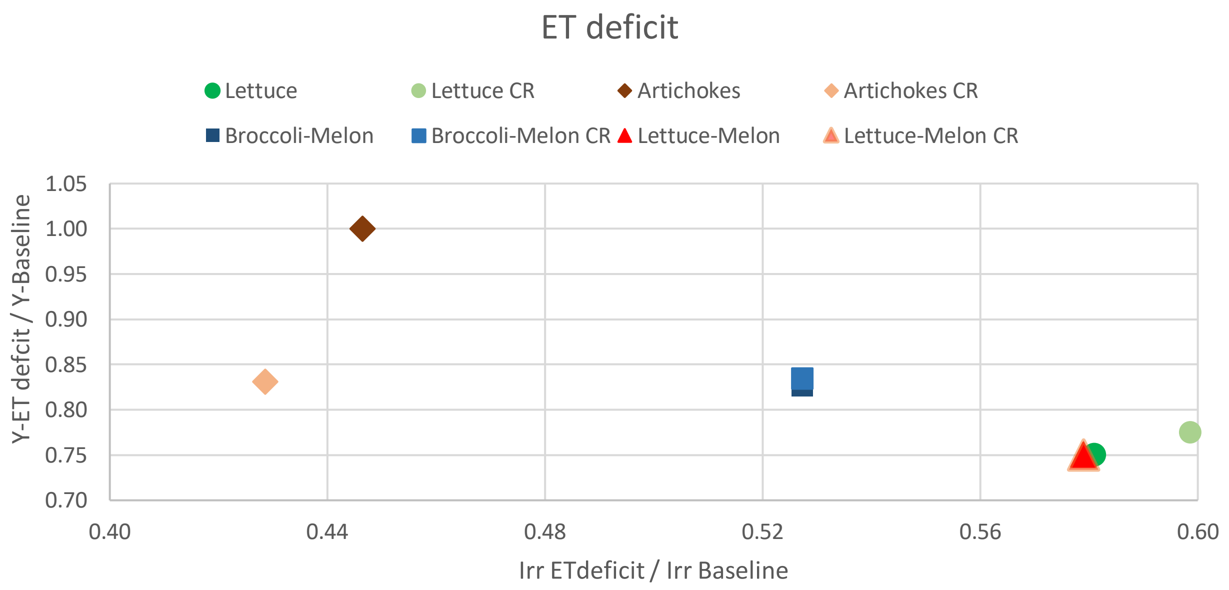

Figure 16 Irrigation and yield relationship for ET deficit approach to the baseline scenario Axes data in $\mathbf{m^3}/\ \mathbf{ha}/\ \mathbf{y}$

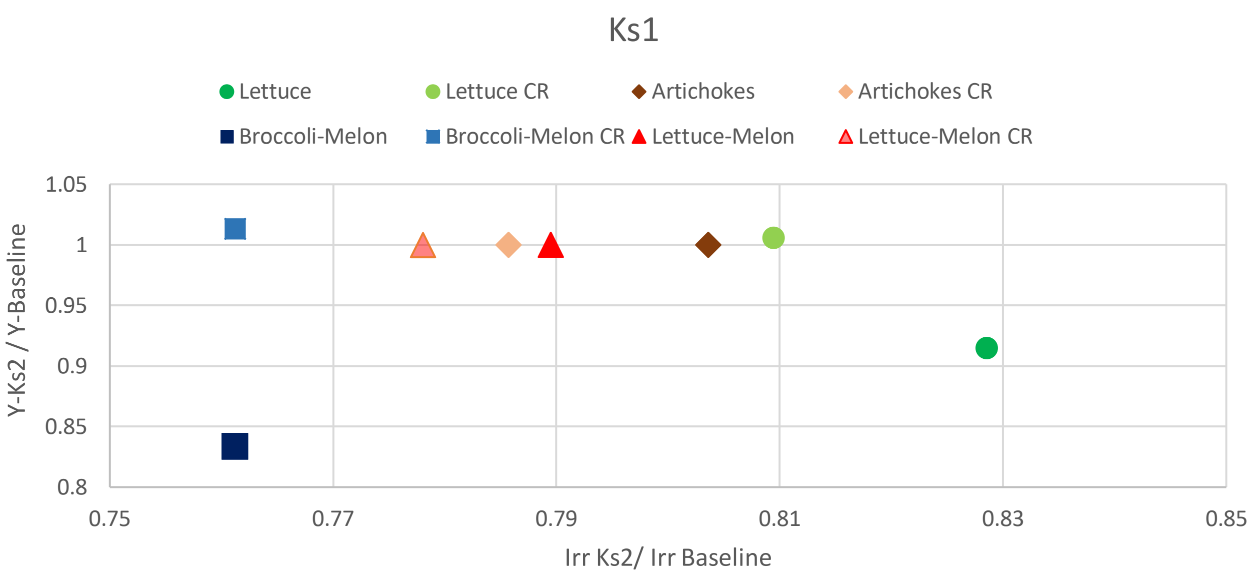

Figure 17 Irrigation and yield relationship for Ks1 static crop water stress threshold approach to the baseline scenario Axes data in $\mathbf{m^3}/\ \mathbf{ha}/\ \mathbf{y}$

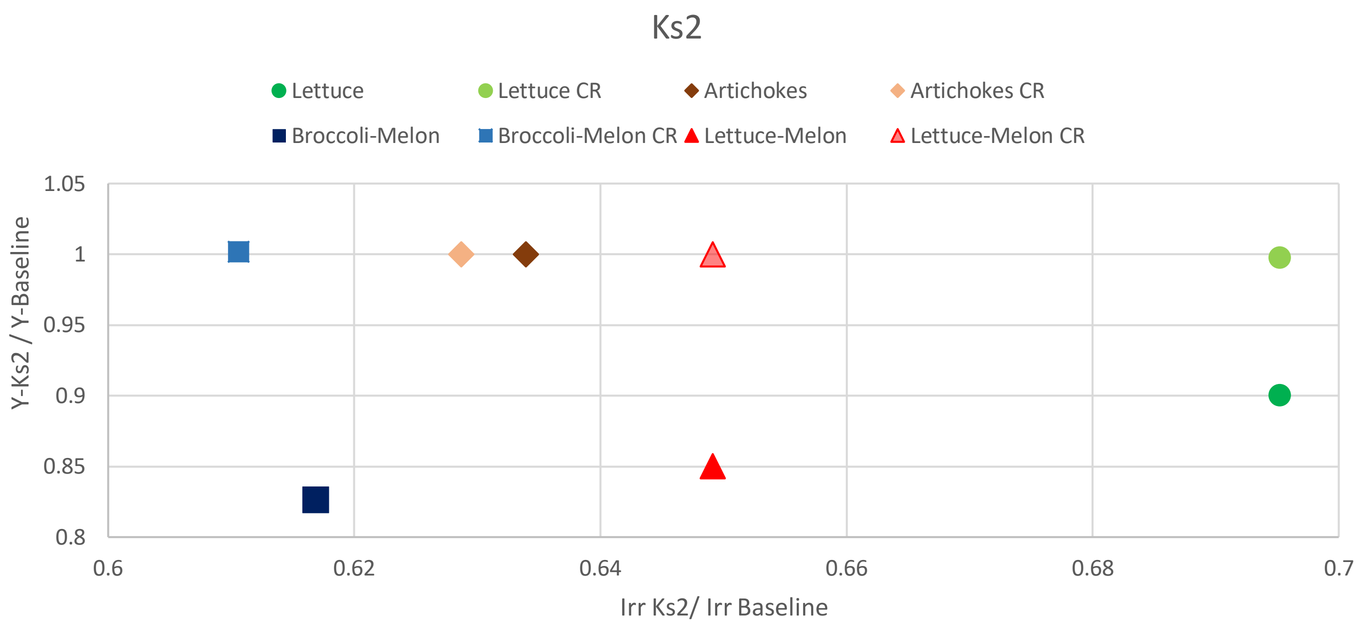

Figure 18. Irrigation and yield relationship for Ks2 static crop water stress threshold approach to the baseline scenario Axes data in $\mathbf{m^3}/\ \boldsymbol{ha}/\ \boldsymbol{y}$

6. DISCUSSION

In this section results obtained throughout the project are compared with findings from previous studies. Then, limitations are shown in 6.2. Finally, in the paragraph 6.3 practical implications of Sustainable Land Management in intensive agriculture are discussed.

6.1 Comparison with previous studies

No studies have been carried out in assessing agriculture water consumption in the Rambla del Albujon hence, the Campo de Cartagena has been taken as reference. However, in the Campo de Cartagena few studies have been developed to assess irrigation water used in horticulture area. Contreras (2014) analysed the amount of water delivered to meet crop water requirements between 2002-2011 by means of the SPHY model. In the project crop coefficient has been computed through remote sensing data and combined in SPHY. A soil water balance approach has been used and despite the deployment of remote sensing data, final water supply and yield was similar to the one computed in this case study. To this end results have been utilised as reference for the baseline scenario.

Regarding the Evapotranspiration Deficit approach, it has been used by Baties (2012) and Wehling (2014) to assess irrigation. As mentioned in paragraph 1.2, they made used of Remote Sensing to assess the irrigation timing and quota turning out to be a suitable method for supporting irrigation management decision. However, a proper comparison between the studies cannot be made since in the Romanian case study remote sensing was employed to appraise the crop coefficient (K_c) and mostly the canopy cover. These played an important role in the computation of actual and potential evapotranspiration which in turn affected the evapotranspiration deficit estimation. On the other hand, when assessing scheduling irrigation techniques by means of remote sensing the latter does not keep track of vegetation response to irrigation method application which makes remote sensitive not suitable for the case state. The present study is in line with the findings from Osroosh et al (2016) where significant irrigation water reduction was observed when irrigation was scheduled through the evapotranspiration deficit approach. Both studies made use of the Hargreaves equation to estimate ET reference

The present study employs a static crop water stress threshold approach to schedule irrigation.Model results show 21 percent reduction in irrigation amount when low stress was allowed to crops while 36 percent when the stress thresholds were higher. Both scenarios are associated with an increase in IWP and a reduction yield. Ahmadi et al (2014) experimented deficit irrigation techniques on potatoes in a semi-arid horticultural area in Iran. The researchers reported a 25 percent water save compared to full irrigation when a static deficit irrigation strategy was deployed associated with a 28 % increase in IWP. However, the strategy led to just a 7 percent yield diminution of the shallow- root crop while higher losses were reported in the herein project. Allen (1998) ranked vegetables featuring shallow-rots as lettuce highly sensitive to water shortage. Molina-Montenegro et al (2011) performed trials on lettuce reporting on average a 10 percent reduction in yield owing to stress by means of deficit irrigation applications in line with Ahmand (2016) . Ruttanaprasert (2016) studied the responses of Artichokes to deficit irrigation under drip irrigation stating that the perennial crop is not resistant to water shortages as biomass was reduced greatly under stress with a high reduction in yield contrary to what found in the project where artichokes turned out to be the best crop to a decrement in watering

SPHY had been applied with the purpose of providing field specific irrigation advice for a small farm in countries like waster Romania ,Wehling (2014) , and Angola ,Baties (2012). Both approaches made use of remote sensing while in the present approach soil moisture data and the the crop coefficient parameters are used to estimate irrigation water supply. The model responded well to hydrological changes although contrary to simulation carried out by means of the Soil Water Atmosphere and Plant model (SWAP) it does not feature yield calculation. The SWAP model was deployed by Rezavirdinejad et al.(2012) to simulate the effects of different quality and quantity levels of irrigation water on crop yield, soil water and solute transport with shallow groundwater level conditions. Result of the model analysis showed that with a precise calibration the SWAP model was able to predict soil water and solute transport, water table balance and crop yield with high degree of accuracy. Rezavirdinejad et al (2012) findings were in line with Ma et al(2011) wo highlighted how the SWAP model can be used as a powerful tool to simulate crop yield and evaluate irrigation practices. The study was conduct in Beijing, China , where the model was employed to suimulate the field-water cycle under drip irrigation.

