Precision Irrigation under Full and Deficit Irrigation for Adaptation to Climate Change

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Introduction

❖ **Agriculture with irrigation** is the main consumer of the world's water resources.

❖*The contribution of irrigated agriculture to food production is important.*

❖Sustainability of irrigated agriculture would demand the efficient management of the available finite water resources under the existing constraints.

Introduction

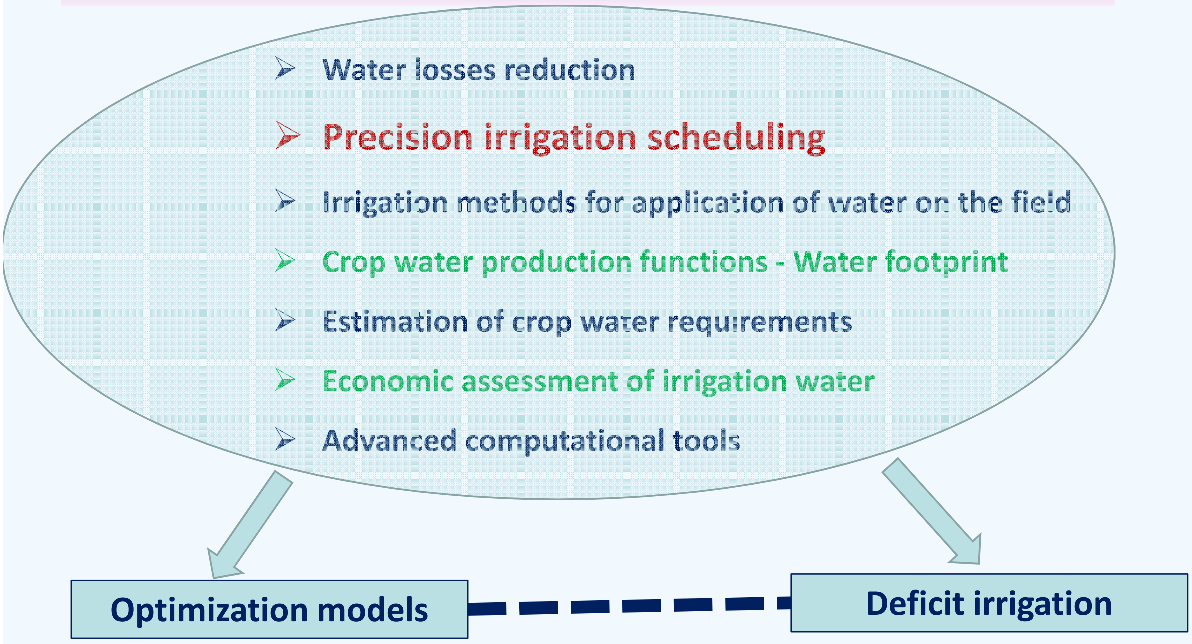
- **Climate change** is considered as a critical factor for water resources management.
- *Negative consequences of climate change are directly related to hydrological processes and **crop production**.*
- To address the challenges caused by climate change, **adaptation measures** should be adopted by decision makers.

Introduction

- Traditionally, agricultural research is focused primarily on maximizing the yield per unit area by allocating water to different crops according to their water requirements.
- ***In the recent years, the research focuses to increase water productivity within the constraints of available limited water resources.***

Introduction

Best Irrigation Management Practices



- Water losses reduction
- Precision irrigation scheduling
- Irrigation methods for application of water on the field
- Crop water production functions - Water footprint
- Estimation of crop water requirements
- Economic assessment of irrigation water
- Advanced computational tools

Optimization models

Deficit irrigation

Introduction

❖ **Deficit irrigation** has been suggested as a way to increase system benefits, at the cost of individual benefits, by decreasing the crop water allocation and increasing the total irrigated land.

❖ *For an irrigation area with limited available water resources, deficit irrigation can be applied successfully by means of the optimization of the crop water allocation; the reduction of the profit compared to full irrigation condition is minimized.*

Introduction

❖ The purpose of this study is to develop an **optimization model** with an **integrated soil water balance model**, in the framework of ***precision irrigation principles,*** to determine

- ❑ the optimal reservoir release policies,
- ❑ the irrigation allocation to multiple crops and
- ❑ the optimal cropping pattern

under **different climate change scenarios** and **irrigation conditions**.

Problem Formulation

❖ The **optimization model** is developed for optimal operation of an irrigation reservoir for determining the ***optimal water allocation and crop pattern*** of an irrigated area under **full and deficit irrigation.**

❖*The problem may be considered to be one of maximizing the utilization of the available water supply when conflicts between supply and demand occur during each time interval in the irrigation season.*

Problem Formulation

❖ *The reservoir storage constitutes the system's state variable, whereas the system inputs – commonly referred to as decision variables - are the water release by the reservoir for each crop in each time interval to satisfy irrigation requirements.*

Problem Formulation

❖ *Decision making for irrigation water allocation involves many subtle considerations such as:*

- ❑ *the nature and timing of the crop being irrigated,*
- ❑ *its stage of growth,*
- ❑ *the competition among different crops for the available water,*
- ❑ *the effect of a deficit water supply on the crop yield and*
- ❑ *the variability of soil characteristics.*

