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Abstract:

One of Tunisia's main challenges is to conserve and protect water ressources for current and future generations. Using non-conventional water in agriculture, such as treated wastewater, can be a sustainable water-saving solution. Therefore, The objectives of this study are (i) to analyze the value chain of treated wastewater for olive growing farms production and (ii) to apply mathematical modeling to maximize the olive production in optimizing irrigation distribution and nitrogen amendment in olive growing farms. The work is carried out in a peri-urban irrigated perimeter of Masken, Sousse which is mainly occupied by olive trees and irrigated by treated wastewater. A SWOT analysis is also applied to identify the strengths and weaknesses of reuse in this study area. Moreover, mathematical models are used to determine the optimal schedule for fertigation with treated wastewater. In this process, data on rainfall, soil, water quality and olive production were collected from local farmers, local decision makers, field and laboratory experiments. SWOT results determine farmers' perceptions of reusing treated wastewater for irrigation. The viability analysis, in terms of soil humidity and nitrogen, shows that the nitrogen stress is not a limiting factor for olive biomass production, but water stress is. This analysis provides numerical values for the maximum irrigation rate and total amount of irrigation water to ensure maximum olive production. It was found that the maximum irrigation could be 5.77 m3/day/ha and the total annual water requirement is 1240 m3/ha.

Modeling appears to be an important tool to help local decision makers and to support and encourage local farmers to reuse treated wastewater under safe conditions and without environmental risks.

Keywords: Olive; Mathematical Modelling; Nitrogen; Reuse; Viability theory, Farmers' perception

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1. Introduction

Population growth and its high concentration in urban and peri-urban areas combined with climate change induce an increasing pressure on water resources and an important impact on the degradation of water quality [1,2]. It is estimated that about 2.3 billion people are in water-stressed countries, of which 733 million people are located in high water-stressed countries [3]. Indeed, the highest stress levels occur in Northern Africa and in Western, Central and Southern Asia [4]. Due to the gap between water supply and demand and the competition between economic sectors, water scarcity situation is becoming more severe. Agriculture sector is the largest water consumer with more than 70% of all withdrawals globally and the water withdrawal ratio for agriculture can reach 90% in some arid countries [4]. Indeed, irrigated agriculture is essential to preserve agriculture productivity, food security, to attenuate the effect of climate and to contribute to the national economy. In this context, international communities are more conscious about water issues and the United Nations has included among the 17 Sustainable Development Goals (SDGs), goal 6 which is dedicated to water and sanitation. Additionally, climate change and anthropogenic activities have significant effects on water availability which may cause decision and policy makers to focus on new strategies for water resource management and water security for sustainable allocation and use [5].

In water-scarce countries and regions, the reusing of wastewater provides a significant opportunity to substitute limited freshwater resources with reclaimed water for specific purposes [6][7]. In addition to efficient water distribution systems and sustainable agriculture, reuse of wastewater is a relevant action in reducing water stress [4]. Certainly, wastewater is a possibly inexpensive and sustainable source of water, energy, nutrients, organic matter and other useful by-products [8]. However, several barriers such as public perception, pricing, technical and regulation are affecting the possibility of implementing efficient water reuse strategies [9]. Like many countries in the MENA regions,Tunisia also suffers from the problem of water shortage. Annual water resource potential is estimated at 4898 million m^3 with about 2700 million m^3 is surface water and 2198 m^3 is groundwater [10] ~~[24]~~. In fact, the total renewable water resource per capita is estimated at 420 m^3/inhabitant/year which is considered a Key indicator of water scarcity [10] . Freshwater is not used only for domestic purposes such as drinking but also for economic activities such as agriculture or Industry. Furthermore, the agriculture sector has a great importance due to its social impact. Agriculture is the first user of water compared to the other sectors, accounting for about 79% of freshwater [11]. However, water drinking is estimated at 15%, Industry at 3% and tourism sector at 1% and other use at 2% [11]. In addition, population growth and rapid development of the economic sectors have increased the problem of water scarcity in Tunisia. Therefore, the government is facing a major challenge that deals with preserving and protecting this scarce resource to fit the supply and demand of water. For this reason, the government adopted several strategies to protect it and to maintain balance between water demand and supply. The main strategies can be summarized as (i) water surface mobilization through appropriate infrastructures such as dam ; (ii) support farmers to adopt techniques of water saving with incentive allowance ; (iii) implementation of appropriate legislation and institutional systems for water resource management ; (iv) promote non-conventional water use in agriculture such as treated wastewater reuse or brackish water desalination (v) improvement the involvement of local people in the strategy through the etablishement of local water user association. Additionally, the Tunisian government developed two key strategies for the year 2050 related to water resource management "Water 2050"and reuse "WATER REUSE 2050". Both strategies focus on developing appropriate action plans to support and guide decision makers and water managers. The Water 2050 strategy included several recommendations for water resources management based on forecasting models of supply and demand. These recommendations ar primerly related to water, infrastructure, governance, economy, and ecology [12]. However, the WATER REUSE 2050 focuses on reuse as an alternative solution to conserve freshwater. The goal of this strategy is to implement a sustainable action plan in terms of assessment, technologies, regulation, financing of treated wastewater [13]