6.2 Limitations

The deficit irrigation method has been computed by means of a static crop water stress coefficient during the crop growing period. This has limited the effectiveness of the approach. Using a dynamic strategy would have led to a major water savings since irrigation supply would have been delivered in the most sensitive crop growth stage i.e. mid-development stage. Furthermore, the soil would have benefitted as well. Indeed when crops undergo deficit irrigation they develop roots which make the soil ready for the next crop by creating air within the soil pores. On the other hand, when the plant is subjected to the same water stress throughout its growing period, hardening process takes place which make plants less sensitive to renewed stress by osmotic adjustment of the leaves. (Ali et al 2008). Optimal sequencing of water deficit reduces the detrimental effect on yield, and hence increases WP (Ali et al., 2007, Liang et al., 2002). Liang et al. (2002) and Geerts et al (2006) demonstrated that alternate deficit had a significant compensatory effect on WP and IWP by imposing deficit at plant establishment and then at flowering stages of the growth period.

Another limitation of the present study is that water balance and static crop water stress irrigation approaches have been carried out without considering the root depth of each crop. Each crop root depth has been sampled to a standard value of 500mm employed all through the project. If the root depth of each crop would have been included a better evaluation of the soil water balance and the static crop water stress threshold approaches would have been made. The root zone affects the TAW which in turn plays an important role in both the soil water balance computation and the static crop water stress approach in terms of irrigation timing

6.3 Practical implication of SLM

In the introduction chapter has been mentioned the limit sustainable land management practical application and has been stressed as techniques aiming at improving water management in agriculture have been mainly tested in laboratory.

Farmers have been scheduling irrigation to better exploit water resource. When put into practice scheduling irrigation based on soil moisture content requires (1) a target water volume, (2) guidelines on how and when to split irrigation, (3) a method to account for rainfall and (4) practical method to monitor soil moisture. Irrigation amounts may be estimated using historical weather data climatic measurement in real time, class A pan evaporation, atmometers (Simonne et al., 2019).Soil moisture may be reported in terms of soil water tension or volumetric water content. Monitoring soil moisture level daily gives insights into how much water stress the crop is exposed to. To succeed in the scheduling irrigation vegetables growers are required to keep pesticide records. Fertilization records are usually kept in relation to soil testing. Furthermore, it is paramount that the drip irrigation system is maintained to allow a uniform application of water and fertilizers during the crop growing period.

Deficit irrigation, the application of irrigation below the full crop evapotranspiration ($\mathrm{ET_p}$), has not been adopted as a practical alternative to full irrigation by either academics and practitioners until the 1990s, though its concept is dated in the 70s. (Capra et al.,2008). Nowadays although the theoretical basis and analytical frameworks for deficit irrigation are well established its practical application is difficult. There are several obstacles hindering the deficit irrigation application such as the use of precise irrigation, the knowledge required span a wide range of disciplines from ecophysiology and plant sciences to hydrologist, engineering, and economics(Capra et al.,2008). Furthermore, there is a need to convince farmers and irrigation practitioners not only of the economic value of deficit irrigation but also of its practicability. The feasibility of deficit irrigation involves more than economic concerns and agronomic and legal aspects are also important in improving farm operation. The context in which deficit irrigation is applied is paramount.

Crop rotation entails practical procedures to be undertaken. To achieve the crop rotation benefit farmers, seek a balance between the combination of crops and the sequence in which they are cultivated. Often the first sequence in a rotation is used to prepare and regenerate the soil, using crops such as legumes and grassland, while the second sequence takes advantages of the increased fertility of the regenerated soil, ideally leading to a farming practice which is economically more sustainable. Practical consideration of factors as duration of crop rotation, climate , soil quality and type and availability of water need to be considered before implement the crop rotation. However, farmers tend to choose crops depending on the preceding crop, and not following a rotation pattern which makes them often think in terms of crop succession, and not in terms of rotation. One of the main reasons is the possible decrease in profit during the implementation.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

1) *To which extent does the baseline scenario reflect the current situation in response to irrigation supply and yield within the study area?*

The SPHY model succeeded in simulating the current situation in terms of irrigation water supply to the horticulture area. The 70 percent RAW depletion with a refilling rate of 10 percent of its content resulted in the best scenario to reflect the current situation within the Rambla del Albujon by providing an irrigation amount of 4750 $\mathrm{kg}\ /\mathrm{m}^3$ /y. The data from literature reported a total annual irrigation water supply of 4800 $\mathrm{kg}\ /\mathrm{m}^3$ /y.

2) *How has the evapotranspiration deficit technique affected irrigation water use and yield compared to the baseline scenario?*

Irrigation water supply has gone down up to 47 percent when the evapotranspiration deficit scenario has been employed. Higher percolation rates in the root zone compared to the baseline scenario have led to just up to a 18 percent reduction in $\mathrm{ET_a}$. This, has decreased crop combinations yield excepting for Artichokes which yield has not changed. On the other hand, artichokes IWP has increased of 100 % in relation to the baseline scenario compared to 50 and 43 percent for Lettuce-Melon and Broccoli-Melon combinations. ET deficit resulted in a sustainable approach at basin level since the water remained into the soil could be deployed to irrigated more land or for other activities.

3) *How have irrigation water use and production changed compare to the baseline scenario when the static crop water stress threshold approach is employed?*

For the $\mathrm{K_s}1$ static crop water stress threshold irrigation has decreased up to 21 percent compared to the baseline scenario whilst up to 36 percent for the $\mathrm{K_s}2$ scenario. A 7 percent $\mathrm{ET_a}$. reduction rates were observed for the $\mathrm{K_s}1$ whereas 16 percent for the $\mathrm{K_s}2$. When low stress was allowed only the Lettuce-Melon combination has shown an increase in IWP. On the other hand, for the $\mathrm{K_s}2$ approach IWP has risen for all combinations excluding the Broccoli-Melon. As for the evapotranspiration deficit approach no change in WP was observed in relation to the baseline scenario. The static crop water stress approach has proven to be an effective sustainable land management techniques with regards to the reduction in water and yield losses, especially when higher stress was allowed to crops. Here more water has been saved and just the Lettuce-Melon combinations has seen its yield decreasing compared to the $\mathrm{K_s}1$. approach

4) *To which extend has crop rotation contributed to reduce irrigation water use and yield within the Rambla del Albujon?*

Simulating crop rotation has led to a slight reduction in irrigation water supply for the static crop water stress approaches and a reduction in Eta for all the deficit scheduling irrigation techniques. When crop rotation was simulated along with the static crop water stress threshold approach an increase in IWP has been observed for Lettuce, and Lettuce-Melon combinations in case of K_s1 and Lettuce, Lettuce-Melon and Broccoli – Melon in case of K_s2 . When scheduling irrigation techniques where simulated along with crop rotation WP has increased. The increase in WP due to crop rotation is due to an increase in yield and a reduction in ET_a. This is not in line with the linear relationship expressed in the yield response facto formula, equation 11.because a reduction in ET_a. should entail a linear reduction in yield based on the crop yield response factor K_y.Therefore, a yield reduction of lettuce should be matched with an increase in ET_a.values for the crop.

5) *How crop combinations responded to SLM implementation in terms of water use and yield?*

Crops responded well to a reduction in water supply due to SLM application techniques. Regardless less water delivered lettuce and lettuce-melon combinations have experienced the highest yield reduction when ET deficit approach was employed. Their yield decreased up to 15 percent compared to the baseline scenario. All combination responded well to crop rotation simulation by increasing their production although irrigation decreased. All in all, the crop responded best to SLM has been Artichokes since its yield has not changed compared to the baseline scenario when less water was delivered.

To evaluate the effectiveness, in terms of water use and production, of deficit irrigation scheduling and crop rotation in intensively irrigated agriculture to reduce irrigation water supply

Answering the research questions has given insights onto the main objective of the report. The K_s2 static crop water stress threshold approach, simulated with crop rotation turned out to be the best SLM techniques in terms of water use and production. Contrary to the K_s1 approach the amount of irrigation delivered to crop combinations is lower and the yield has not changed. Furthermore, in case K_s2 had been applied without crop rotation the only combination had seen its yield reduced would have been Lettuce – Melon. However, the lower irrigation water supplied would compensate for the 15 percent yield loss in relation to the baseline scenario, Figure 18. Broccoli – Melon combination which covered the lion's share in the horticulture area (9104 ha) has not changed its yield regardless of a lower irrigation application in relation to the K_s1 approach.

The evapotranspiration deficit turned out to be the best SLM techniques at the basin scale. However, contrary to the K_s2 approach more stress has been experienced by the crops during their growing period as showed in Figure 19 This would play an important role in the quality of the harvested crops. Furthermore crop water stress can be better monitored through a static crop water stress threshold approach than by means of evapotranspiration analysis which does not keep track of plant growth stages. In addition the static crop water stress threshold approach has more room from improvement than the ET deficit. Whether irrigation would have been delivered just for the most sensitive growth stages water would have been saved and yield improved.

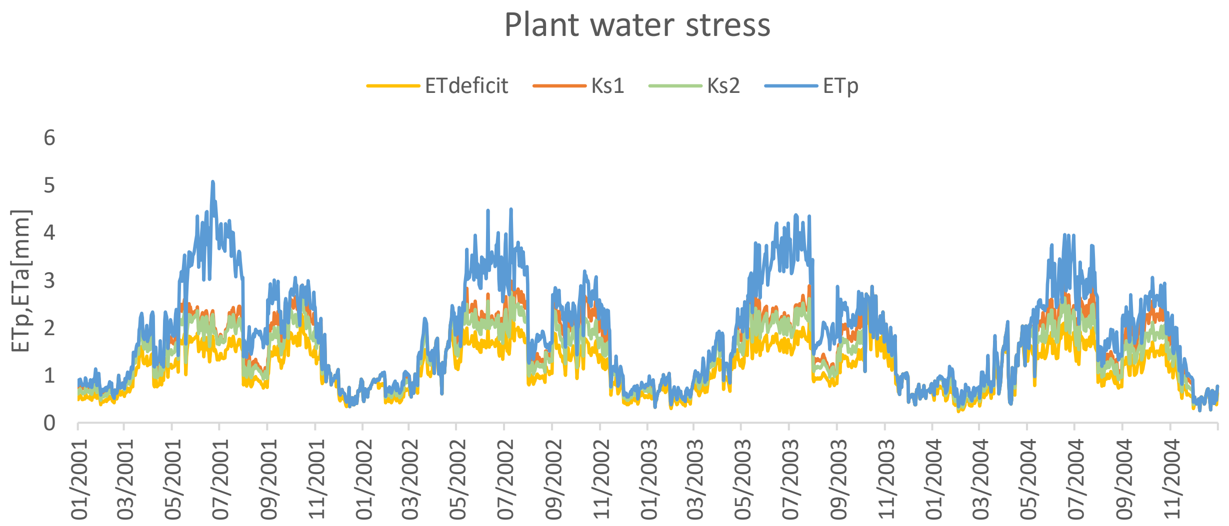

Figure 19.Potential and actual evapotranspiration at comparison between the deficit scheduling irrigation approaches to show plant water stress degree

The SLM techniques have highlighted the inefficiency of the full scheduling irrigation approach employed for the baseline scenario. When SLM measures have been applied a reduction in irrigation is shown as well as in ET_a and in turn in yield. However, WP does not change while IWP increases. This leads to the conclusion that when full irrigation is employed overirrigation occurred. Water infiltrates into the soil or whether not infiltrates ends up as surface run off. This is confirmed by the fact that when less irrigation is applied with SLM measures there is enough water for the plant since WP is the same. Therefore, thanks to the SLM techniques extra irrigation is reduced.