Problem Formulation

Objective Function

$$Z=\begin{cases}\max\limits_{A_i,R_{i,j}}\sum\limits_{i=1}^{n}\left[P_i\cdot(Y_m)_i\cdot\prod\limits_{j=1}^{k}\left((ET_a)_{i,j}/(ET_m)_{i,j}\right)^{\lambda_{i,j}}-\left(B_i+C_i\right)\right]A_i, & \text{deficit irrigation}\\ \max\limits_{A_i}\sum\limits_{i=1}^{n}\left[P_i\cdot(Y_m)_i-\left(B_i+C_i\right)\right]A_i, & \text{full irrigation}\end{cases} \quad (1)$$

where: **Z=** total net farm income (€),

P= product price (€/kg),

Y_m= maximum crop yield under given management conditions that can be obtained when water is no limiting (kg/ha),

ET_a= actual evapotranspiration (mm),

ET_m= maximum evapotranspiration (mm),

λ= sensitivity index,

B= fixed cost (€/ha),

C= variable cost (€/ha),

A= cultivation area (ha), **n=** number of crops, **k=**number of time intervals, **i=** cultivation crop and **j=** time interval.

Problem Formulation

Constraints

Reservoir water balance

$$S_{j+1}=S_j+Q_j+P_j-\sum_{i=1}^{n}R_{i,j}-E_j-L_j-SP_j \quad (2)$$

where:

S= reservoir storage,

Q= reservoir inflow,

P= rainfall in reservoir,

R= reservoir release,

E= reservoir evaporation,

L= leakage to groundwater,

SP= spillway overflow,

i= cultivation crop and **j=** time interval.

Problem Formulation

Soil water balance

The soil water balance, express in terms of depletion for any given crop i and time interval j is given as follows:

$$(D_r)_{i,j+1} = (D_r)_{i,j} - ERAIN_{i,j} - IR_{i,j} + (ET_a)_{i,j} + (TAW_{i,j+1} - TAW_{i,j}) \quad \textbf{(3)}$$

where:

$(D_r)_{i,j+1}$= root zone depletion of crop i at the end of time interval j+1 (mm),

ERAIN= effective rainfall (mm),

IR= net irrigation depth that infiltrates the soil (mm),

ET_a= actual evapotranspiration (mm) and

TAW= total available soil water in the root zone (mm).

Problem Formulation

- The **total available soil water (TAW)** refers to the total amount of water available in the root zone that can be utilized by the crop.
- *The soil water content at **field capacity (FC)** and **permanent wilting point (PWP)** are respectively the upper and lower limits of TAW.*
- FC is the quantity of water that a well-drained soil would hold against the gravitational forces.
- PWP is the soil water content at which plants stop extracting water and will permanently wilt.

Problem Formulation

Reservoir release

The irrigation requirements specify the maximum releases of the reservoir, which are given by:

$$\left(R_{max}\right)_{i,j} = IR_{i,j} / CE = \left[\left(1-p_{i,j}\right)TAW_{i,j} + \left(ET_m\right)_{i,j} - \left(SW_{in}\right)_{i,j} - ERAIN_{i,j}\right] / CE \qquad \textbf{(4)}$$

where:

R_{max}= maximum release from reservoir to meet irrigation requirements (mm),

$P_{i,j}$= allowable deficit level (fraction of TAW),

SW= available soil water (mm) and

CE= conveyance efficiency.

Problem Formulation

Actual evapotranspiration

The actual evapotranspiration ET_a is determined by:

$$ET_a = k_s \cdot ET_m \qquad \textbf{(5)}$$

$$k_s = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{\left(1-p_m\right)TAW} \qquad \textbf{(6)}$$

where:

k_s is soil water stress coefficient,

RAW= readily available soil water in the root zone (mm),

Problem Formulation

D_r will be greater than RAW at the water stress condition (deficit irrigation) and can be written as:

$$D_r = \begin{cases} p_s \cdot \mathrm{TAW}, & \text{deficit irrigation} \\ p_m \cdot \mathrm{TAW}, & \text{full irigation} \end{cases} \qquad \textbf{(7)}$$

where:

p_s= allowable deficit level (fraction) of TAW at water stress condition (deficit irrigation) and

p_m= the fraction of TAW without suffering water stress (full irrigation).

Optimization Algorithm

- ❖ **Simulated annealing (SA),** is an efficient method for finding the global optimal (or a suboptimal) solution to multidimensional optimization problems based on mathematical simulation of systematic heating and cooling of materials and formation of crystals having minimum energy.
- ❖ *The main structure of a SA is mainly based on three operators:*
  - ➢ ***a temperature cooling schedule,***
  - ➢ ***a function for generating a perturbation and***
  - ➢ ***a state transition with an acceptance probability.***

Optimization Algorithm

- First, a feasible set of random normally distributed crop areas and reservoir releases is created.
- *These random releases effectively produce a random-walk for the system state trajectory, which satisfies eq. (2).*
- In the context of SA, the solution vector of reservoir releases and crop areas corresponds to an aggregated state q.
- *The total net farm income (eq. 1) can be expressed as a function Z=-E(q), and corresponds to an energy, which can be minimised by simulated annealing.*

Optimization Algorithm

- The **SA procedure** as all metaheuristic algorithms, in problems of high multidimensionality and for a quite large – yet finite number of iterations, usually **produce near-optimal solutions**.
- In order to enhance the performance of our optimization approach in terms of time consuming and accuracy, the SA solution is further refined with the incorporation of a stochastic gradient descent algorithm.