The reuse framework in Tunisia started by launching research programs, the construction of several WasteWater Treatment Plants (WWTP) with advanced technologies and appropriate sanitation systems, the involvement of several actors and the adoption of several standards and guidelines for safe use [14]. Despite the efforts provided by the Tunisian government, the reuse rate is still low compared to potential treatment of wastewater. Among 122 WWTP, only 61 treated plants are designed for reuse. In 2019, about 284 million m3 were generated but only 13,4 million m3 are recycled for agriculture purposes [15].

From a circular economy perspective, recycling and reuse are the central concern and water supply can be improved through better wastewater management strategies [16]. Conversely, risks associated with water quality and human health must also be taken into account [16]. Furthermore, it was estimated that 80% of all industrial and municipal wastewater are rejected to the environment without treatment affecting overall water quality, leading to negative impacts on human health and ecosystems [8]. Therefore, the focus on appropriate technologies for an efficient water treatment is important to determine reuse purpose [9]. Wastewater treatment is based on a combination of physical, chemical, and biological processes to eliminate wastewater components [8]. Several techniques and methods for wastewater treatment are applied. Indeed, conventional methods for removing metals are becoming inappropriate to meet rigorous permissible effluent standards for an intended use [17]. Additionally, the implementation of advanced techniques as a tertiary treatment process may lead to good water quality for supplying irrigation or domestic uses [18]. For example, Kalboussi et al. [19] conducted a life cycle assessment study to evaluate the environmental efficiency of water reclamation for agricultural irrigation among other conventional options. They found that the environmental impact of reclaimed water depends directly on the type of tertiary treatment technology and the location of the treatment plant in relation to the field and other water sources. Natural landscapes such as forests and wetlands have an important contribution in improving water quality by decreasing sediment loadings, capturing and holding pollutants and recycling nutrients [8]. Nature-Based Solution (NBS) creates opportunities as an innovative solution to improve ecosystem services, boost resilience and livelihood in water planning and management [8].

Treatment may improve the quality of treated wastewater to meet standards, but, should also preserve nutrients. As wastewater is rich in nitrogen and phosphorus which can provide nutrients to crops, the serious challenge for reuse agricultural irrigation is not only to preserve quantities of nitrogen and phosphorus contained in the wastewater, because these nutrients are essential for plant growth [20] but also to respect appropriate guidelines for safe use [21] , [22] . In order to implement sustainable and effective reuse strategies, a good knowledge of soil-plant-water interactions is required. In this context, crop models have been developed by several teams and have led to several software such as AquaCrop [23] , STICS [24], OPTIRRIG [25]among other ones. The simulations provided by these models serve as predictive and decision support tools for agricultural practices. More complex and comprehensive models have been developed as Global Change decision support system DANUBIA [26]. For the processing, DANUBIA crop growth model needs several data such as meteorological date, site-specific information, soil characteristics and farming practices. Additionally, the Nitrogen cycle was also integrated in DANUBIA model to determine nitrogen turnover, nitrogen fluxes and storages [27]. These approaches are based on relatively complex models with many variables and parameters, which provide quite precise descriptions of the state of the soil-crop-climate system, but are also quite heavy to conduct intensive optimization over a tactic time horizon [23,24]. Other approaches are based on much simpler models (i.e. reduced models) that do not intend to give a precise description of the internal functioning of the soil-crop system, but rather focus on flux balance, and can therefore predict soil composition, water consumption, and biomass production at the field scale only [28,29,30,31,32]. This kind of models is thus better suited to apply optimization tools, because of their relatively small size. Moreover, the manipulated variables that typically describe irrigation and fertilization, and measurements such as soil humidity and crop water demand are usually considered at the field scale by practitioners. These reduced models can be validated on the more sophisticated models, which can also provide parameters sensitivity [28]. In this context, Pelak et al. [29] focused on the relationship between canopy cover, soil moisture and soil nitrogen content to optimize strategies of fertilization and irrigation. Moreover, Kalboussi et al. [30], [31] proposed a generic crop model named "TOYCROP" which is the basic version of the more advanced model "OPTIRRIG model". TOYCROP was developed to determine optimal irrigation and nitrogen management via treated wastewater [31], [32].