7.2 Recommendations

Based on the results of this study, it is recommended to carry out future research on SLM techniques in regard to water use for irrigation within the Rambla del Albujon. More detailed data on the amount of water supply and other crops used would improve eventual study. Knowing which other vegetables grow in the study area allows a wider research and a chance to swap to less sensitive crops to water shortages. Besides, it is important that, when employing the static crop water stress threshold approach the same amount of water should not be supplied during the plant growing period but should be diminished to the less sensitive growth stages of the plant. In order to ensure successful deficit irrigation, it is necessary to consider the water retention capacity of the soil. In sandy soils plants may undergo water stress quickly under deficit irrigation,whereas plants in deep soils of fine texture may have ample time to adjust to low soil water matric pressure, and may remain unaffected by low soil water content. Therefore, success with deficit irrigation is more probable in finely textured soils. However, one consequences of decreasing irrigation water use by deficit scheduling irrigation , as mentioned in the introduction chapter, section 1.2, is the greater risk of increased soil salinity due to reduced leaching, and its impact on the sustainability of the irrigation (Schoups et al., 2005).Furthermore , crop Therefore, more detailed study on the deficit scheduling irrigation approach must be carried out. While deficit irrigation can be used as a tactical measure to reduce irrigation water use when supplies are limited by droughts or other factors, it is not known whether it can be adopted over long time periods. It is imperative to investigate the sustainability of deficit scheduling irrigation via long-term experiments and modelling efforts to determine to what extent it can contribute to the permanent reduction of irrigation water use.

Results highlighted the benefit of crop rotation in reducing water without affecting crop production. Therefore, is advisable to consider crop rotation for irrigation water management application in a semi-arid agriculture domain.

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APPENDICES

A1 SPHY

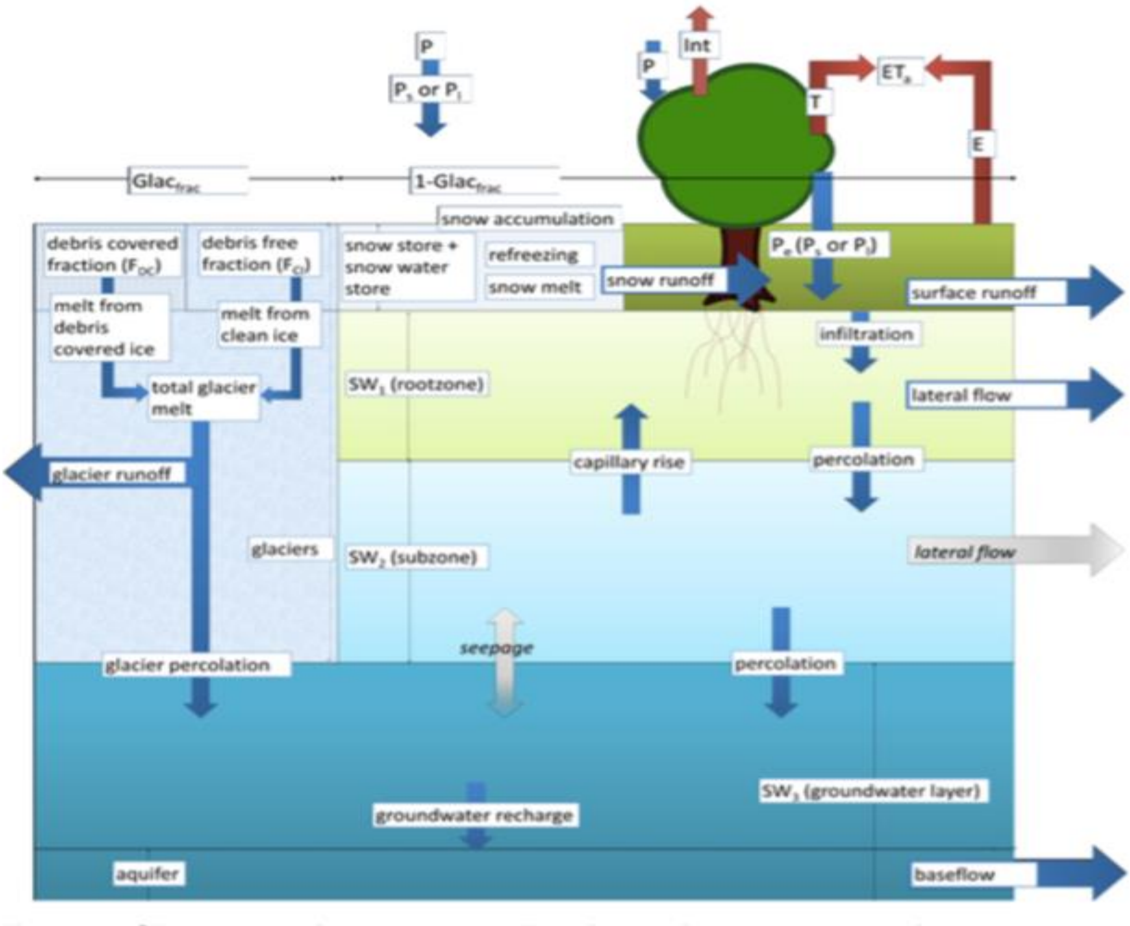

Figure 20 SPHY modelling concepts. The fluxes in grey are only incorporated when the groundwater module is not used.

```python
print('Irrigation module imported')


#-init processes irrigation
def init(self, pcr, config):

    #Irrigation scenarios
    self.IrrigationMethod = config.getint('IRRIGATION', 'IrrigationMethod')
    # Irrigated land use
    self.IrrigationTable = self.inpath + config.get('IRRIGATION','IrrigationTable')
    self.IrrigatedLand = pcr.lookupscalar(self.IrrigationTable,self.LandUse)
    #Irrigation Efficiency tells the amoun of water flows directly to the crop
    self.IrrigationEfficiency = config.getfloat('IRRIGATION','IrrigationEfficiency')
    #Baresoil parameter = 0.15
    self.KcBaresoil = config.getfloat('IRRIGATION','KC_baresoil')
    # Maximale Allowable Depletion factor. How much water can be depleted in the RAW before supplying water
    self.MAD = config.getfloat('IRRIGATION', 'MAD')
    #RAW replenishment rate
    self.Replenishment  = config.getfloat('IRRIGATION','QUOTA')
    #Crops water stress coefficient
    self.Ks = self.inpath + config.get('IRRIGATION' , 'Ks')
    self.KsTable = pcr.lookupscalar(self.Ks, self.LandUse)

#-initial conditions irrigation
def initial(self, pcr):

    # Irrigation input as model runs
    self.IrrigationWater  = 0
```

Figure 21. Irrigation module. Def_init expresses the connection within the configuration file while Def_initial is about the initial conditions for the model to compute irrigation at day 0

```
# dynamic processes irrigation
def dynamic(self,pcr,pcrm,ETpot,ETact,rootwater):

    # Irrigation to be applied only when Crops are into the field.
    UnderCultivation = pcr.ifthenelse(self.Kc != self.KcBaresoil , self.IrrigatedLand ,0)
    #Crop Available water within RootZone
    Taw = (self.RootField-self.RootDry)
    #Depletion Factor
    d   = pcr.max(pcr.min(self.PMap + 0.04 * (5 - ETpot), 0.8), 0.1)
    # Readily available water
    Raw = (Taw * d )
    #Plant and soil specific soil moisture content from which plant water stress starts to occur
    RootPWS = (self.RootField - Raw)
    # Crop water Stress coefficient
    Ks = pcr.max(pcr.min((self.RootWater - self.RootDry) / (RootPWS - self.RootDry),1),0)
    #Actual Evapotranspiration horticulture area Rambla del Albujon
    CropETa = ETact * self.IrrigatedLand
    #Potential Evapotranspiration horticulture area Rambla del Albujon
    CropETp = ETpot *self.IrrigatedLand

    #BASELINE SCENARIO
    if self.IrrigationMethod == 1:
        #RAW depletion threshold.
        threshold = (self.RootField - Raw*self.MAD ) * self.IrrigatedLand
        #Delivering Irrigation
        IrrigationScheduling = pcr.ifthenelse( self.RootWater <= threshold, Raw*self.Replenishment,0) * self.IrrigatedLand

    #ET DEFICIT
    elif self.IrrigationMethod == 2
        IrrigationScheduling= pcr.ifthenelse(ETpot- ETact >0,ETpot- ETact,0) * self.IrrigatedLand

    #STATIC CROP WATER STRESS THRSHOLD
    elif self.IrrigationMethod == 3 :

        IrrigationScheduling = pcr.ifthenelse(Ks <= self.KsTable, Raw*self.Replenishment,0) *self.IrrigatedLand

    #Computation net irrigation water
    IrrigationWater = (IrrigationScheduling/self.IrrigationEfficiency) * UnderCultivation
    #Time series irrigation water samount within the Rambla del Albujon
    IrrigationTOT= pcr.areatotal((IrrigationWater/1000)*pcr.cellarea(),self.clone)
    #Time series actual evapotranspiration withimn the Rambla del Albujon
    HorticultureETa = pcr.areatotal((CropETa/1000)*pcr.cellarea(),self.clone)
    #Time series potential evapotranspiration within the Ramboa del Albujon
    HorticultureETp = pcr.areatotal((CropETp/1000)*pcr.cellarea(),self.clone)


    return IrrigationWater,IrrigationTOT,HorticultureETa,HorticultureETp
```

Figure 22. Irrigation model. Def_dynamic holds all the computation done in order to implement each scheduling irrigation method

A2 Rambla del Albujon data

No data are available for the study area hence, data on crop yield and irrigation delivered to the Campo de Cartagena have been clipped to the Rumbla del Albujon. To do so, surface land data of the Rambla del Albujon are required. Then, thanks to QGIS has been possible to adapt the data of the Campo de Cartagena to the new study area. The function used to retrieve the area of each land use has been the Raster unique value function whilst a simple raster calculation has made conceivable the clipping of data. Table 13 provides the surface area of each rotation from the Campo de Cartagena to the study area

Table 13 Crop combination surface area (km^2) Campo de Cartagena & Rambla del Albujon

Crop Rotations	Campo de Cartagena	Rambla del Albujon
Lettuce	7033	4324
Artichokes	9824	6360
Broccoli – Melon	11241	91040
Lettuce – Melon	3757	23120

Yield for each land use and irrigation delivered to the Campo de Cartagena have been obtained through literature researches. Contreas and Hunink (2014) conducted a study within the Campo de Cartagena stating that the amount of water supplied to the agriculture area in order to meet crop water requirements was about 155 hm^3 /y in an agriculture acreage of 32.366 ha. Estructura agraria (2011) stated that the irrigated area in the period between 2002-2011 swung from 30.831 and 34.131 ha. Yields data throughout the Campo de Cartagena come from Martin-Gorriz et al (2016) Final yields and the total irrigation supply have been adapted to the study area as follows:

$$\frac{22100\ (\text{ha})}{32366(\text{ha})} * 155\ \left(\frac{\text{m3h}}{\text{y}}\right) = 106\ \text{hm}^3/\text{y} \tag{12}$$

Then:

(106*1000000) / 22100 = 4800 m^3/ha (13)

Where:

22100 ha = Horticulture area of the Rabla del Albujon

32366 ha = Agriculture area of the Campo de Cartagena

155 hm^3/y = Amount of Irrigation delivered to the Campo de Cartagena (Contreas et al.,2014)

4790 m^3/ha = Reference irrigation amount for the Rambla del Albujon

Same procedure has been carried out to adapt reference yield values of each rotation to the Rambla del Albujon. Contrary to equation 13 the ratio was different for each land use class.

Table 13 Yield (ton/ha)for the Campo de Cartagena (Soto & Garcia et al., 2013) adapted to the Rambla del Albujon for the four combinations

Combinations	**Ratio**	**Yield Cartagena**	**Yield Albujon**
Lettuce	*0.6*	*35*	*20*
Artichokes	*0.65*	*23*	*15*
Broccoli -- Melon	*0.8*	*25*	*20*
Lettuce – Melon	*0.6*	*38*	*23*

A3 Studies on crops sensitivity to water stress

Horticulture crops respond differently to water shortage based on their growing period. The mid-season stage is the most sensitive to water shortages (Brouwer et al., 1989). This is mainly because it is the period of the highest crop water needs and when water shortages occur during the mid-season stage, the negative effect on the yield will be pronounced. Yet crops grown for their fresh leaves or fruits are more sensitive to water shortages than those grown for their dry seeds or fruit. Crops such as lettuce and broccoli are featured with shallow roots. Shallow roots require more frequent application of water than deep root crops by lowering their receptiveness to water shortage. At the experimental research fields of the Agricultural Faculty of Canakkale in Turkey four different water deficit were applied to test the effects of water stress on Broccoli. Irrigation was applied when TAW was depleted till 90,80,60 and 40 percent of its content. Data obtained from treatments revealed that severe levels of water deficit should not be implemented for an economical broccoli culture in Canakkale (Erken et al., 2013). The centre for Agriculture, Food and the Environment of the University of Massachusetts(2015) corroborated Erken's (2013) research by underscoring broccoli's sensitivity to water shortage in the head development stage. Studies on lettuce show its sensitivity to water stress by suggesting that an exposure to extensive or intense drought events could negatively affect both physiological performance and productivity. Nevertheless, a slight decrease in water availability can enable lettuce plants to maintaining high levels of physiological performance and productivity(Molina-Montenegro et al., 2011, Ahmad et al., 2016, Kuslu et al., 2008) Contrary melon turns out to be less sensitive to water shortage when irrigation is not supplied throughout its growing period compared to the above mentioned crops. Nonetheless a reduction in water supply during the fruiting phase significantly affects plant yield, water use efficiency and fruit weight (Nwokwu et al., 2018). On the other hand, artichokes response to different water regimes shows a low tolerance to dry conditions. Ruttanaprasert (2016) studied the responses of Artichokes to various soil moisture levels stating that it is not a drought resistant crop as biomass was reduced greatly under stress with a high reduction in yield. Rusttanaprasert (2016) research was in line with Liu (2012) and Monti (2005).