Optimization Algorithm

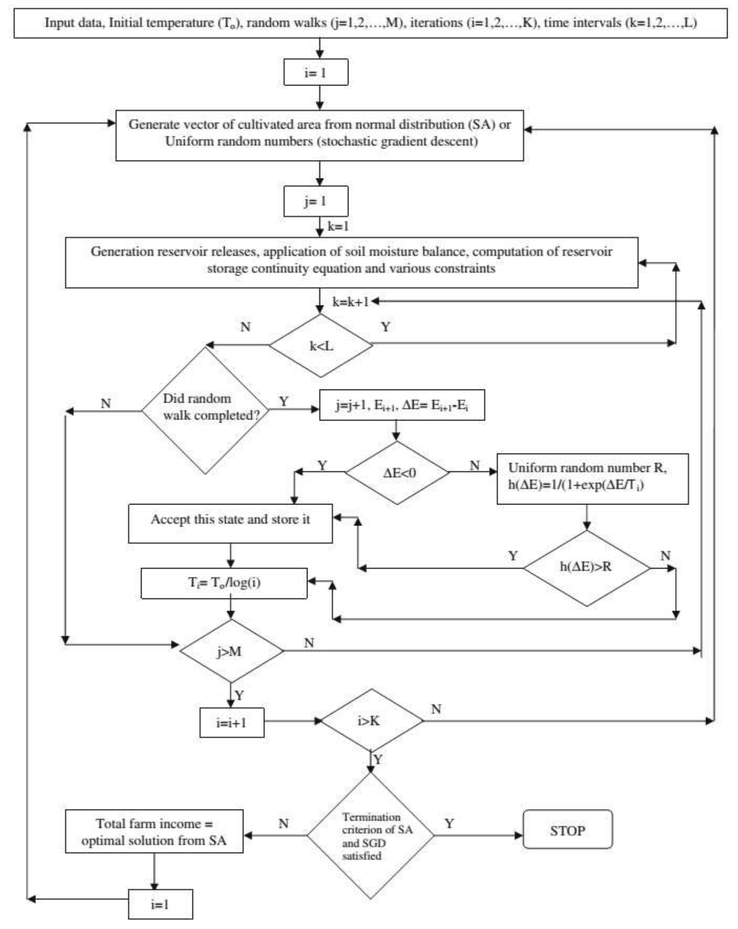


Figure 1. Flow chart of the proposed model which is solved using the simulated annealing (SA) in combination with the stochastic gradient descent algorithm.

Study area and Data

The main source of irrigation water in the region is from a planned reservoir on the Havrias river.

Useful reservoir capacity
26 hm^3

Dead capacity
4.3 hm^3.

Study area and Data

Table 1. Main parameters and critical data of the crops in the study area

	Corn	Cotton	Tomato	Watermelon	Olive	Apricot
Minimum area (ha)	50	50	50	50	50	50
Maximum area (ha)	125	1,350	1,135	590	20,125	1,835
Maximum yield (kg ha^{-1})	14,500	3,900	66,600	80,000	7,540	10,000
Product price (€ kg^{-1})	0.14	0.79	0.32	0.13	1.29	1.00
Variable cost (€ ha^{-1})	1,043	1,565	11,316	3,658	3,724	4,706
Maximum net profit (€ ha^{-1})	987	1,516	9,996	6,742	6,003	5,294

Study area and Data

❑ The proposed optimization model can handle homogenous and heterogeneous soil.

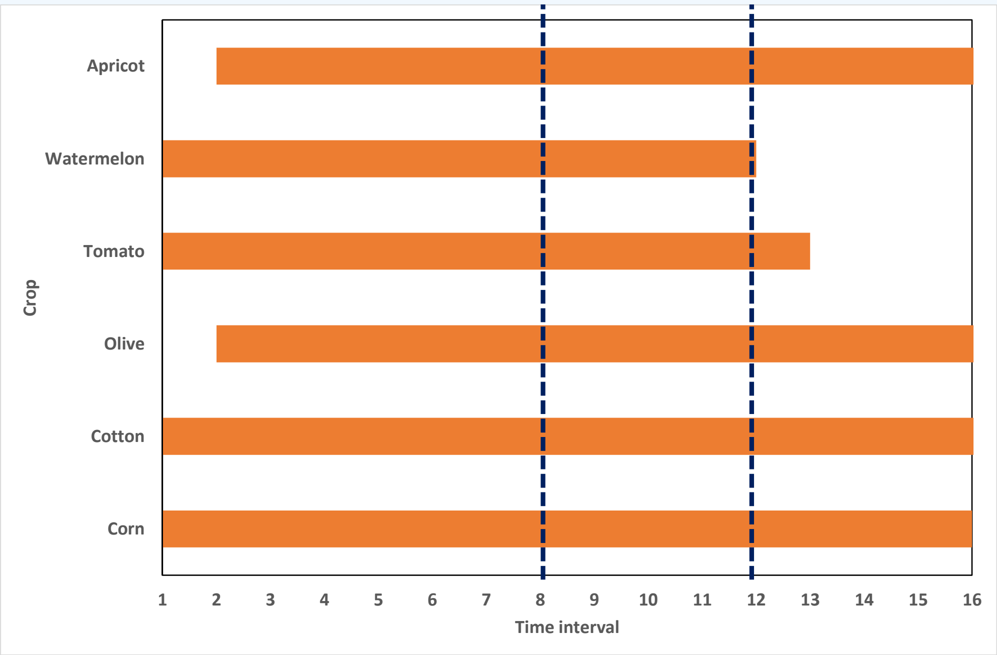
❑ *One soil layer characterized as clay loam (CL) with FC=0.27 cm^3/cm^3 and PWP=0.15 cm^3/cm^3 is used.*