A6 Sensitivity analysis

Figure 23 shows how among the four scenarios only the baseline responded positively to a variation in organic matter(OM). Figure23 displays a reduction in irrigation and in turn actual evapotranspiration when the organic matter content has been increased of 20 percent. This is due to the fact that when the organic matter goes up the water soil water holding capacity increases thereby reducing irrigation application .On the other hand, when its content increases up to 40 and 60 percent the model seems to no perceive such a change. The deficit scheduling irrigation methods have not reacted well to a variation in organic matter. As for the baseline scenario they turned out to be sensitive to a 20 percent change in organic matter but the response in terms of irrigation and actual evapotranspiration is unclear. However, they reacted well to a change in bulk density, Figure 24. As expected, the irrigation supply has increased as the bulk density content has gone down. This is explained by a reduction in actual evapotranspiration which has triggered irrigation water supply due to high stress experienced by the crops. An increase in bulk density, lower soil porosity, has led to low values of $ETred_{dry}$and $ETred_{wet}$.

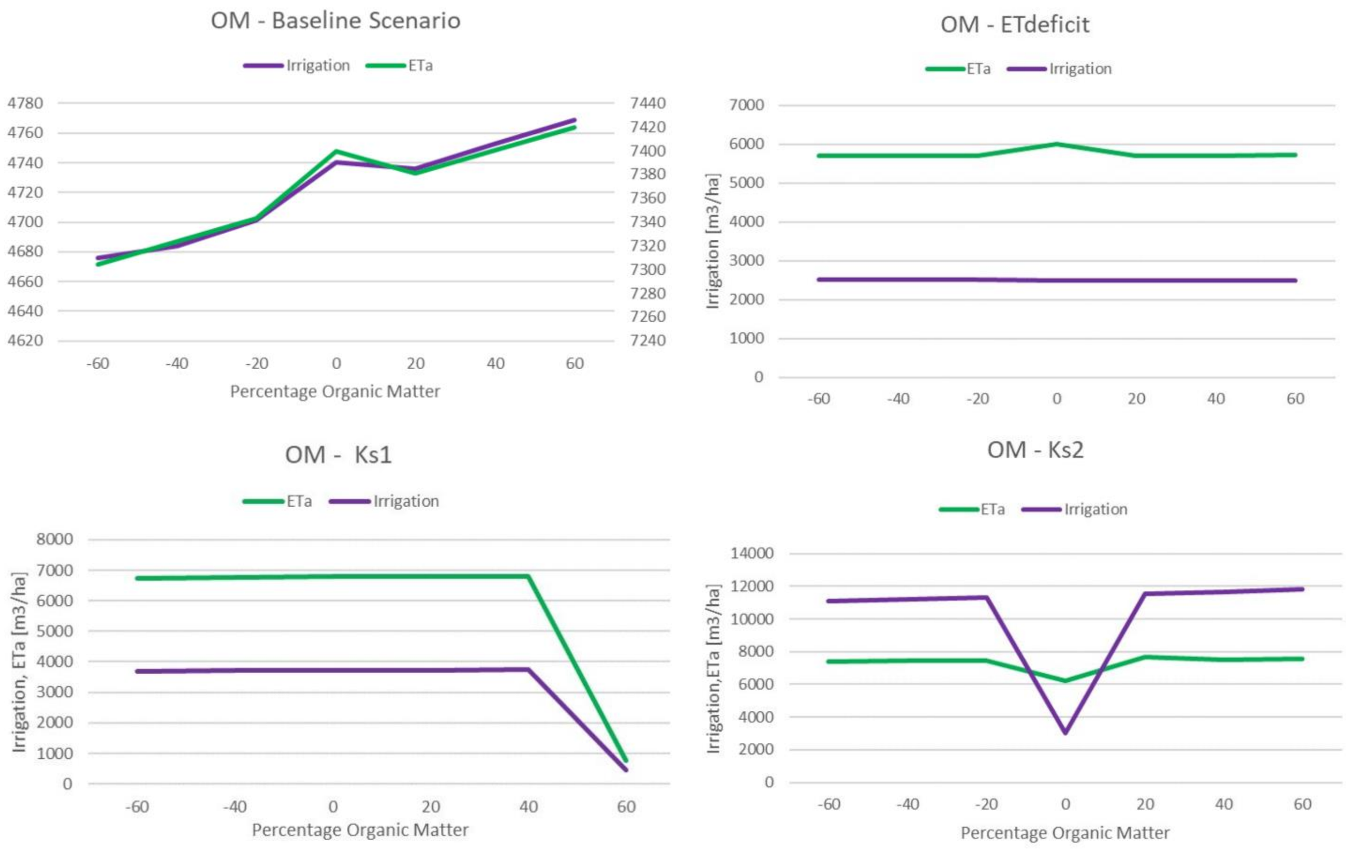

Figure 23.Baseline scenario and deficit scheduling irrigation techniques response to a change in organic matter (OM). Figure (a) displays the baseline scenario response , (b) the evapotranspiration deficit whereas c and d the ks1 and ks1 static crop water stress thresholds

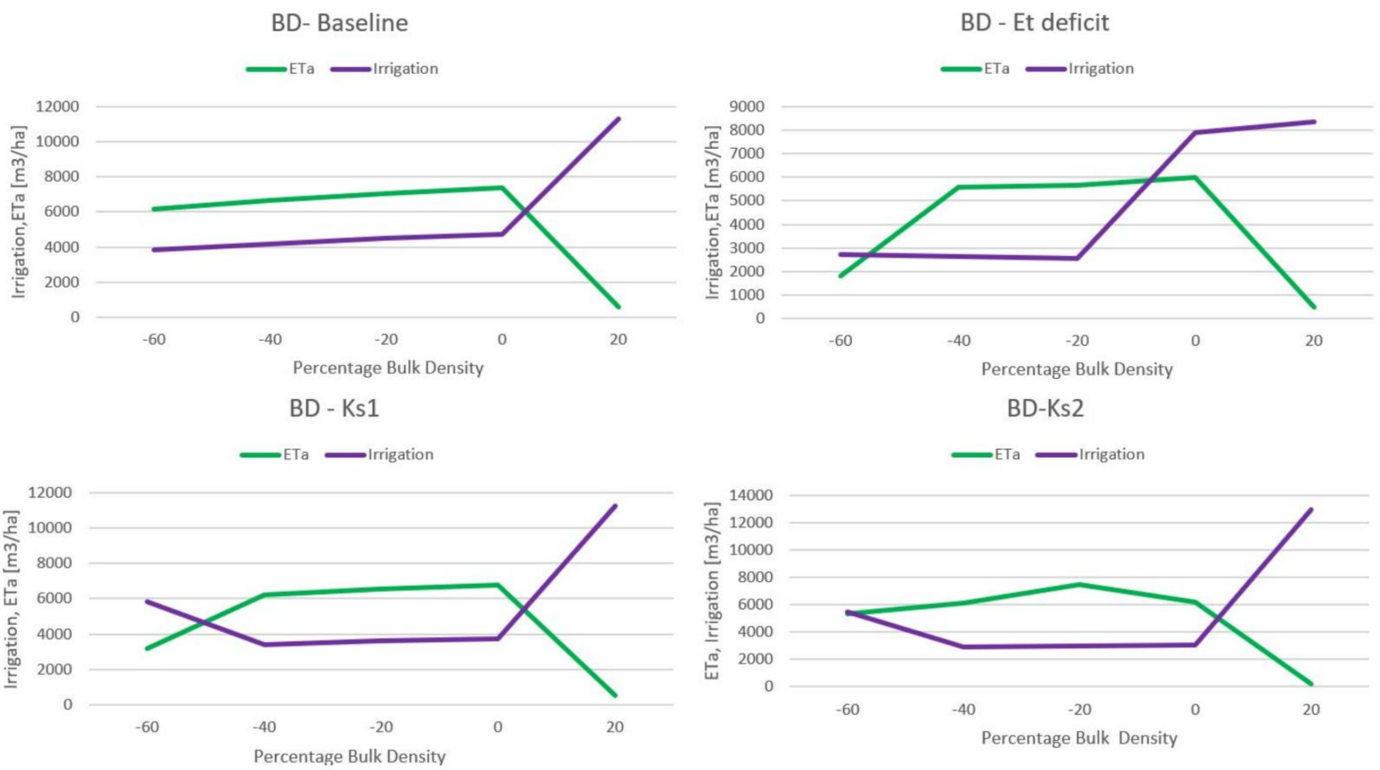

Figure 24. Baseline scenario and deficit scheduling irrigation techniques response to a change in bulk density (BD). Figure (a) displays the baseline scenario response , (b) the evapotranspiration deficit whereas c and d the ks1 and ks1 static crop water stress thresholds

A7 Baseline scenario

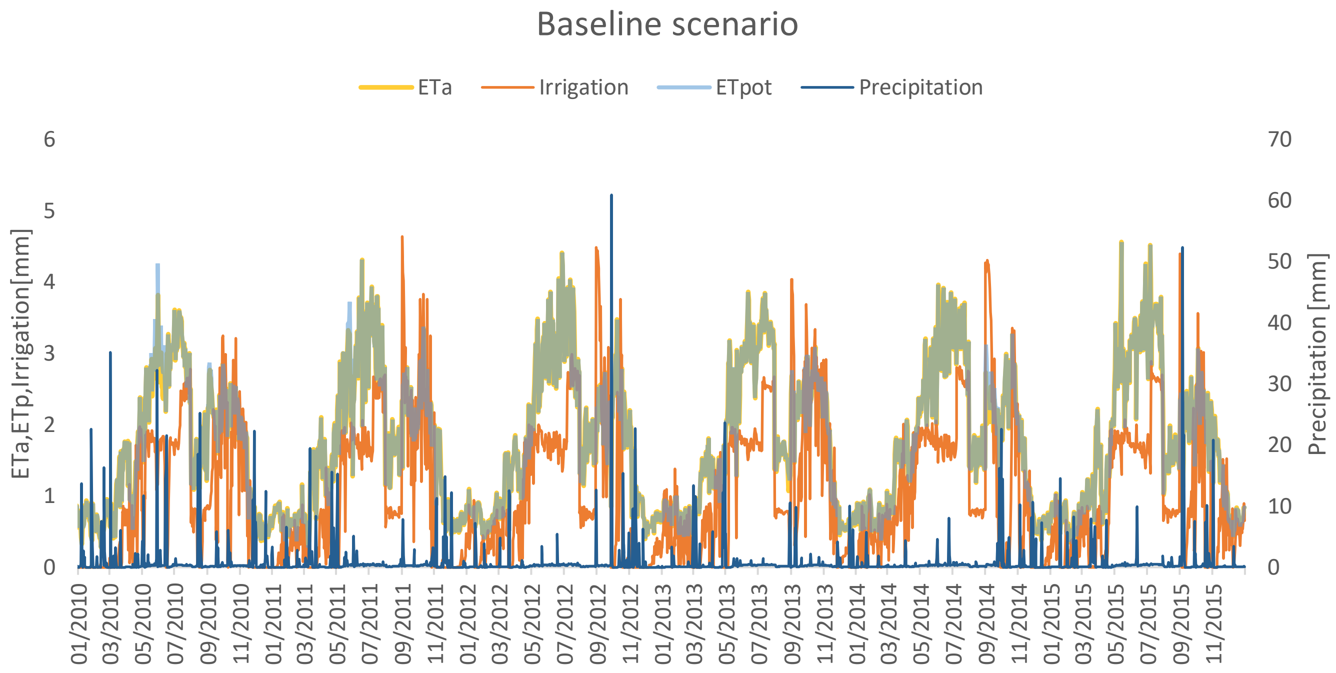

Figure 25 Baseline scenario ETa, irrigation, ETpot and precipitation time series (2010-2015)