❑ Due to higher rainfall during the non-irrigation season, it is assumed that soil water content at the beginning of the irrigation season is at Field Capacity.

❑ *The mean efficiency for drip irrigation method and pressurized irrigation system is assumed to be equal 0.85.*

Study area and Data

Figure 2. Duration of irrigation period for each crop



Climate Change Scenarios

Intergovernmental Panel on Climate Change

Climate change refers to:

- ☐ a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer
- ☐ any change in climate over time, whether due to natural variability or as a result of human activity

Climate Change Scenarios

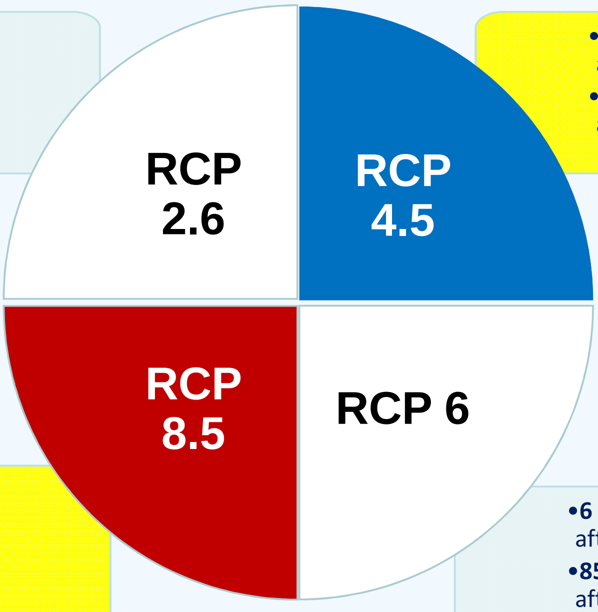
- ☐ *Climate change is considered a major problem worldwide that requires careful assessment:*
- Climate change **is unequivocal and is evident from:**
  - **increases in global average air and ocean temperatures,**
  - **widespread melting of snow and ice,** and
  - **rising global sea level**
- **Global mean temperature will increase** by the late 21st century (2081-2100) relative to 1986-2005, by **1°C to 3.7°C according to RCPs scenarios** (IPCC)
- Climate warning **is associated with changes on hydrological and meteorological systems** (changing precipitation patterns, intensity and extremes, melting of snow and ice, increasing atmospheric water vapour and evaporation and changes in soil moisture and runoff)

Climate Change Scenarios

Representative Concentration Pathways - RCPs

- **a set of four new pathways** developed for the climate modeling community which are **used as input to climate models for long-term and near-term projections of possible future climate change**
- **important development in climate research and provide plausible descriptions of how the future may evolve with respect to a range of variables** (socio-economic change, technological change, energy and land use and emissions of greenhouse gases)

Climate Change Scenarios



- **peak at 3 W m^{-2}** before 2100 and then declines
- **peak at 490 ppm CO_2** before 2100 and then declines

- **4.5 W m^{-2}** at stabilization after 2100
- **650 ppm CO_2** at stabilization after 2100

- **> 8.5 W m^{-2}** in 2100
- **> 1370 ppm CO_2** in 2100

- **6 W m^{-2}** at stabilization after 2100
- **850 ppm CO_2** at stabilization after 2100

Climate Change Scenarios

☐ Climate Models are primary tools for:

- **investigating the response of the climate system** to various forcings
- **making climate predictions** on seasonal to decadal time scales and
- **making projections of future climate** over the coming century and beyond

○ Earth System Models (ESMs):

- **the current state-of-the-art** climate models
- **the most comprehensive tools available for simulating past and future response** of the climate system to external forcing
- **include the representation of biogeochemical cycles** important to climate change

Climate Change Scenarios

Earth System Models - ESMs

CanESM2

- Canadian Centre for Climate Modelling and Analysis (CCCma) - Canada
- 2.81 long x 2.79 lat atm. resolution

HadGEM2-ES

- Met Office Hadley Center for Climate Science and Services (MOHC) - United Kingdom
- 1.875 long x 1.25 lat atm. resolution

Climate Change Scenarios

Climate Models

are run at coarse spatial resolution and ***are unable to resolve important sub-grid scale features*** such as clouds and topography