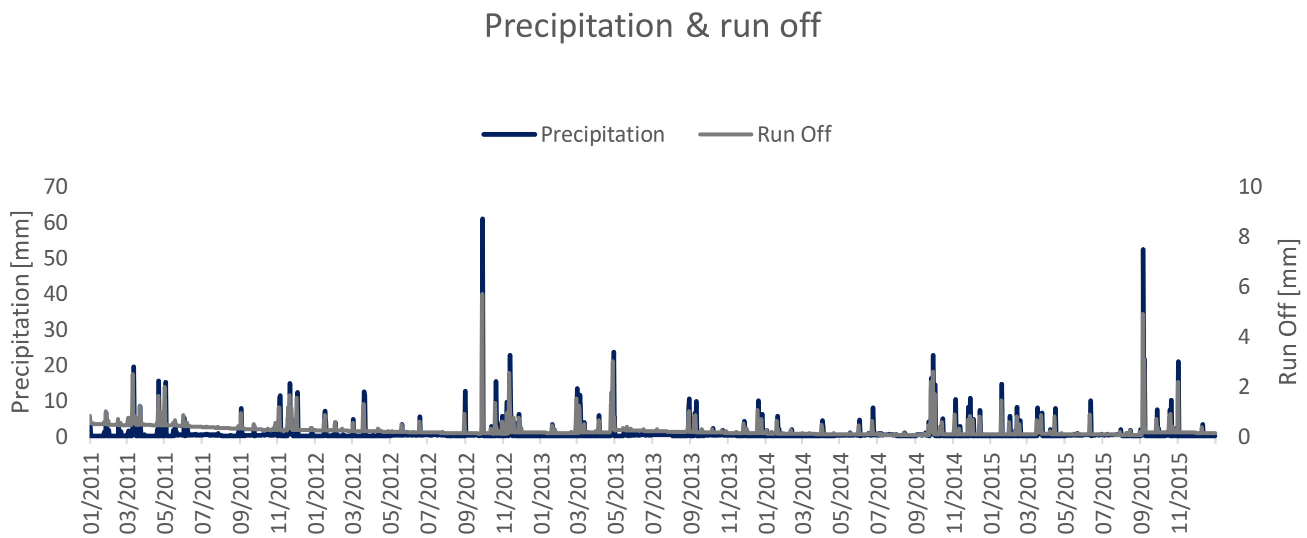

Figure 26. Baseline scenario precipitation & run off time series 2011-2015

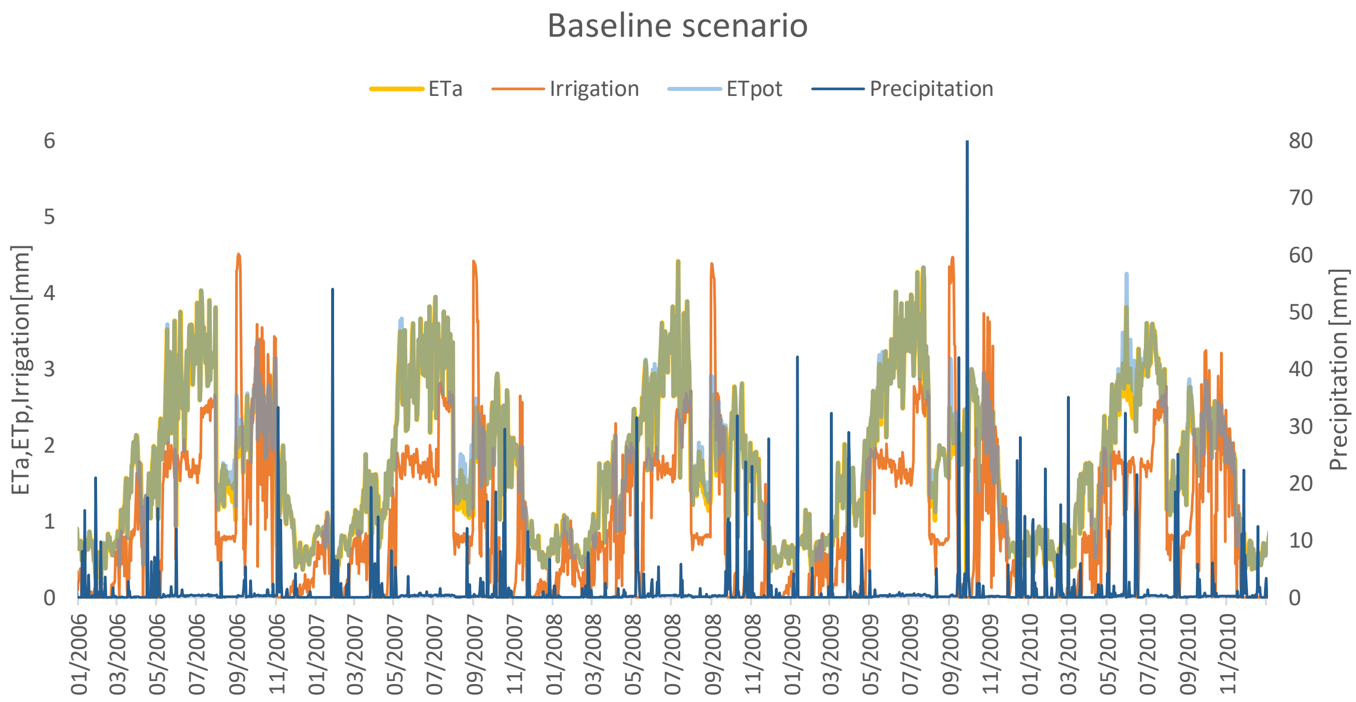

Figure 27 Baseline scenario ETa, irrigation, ETpot and precipitation time series (2006-2010)

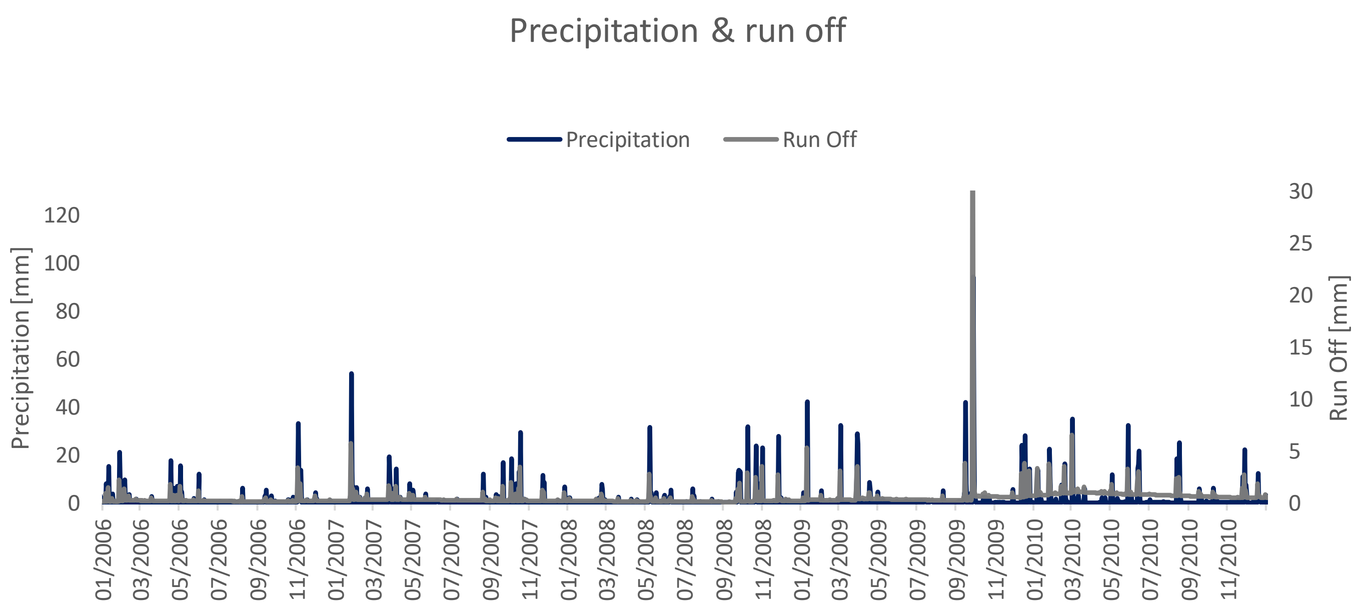

Figure 28 Baseline scenario precipitation & run off time series 2006-2010

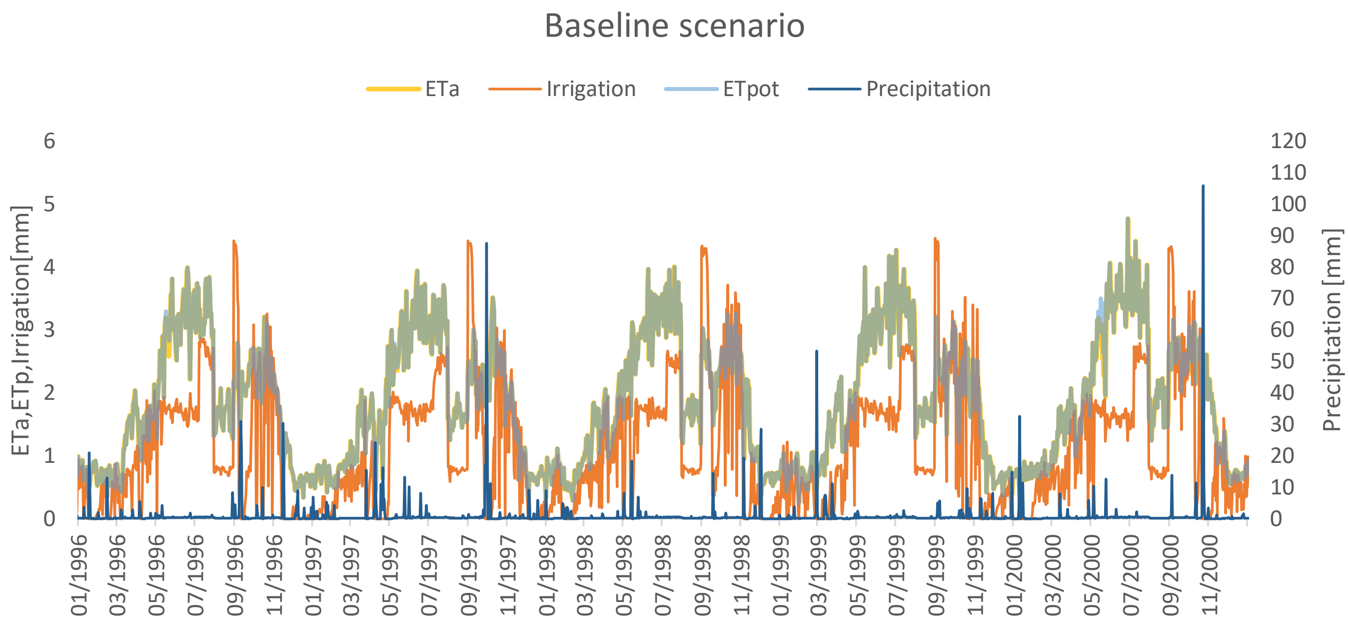

Figure 29 Baseline scenario ETa irrigation, ETpot and precipitation time series (1996-2000)