Downscaling Methods

are developed to obtain local-scale weather and climate

Downscaling Methods

❑ **Downscaling** is any procedure to infer high-resolution information from low-resolution variables

❑ **Downscaling techniques**:

1. **Dynamical downscaling**
2. **Statistical downscaling**
   - ✓ Weather Types
   - ✓ Regression Methods
   - ✓ **Weather Generators**

Climate Change Scenarios

Weather Generator - ClimGen

- **Stochastic Weather Generators:**
  - **used to produce synthetic weather time series**, which are expected to be statistically similar to the observed weather time series for a location of interest
  - **used as downscaling tools** to produce high-resolution climate change projections and
  - **are usually combined with hydrological and environmental models** for water resources and environmental management

ClimGen

Stochastic model that generates synthetic weather time series of weather variables (Pr, T_{max}, T_{min}, Rs, RH_{max}, RH_{min}, U) in daily time step

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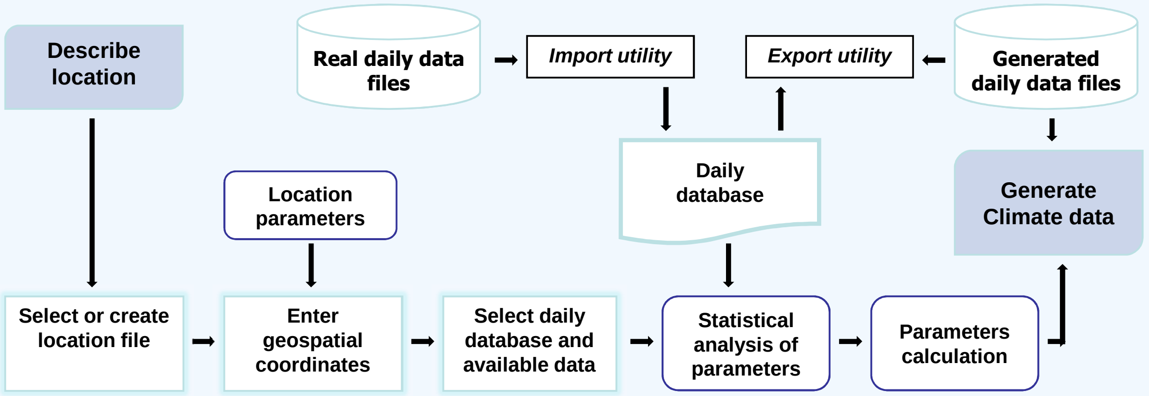
Climate Change Scenarios



Process of generating consists of the following steps:

i. **Describing or geolocating** the study area
ii. **Preparing the location parameters with statistical analysis** of the weather data
iii. **Generating the data**
iv. **Exporting the data** to available file formats

Climate Change Scenarios

- Based on the data derived from the ***two Earth System Models (CanESM2 and HadGEM2-ES)*** the downscaling of a ***21-year data set (1977-1997)*** of daily climate variables performed using the weather generator ClimGen for the generation of synthetic time series which depict the future change of the climate variables.
- The observed and generated weather data series were used for the estimation of reference evapotranspiration, effective rainfall and reservoir inflow for ***the period of climate change 2081-2100 under RCP 4.5 and RCP 8.5 scenarios.***

Results and Discussion

- The reference crop evapotranspiration was derived from daily climatic data of the region by the FAO Penman-Monteith equation.
- Effective rainfall was computed from the procedure which is described by USDA.
- Monthly inflow was computed from a simple rainfall – runoff model.
- In the cost calculations, it was assumed that farmers own the land, thus fixed cost (B) is equaled zero. The variable cost (C) for each crop was computed from data supplied by the Region of Central Macedonia, Greece.

Results and Discussion

The model was run for four cases

- **Historical period 1977-1997 under full irrigation**
- **Historical period 1977-1997 under deficit irrigation**
- **Climate change period 2081-2100 under full irrigation**
- **Climate change period 2081-2100 under deficit irrigation**

Results and Discussion

Table 2. Differences in mean annual temperature (°C) of the region according to CanESM2 and HadGEM2-ES under RCP4.5 and RCP8.5 during 2081-2100 in relation 1977-1997

Mean annual Temperature (T_{mean} °C)				
Historical 1977-1997	**Earth System Model - RCP**			
	CanESM2 RCP4.5	*CanESM2 RCP8.5*	*HadGEM2-ES RCP4.5*	*HadGEM2-ES RCP4.5*
14.36	**17.47**	**20.42**	**18.27**	**20.97**
ΔT_{mean}(°C)	3.11	6.06	3.91	**6.61**

Results and Discussion

Table 3. Differences in mean annual precipitation (mm) of the region according to CanESM2 and HadGEM2-ES under RCP4.5 and RCP8.5 during 2081-2100 in relation 1977-1997

Mean annual Precipitation (mm)				
Historical 1977-1997	**Earth System Model - RCP**			
	CanESM2 RCP4.5	*CanESM2 RCP8.5*	*HadGEM2-ES RCP4.5*	*HadGEM2-ES RCP4.5*
425	**378**	**371**	**420**	**371**
ΔPr(mm)	-47	**-54**	-5	**-54**
	-11.1%	**-12.7%**	-1.2%	**-12.7**

Results and Discussion

Table 4. Differences in mean annual reference evapotranspiration (mm) of the region according to CanESM2 and HadGEM2-ES under RCP4.5 and RCP8.5 during 2081-2100 in relation 1977-1997

Mean annual Reference evapotranspiration (mm)				
Historical 1977-1997	**Earth System Model - RCP**			
	CanESM2 RCP4.5	*CanESM2 RCP8.5*	*HadGEM2-ES RCP4.5*	*HadGEM2-ES RCP4.5*
1066	**1246**	**1362**	**1330**	**1474**
ΔET_o(mm)	180	296	264	**408**
	16.9%	27.8%	24.8%	**38.3%**

Results and Discussion

Table 5a. Differences in mean annual crop evapotranspiration (mm) of crops according to CanESM2 and HadGEM2-ES under RCP4.5 and RCP8.5 during 2081-2100 in relation 1977-1997

Mean annual crop evapotranspiration (mm)				
Crop	**Earth System Model / RCP**			
Historical 1977-1997	*CanESM2/RCP4.5*	*CanESM2/RCP8.5*	*HadGEM2-ES/RCP4.5*	*HadGEM2-ES/RCP4.5*
Corn/520	**638**	**706**	**690**	**778**
ΔET_c(mm)/(%)	118/23%	186/36%	170/33%	**258/50%**
Cotton/508	**623**	**685**	**675**	**760**
ΔET_c(mm)/(%)	115/23%	178/35%	182/33%	**252/50%**
Tomato/420	**528**	**590**	**569**	**644**
ΔET_c(mm)/(%)	118/26%	170/41%	149/35%	**244/53%**

Results and Discussion

Table 5b. Differences in mean annual crop evapotranspiration (mm) of crops according to CanESM2 and HadGEM2-ES under RCP4.5 and RCP8.5 during 2081-2100 in relation 1977-1997

Mean annual crop evapotranspiration (mm)				
Crop	**Earth System Model / RCP**			
Historical 1977-1997	*CanESM2/RCP4.5*	*CanESM2/RCP8.5*	*HadGEM2-ES/RCP4.5*	*HadGEM2-ES/RCP4.5*
Olive/408	**506**	**555**	**546**	**612**
ΔET_c(mm)/(%)	98/24%	147/36%	138/34%	**204/50%**
Watermelon/394	**490**	**552**	**526**	**596**
ΔET_c(mm)/(%)	96/24%	158/40%	132/33%	**202/51%**
Apricot/512	**632**	**691**	**684**	**768**
ΔET_c(mm)/(%)	120/23%	179/35%	172/34%	**256/50%**

Results and Discussion

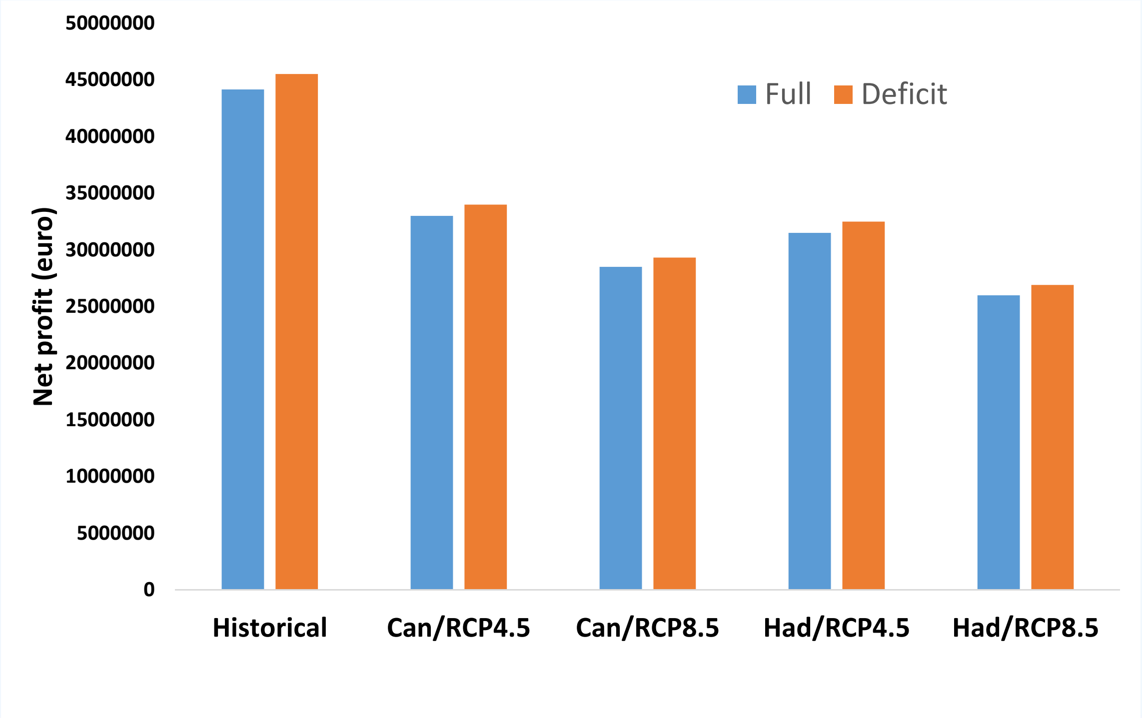
❑ Both optimization stages (simulated annealing and local optimizer) have been implemented in Matlab language.