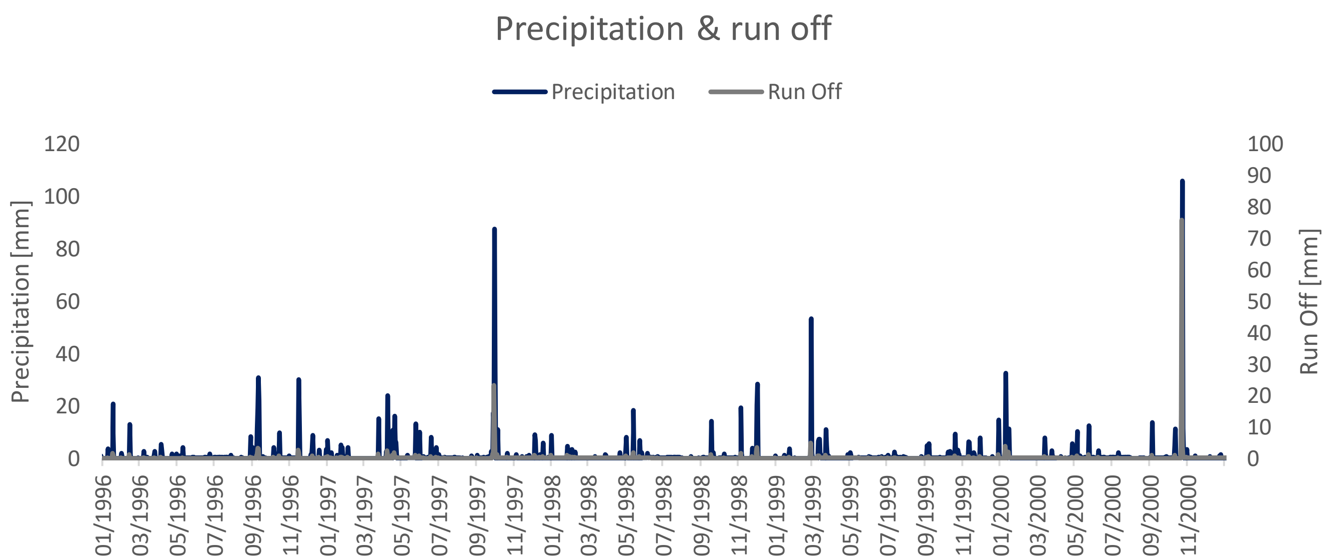

Figure 30 Baseline scenario precipitation & run off time series 1996-2000

A8 Evapotranspiration deficit

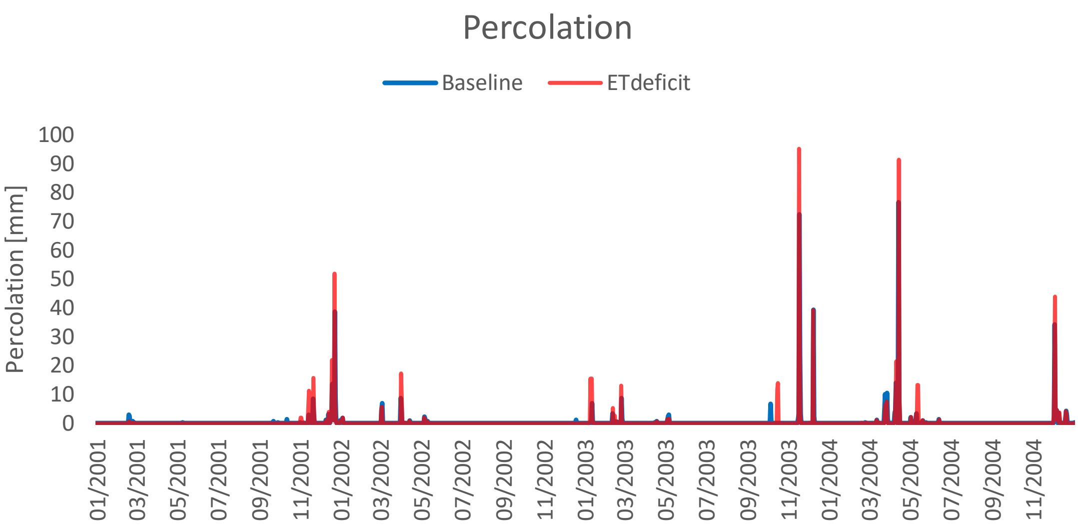

Figure 31 Percolation rates between the Baseline and the ET deficit scenarios (2001-2004)

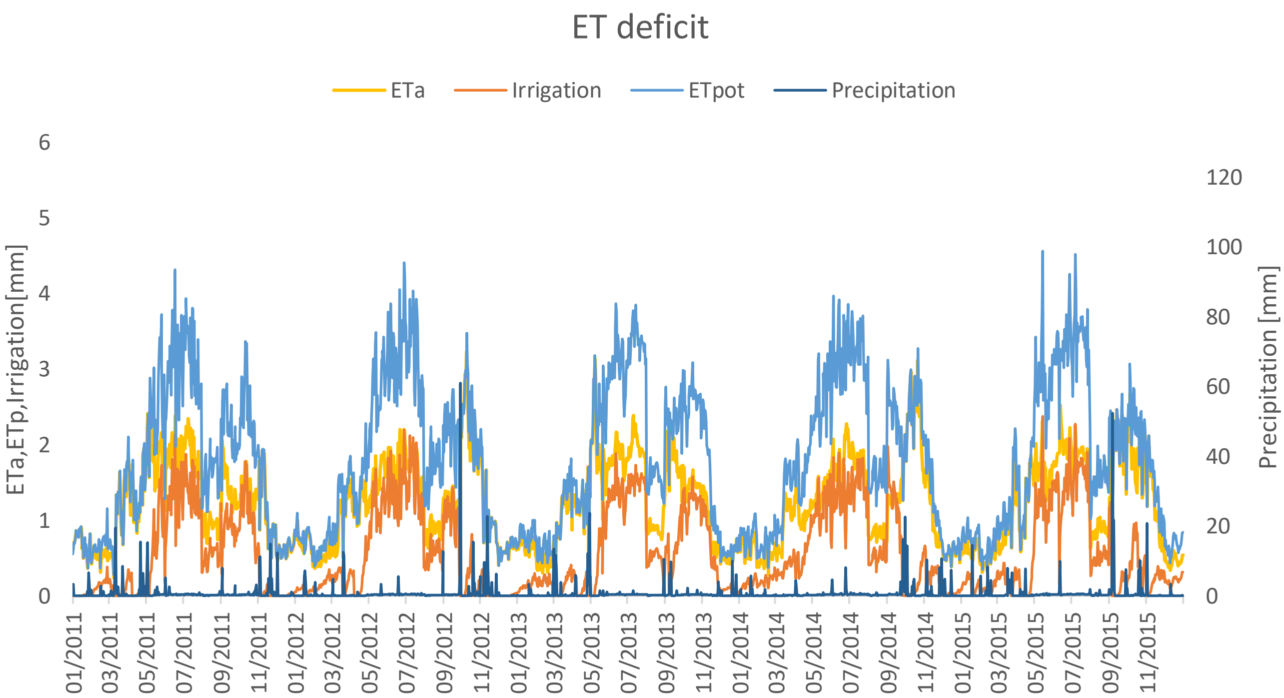

Figure 32 ETa, Irrigation, ETpot, Precipitation for the ET deficit scenario (2011-2015)

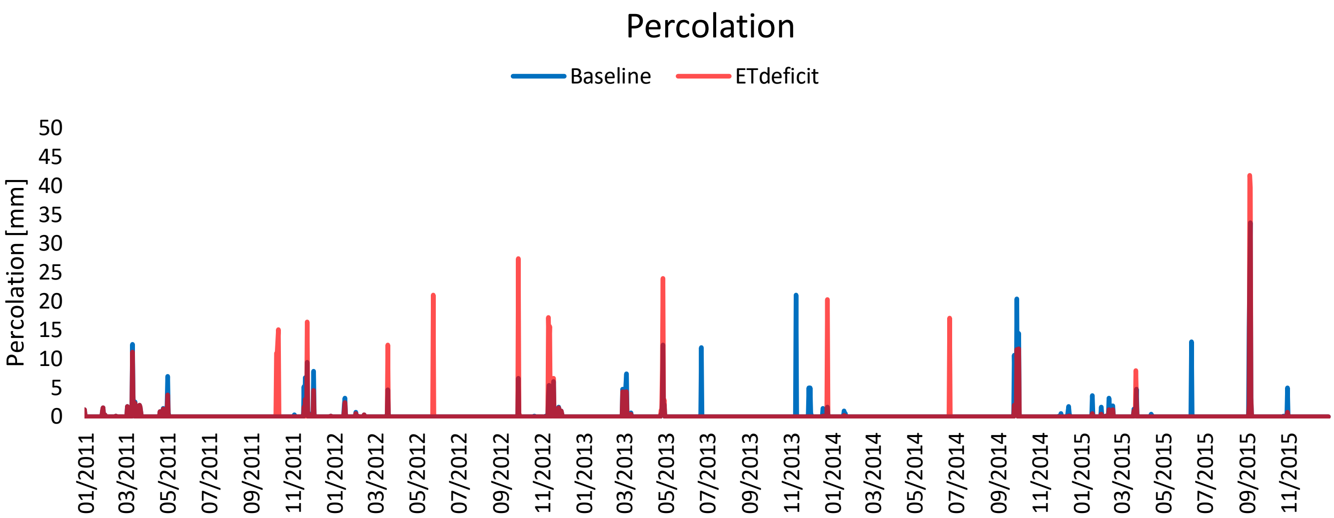

Figure 33 Percolation rates between the Baseline and the ET deficit scenarios (2011-2015)

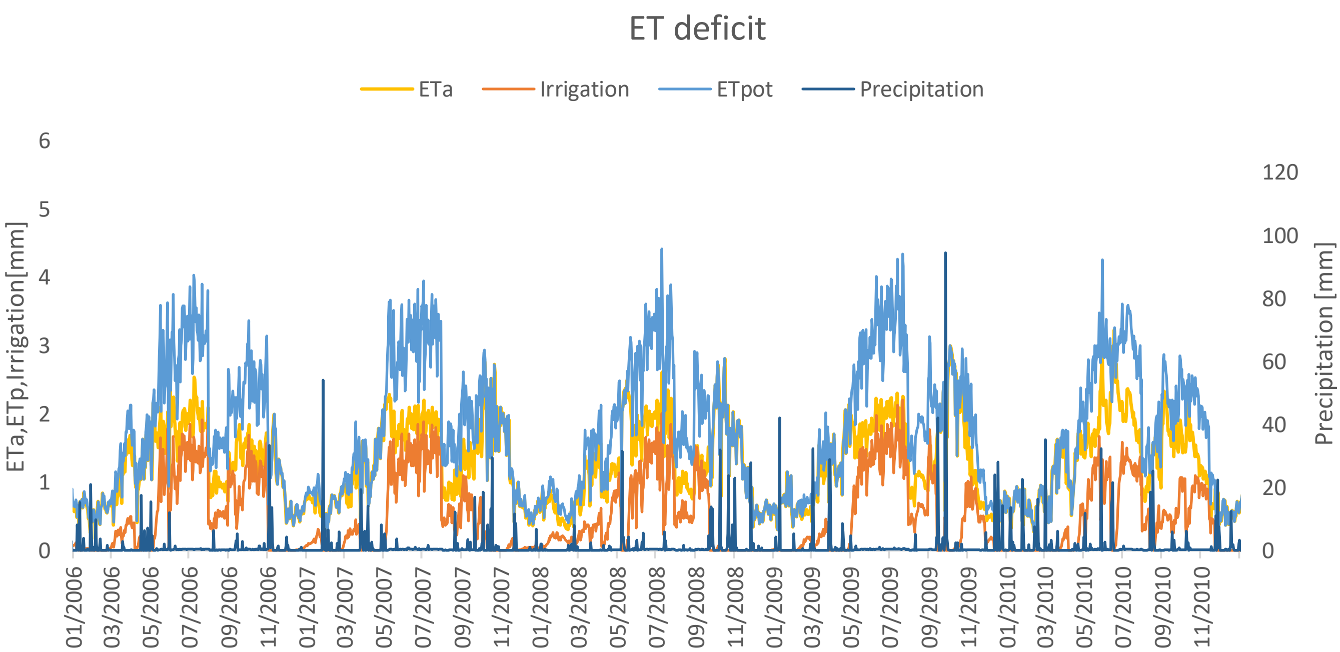

Figure 34 ETa, Irrigation, ETpot, Precipitation for the ET deficit scenario (2006-2010)