❑ *The globally optimal solution was achieved after multiple executions of the optimization procedure for the same initial conditions and parameters.*

❑ The term "globally optimal" refers to the best solution discovered among all executions.

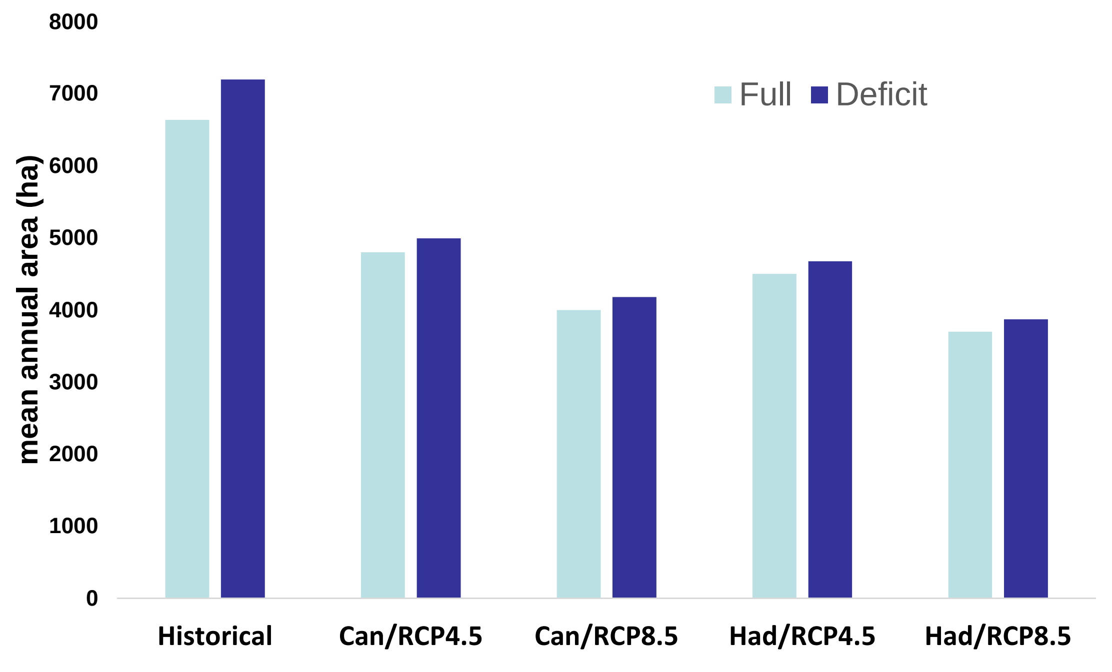
Results and Discussion

Figure 3. Comparison of mean annual net profit for full and deficit irrigation in historical and climate change scenarios periods



Results and Discussion

Figure 4. Comparison of mean total crop area for full and deficit irrigation in historical and climate change scenarios periods

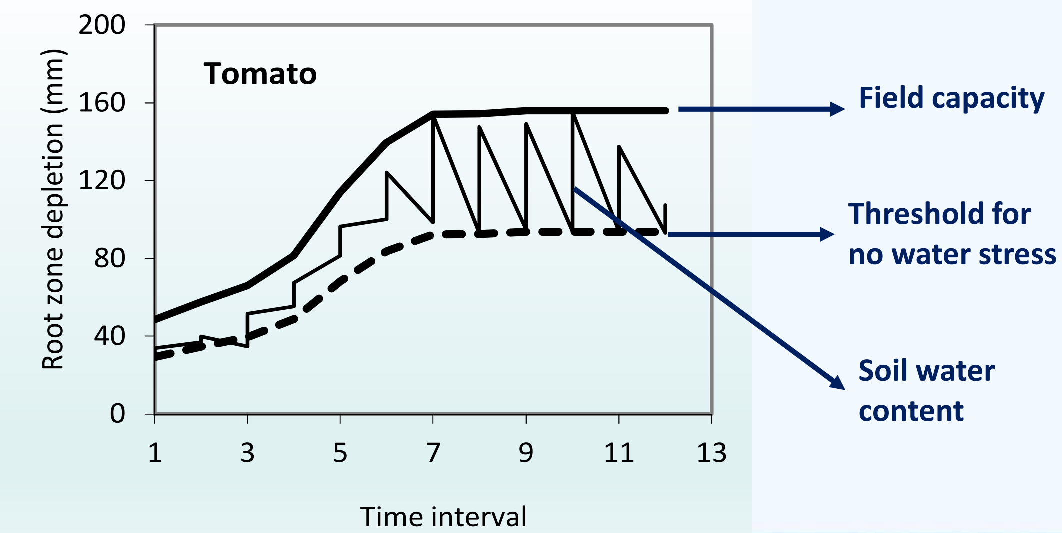


Results and Discussion

- ☐ Another feature of the model is **the calculation of precision irrigation scheduling.**
- ☐ Given the irrigation water allocated and the irrigation time interval, the irrigation scheduling can subsequently be derived by ***plotting the root zone depletion along the time axis for crops with the help of the soil water balance model.***
- ☐ To avoid crop water stress, the root zone depletion should not exceed the threshold value for no stress (lower limit).

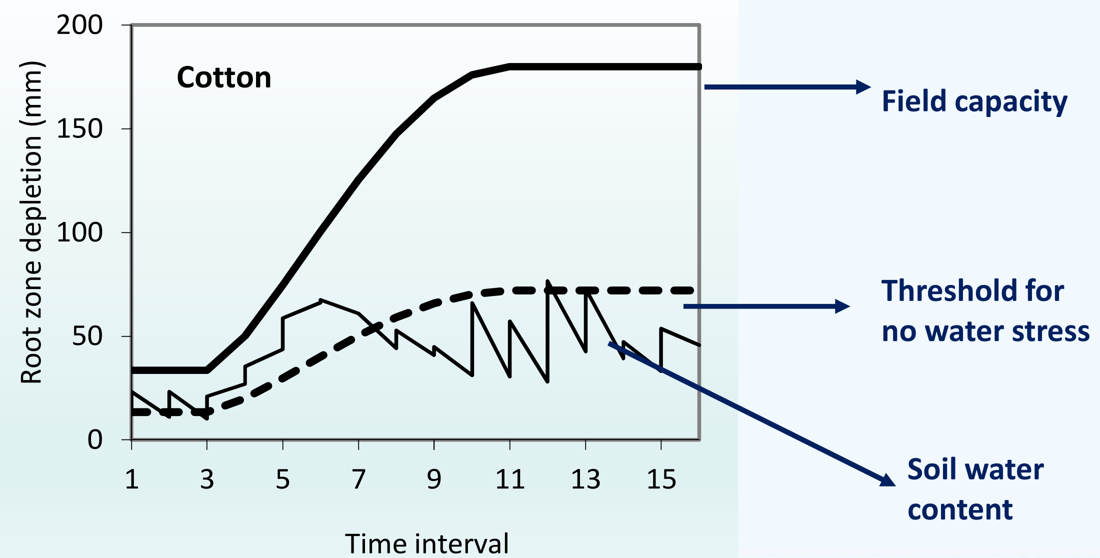
Results and Discussion

Figure 5. Soil water depletion in the root zone at the end of each time interval for the crop of tomato **(full irrigation)** under study. Thick continuous line represents total available soil water in the root zone (TAW), dashed line represents threshold for no water stress and continuous line represents soil water content



Results and Discussion

Figure 6. Soil water depletion in the root zone at the end of each time interval for the crop of cotton **(deficit irrigation)** under study. Thick continuous line represents total available soil water in the root zone (TAW), dashed line represents threshold for no water stress and continuous line represents soil water content



Conclusions

- A multi-crop irrigation model for a single reservoir operating under full and deficit irrigation conditions has been optimized for climate change adaptation using a metaheuristic algorithm combined with a local optimizer.
- *The impact of water deficit on crop yield, the effect of soil moisture dynamics on crop water requirements and competition for water among the crops in an irrigation season are taken into account.*

Conclusions

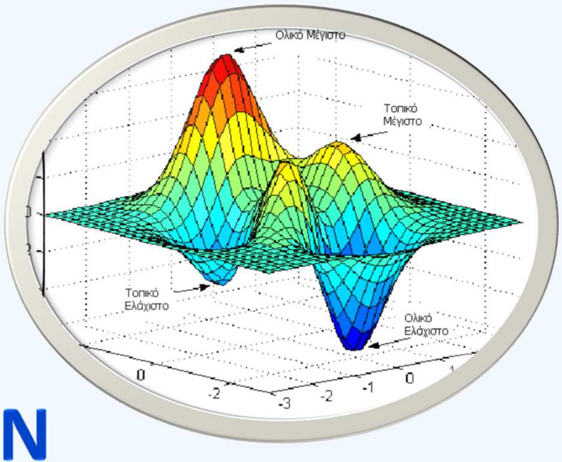
- In the study of climate change, there were differences in temperature, precipitation, reference evapotranspiration etc. variation among the climate models.
- *The above indicates that the use of a number of climate models is required in climate change studies for increasing the reliability of the future projections.*
- Climate change is projected to impact irrigated agriculture. Given the continuous decrease of water resources availability due to climate change, the results of the optimization model reinforce the necessity of adequate deficit irrigation practice.

Conclusions

- The changes in climate will have serious impacts on the agricultural sector and our analysis indicates that adaptation and mitigation measures can and should play an important role in reducing the impacts of climate change on agriculture.
- *An improved agricultural water management aiming at raised productivity will ensure global food supply and global food security.*
- High priority should be given to sustainable management practices for adaptation and associated mitigation of climate change.

Conclusions

- *The model can be used as a decision support tool for irrigation water management and environmental sustainability as it can determine optimal solutions in terms of net profit with limited water resources availability.*
- *The results aim to assist stakeholders as they take up the adaptation challenge and develop measures to reduce the vulnerability of the sector to climate change.*



THANK YOU FOR YOUR ATTENTION

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