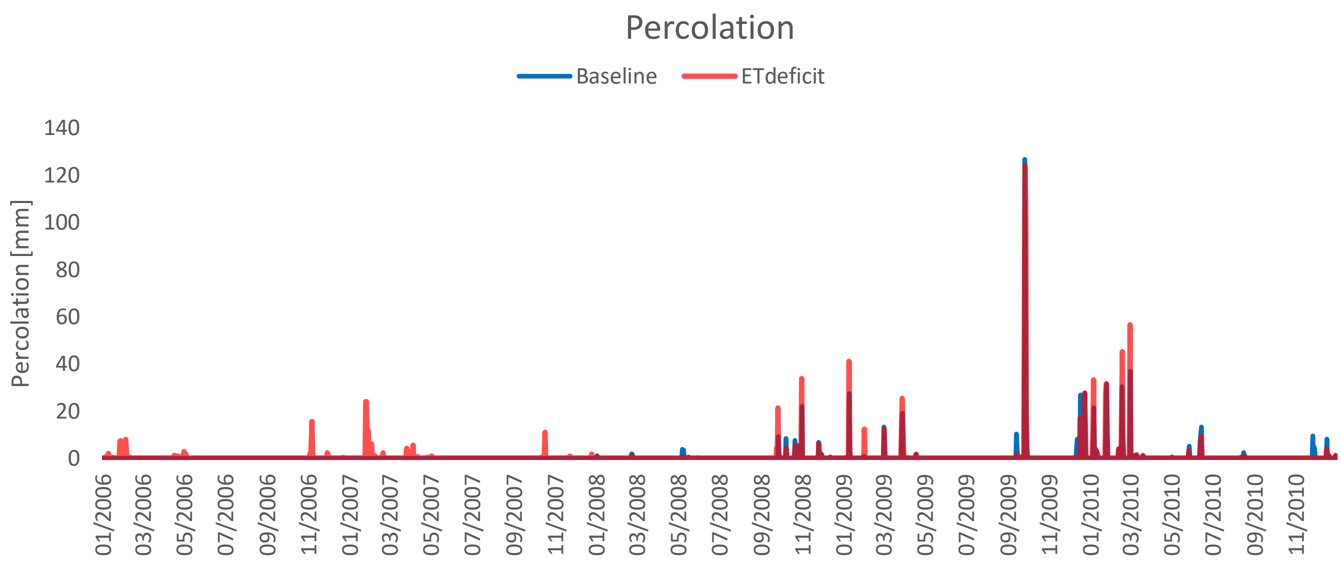

Figure 35 Percolation rates between the Baseline and the ET deficit scenarios (2006-2010)

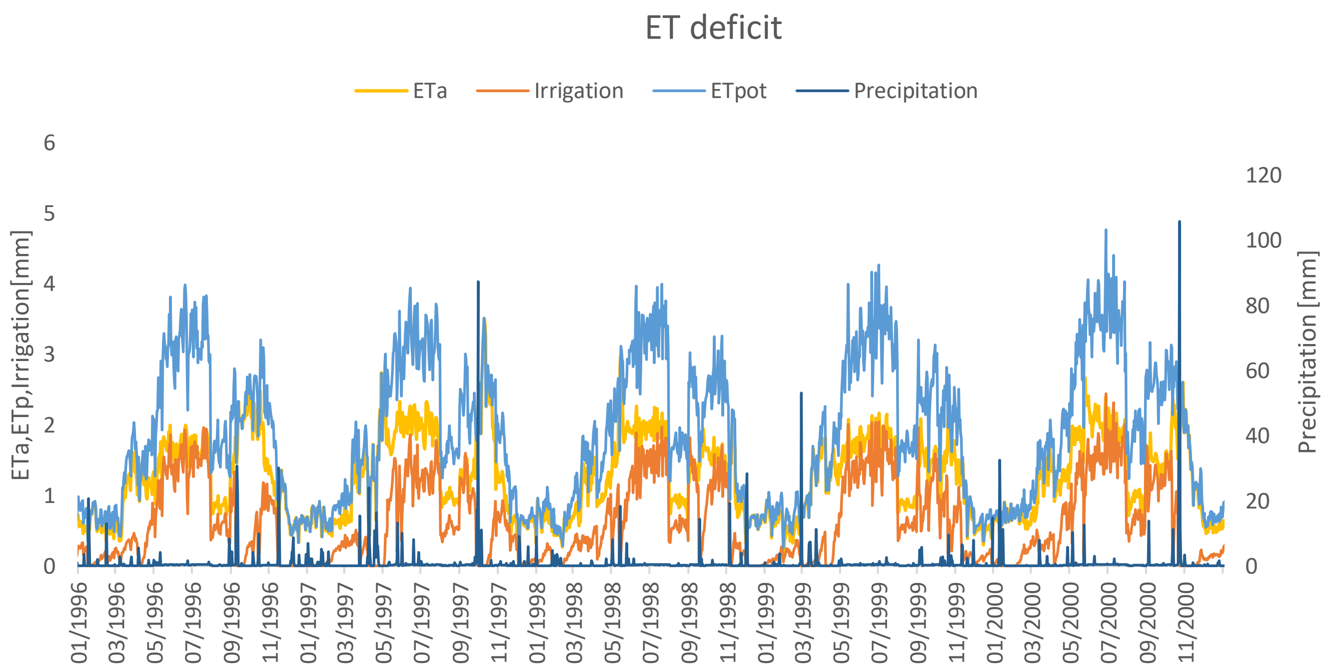

Figure 36 ETa, Irrigation, ETpot, Precipitation for the ET deficit scenario (1996-2000)

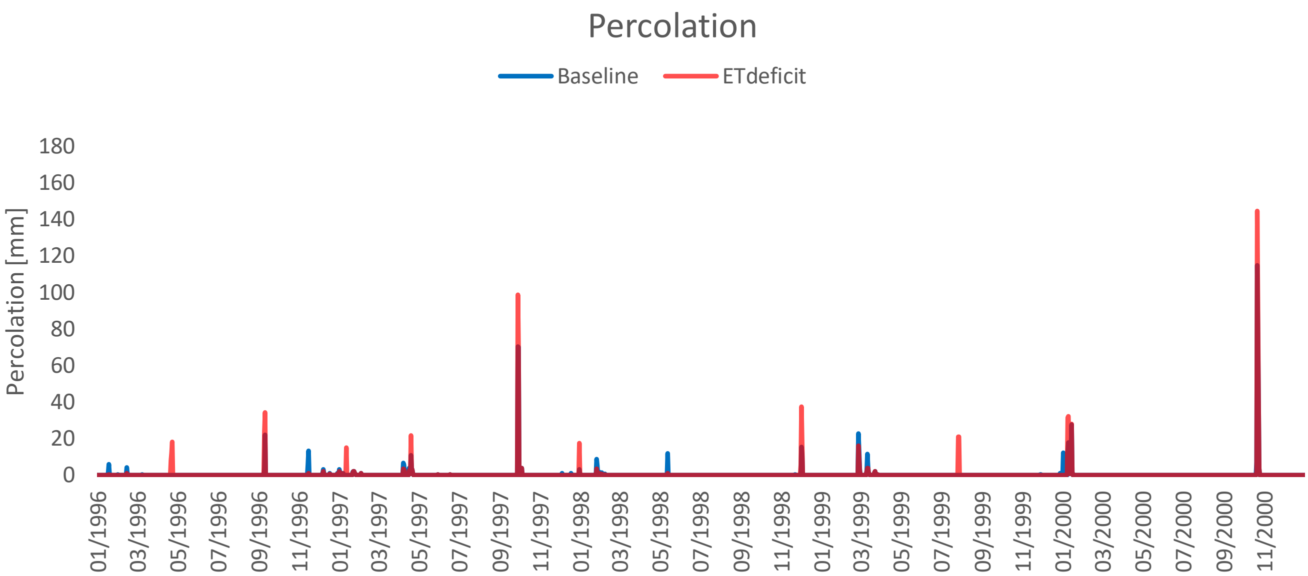

Figure 37 Percolation rates between the Baseline and the ET deficit scenarios (1996-2000)

A9 Static crop water stress threshold

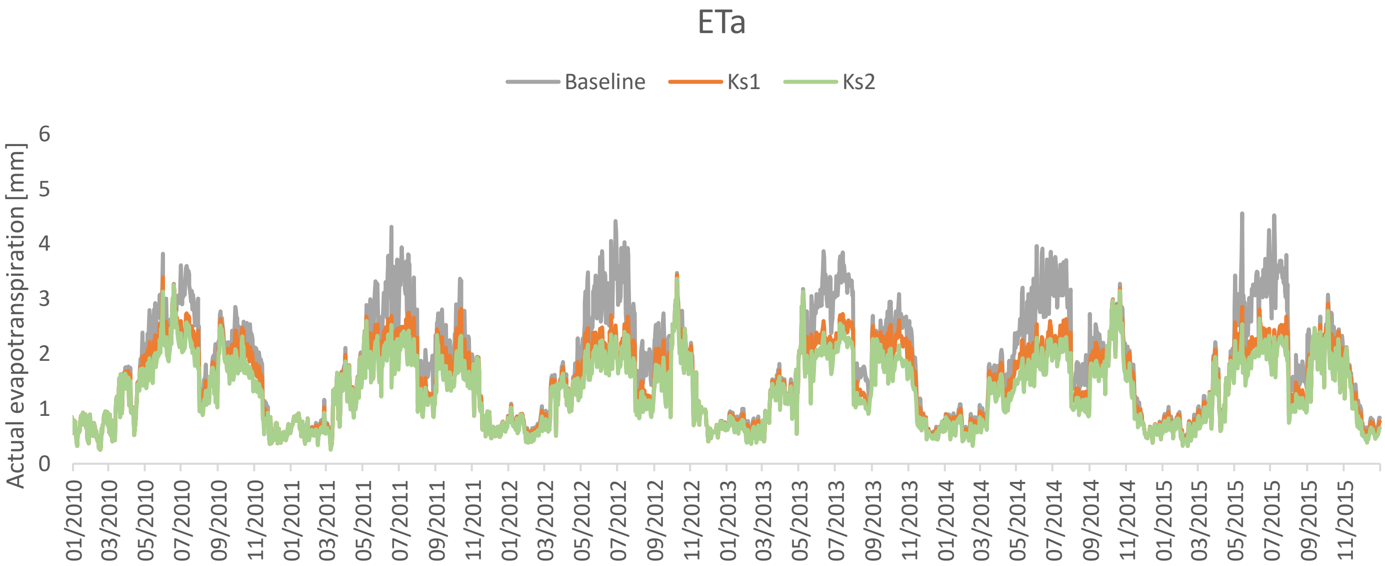

Figure 38 ETa comparison between the baseline and the two static crop water stress thresholds, Ks1 and Ks2. Period 2010-2015

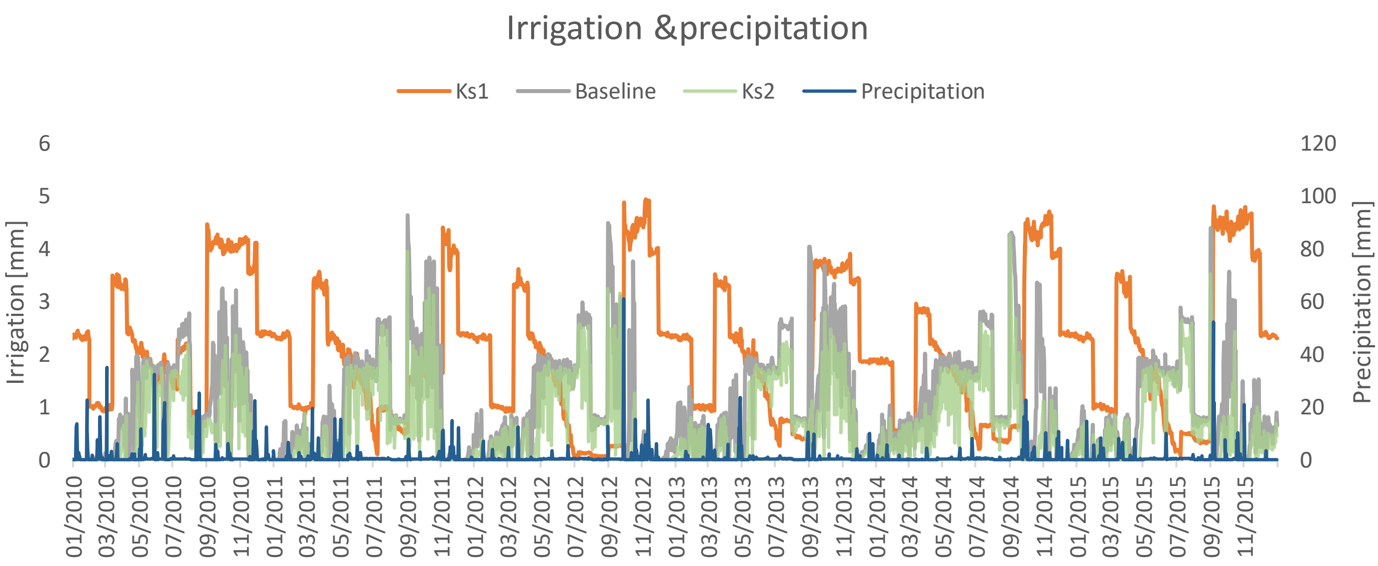

Figure 39 Irrigation amount comparison between the baseline and the two static crop water stress thresholds, Ks1 and Ks2. Period 2010-2015

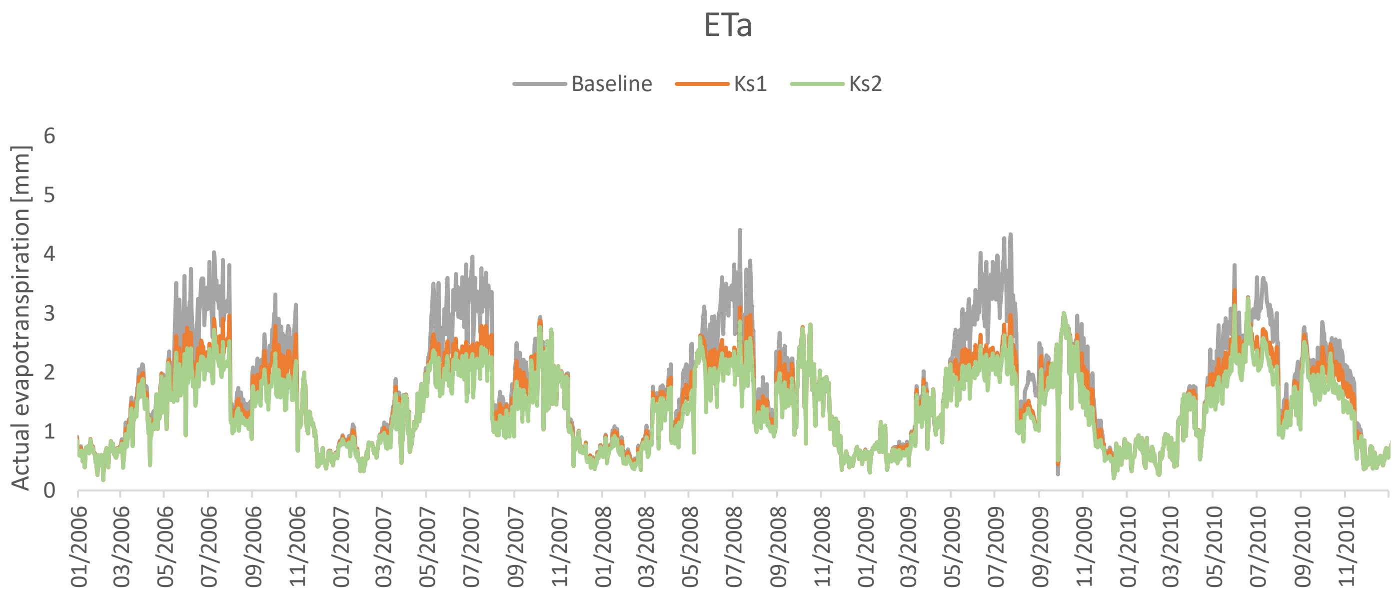

Figure 40 ETa comparison between the baseline and the two static crop water stress thresholds, Ks1 and Ks2. Period 2006-2010

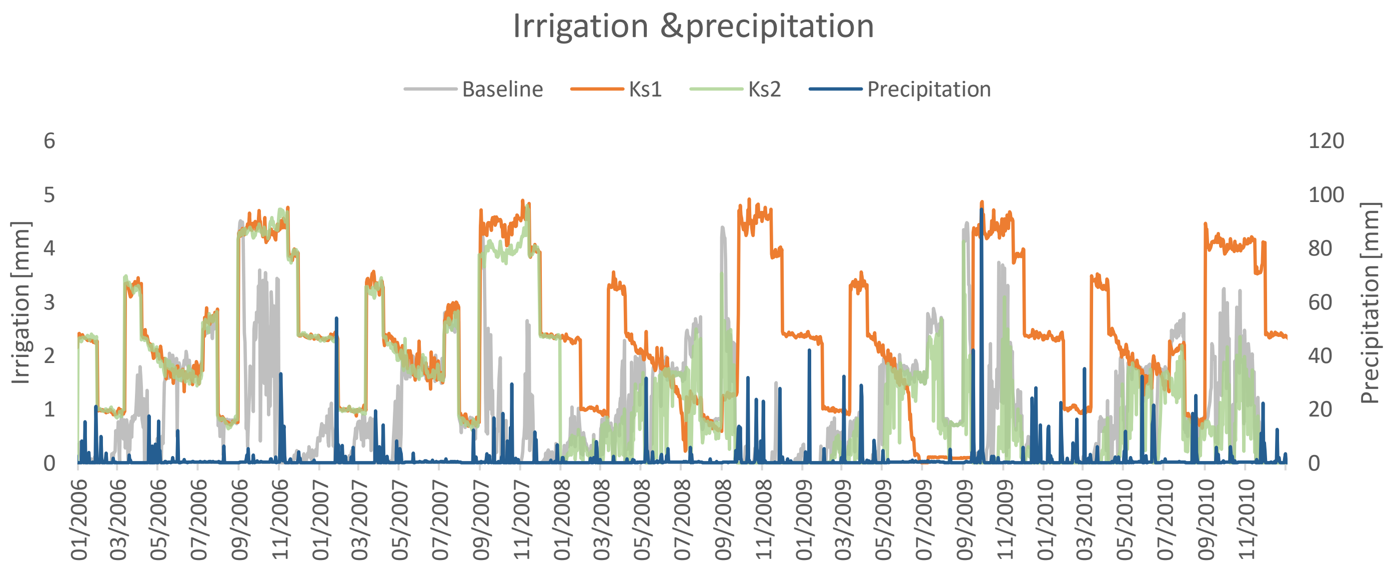

Figure 41 Irrigation comparison between the baseline and the two static crop water stress thresholds, Ks1 and Ks2. Period 2006-2010

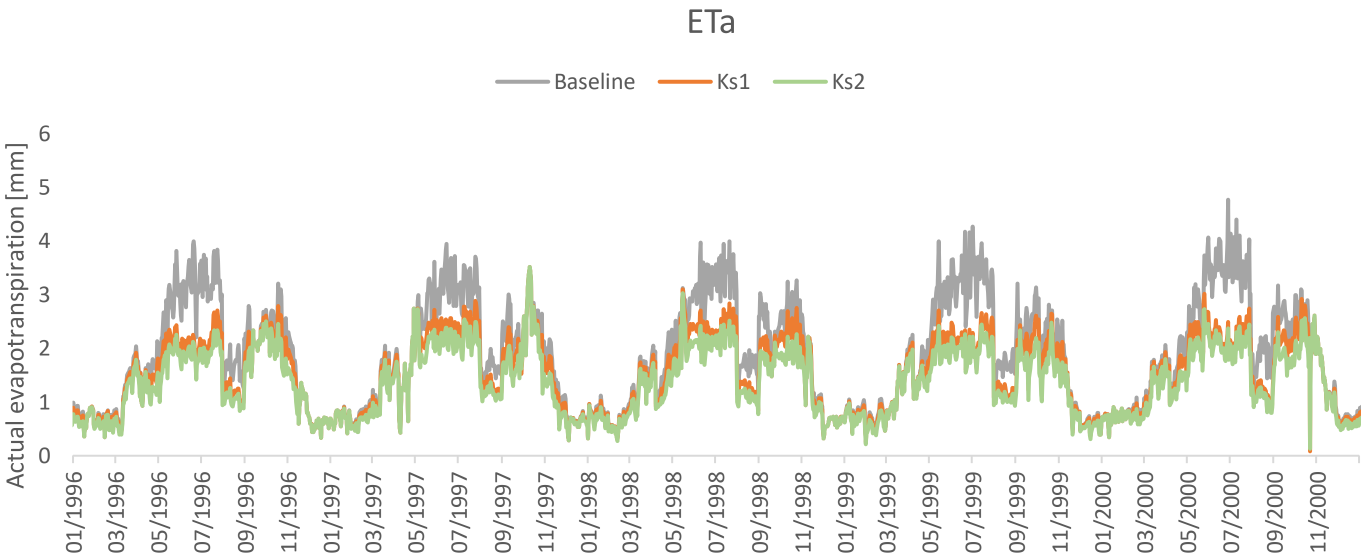

Figure 42 ETa comparison between the baseline and the two static crop water stress thresholds, Ks1 and Ks2. Period 19966-2000

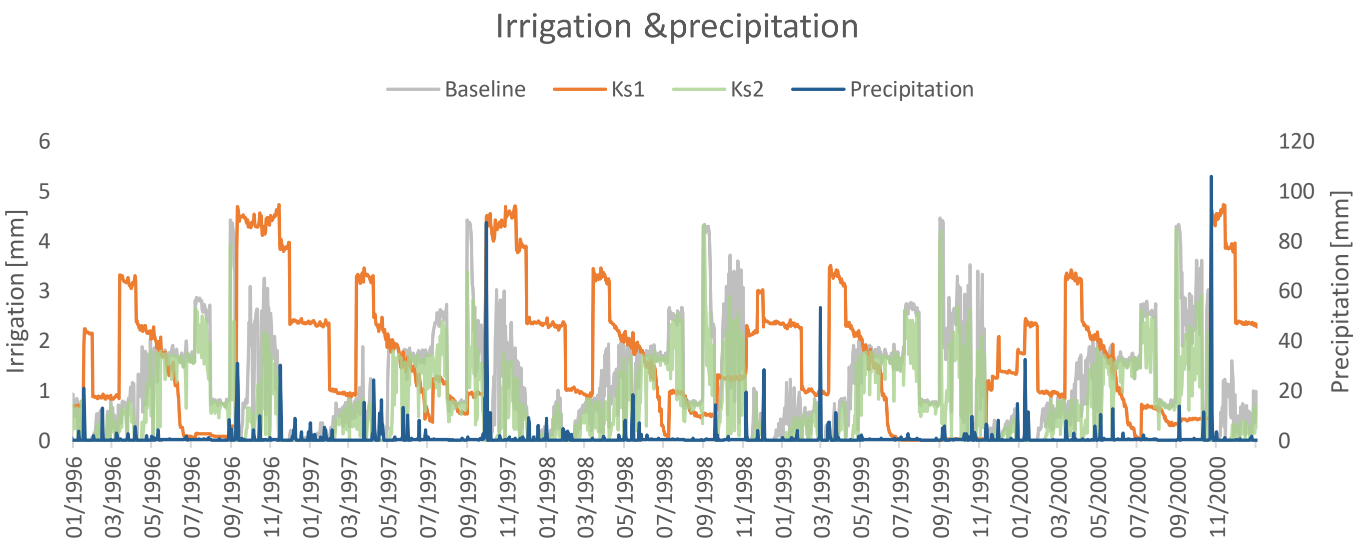

Figure 43 Irrigation comparison between the baseline and the two static crop water stress thresholds, Ks1 and Ks2. Period 1996-2000