Considering water scarcity in Tunisia, this research focuses on promoting reuse as an alternative solution to water saving and implementing of crop models for a sustainable reuse scheme. A feature of this study is the development of a model based on the combination of treated wastewater and nitrogen as nutrient for olive production. Therefore, the main objectives of this study are (i) to analyze the value chain of treated wastewater for olive growing farm and (ii) to apply a mathematical model considering water and nitrogen content in order to maximize olive yield in the treated wastewater (TWW) irrigated perimeter of Msaken, Sousse (Tunisia). This research may be useful for local decision makers to provide appropriate guidance and recommendations for fertigation scheduling.

The next section presents the research framework and the description of the study area, as well as the approach used to characterize the optimal irrigation and nitrogen strategy. The main results related to the value chain and modeling are proposed and discussed in Section 3. Finally, section 4 summarizes the main outcomes of this research.

2. Materials and Methods

2.1 Research Framework

In this study, we focused on the reuse of treated wastewater in the irrigated perimeter in Msaken, Sousse. Figure 1 illustrates the main components of the approach applied. Specific parameters and datasets were used to implement the wastewater value chain and detect the interaction between irrigation and nitrogen based on a crop model analysis.

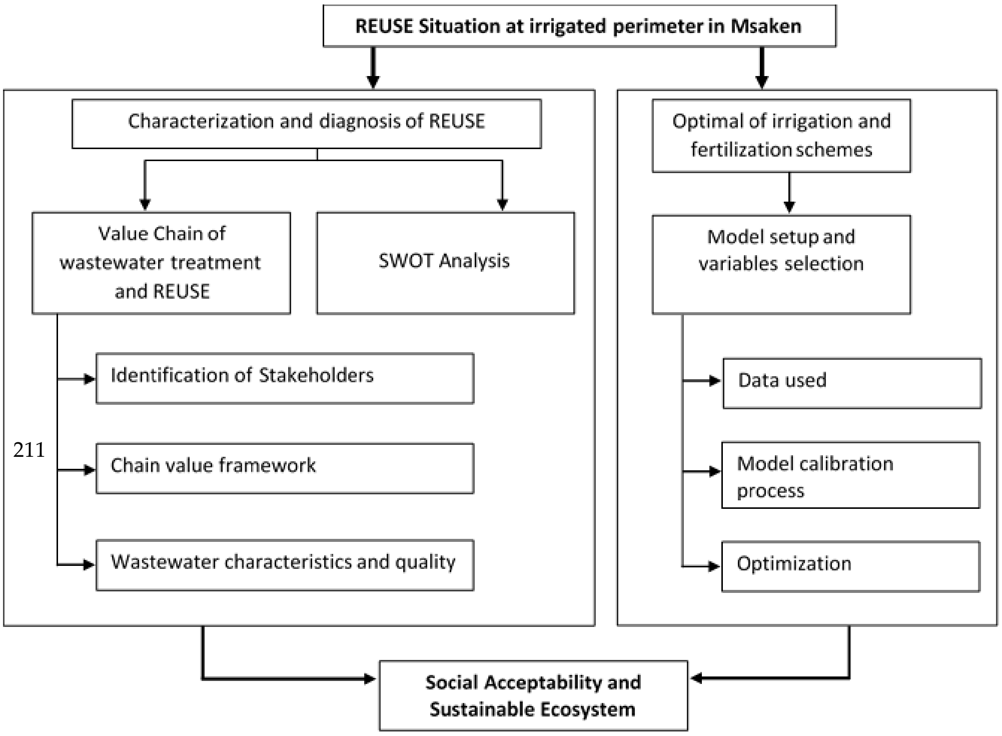


Figure 1. Framework of the applied approach

2.2 Study area description

The irrigated perimeter of Msaken from Sousse governorate is selected as a study area. Sousse is characterized by water stress and overexploited and saline groundwater. In order to provide safe water for users and to ensure water security, the local decision makers adopted a strategy based on a transfer of water from neighboring governorates (Zaghouan and Kairouan)[33]. It was estimated in 2021 that about 65% of distributed water resources is from internal resources including water surface, groundwater and treated wastewater [33]. However, about 35% are external water resources. Among the internal resources distributed, only 7% are coming from treated wastewater [33]. For this reason, the reuse for agriculture purposes can be a way of mitigating water shortage problems in Sousse. This irrigated perimeter of Msaken is located between 10°36"- 10°38" N latitude and 35°45"-35°43"E longitude (figure 2). This perimeter was implemented in 2002 and it was developed to reuse treated wastewater. This region is characterized by a semi-arid climate with mild winter. Average annual rainfall is about 319 mm. The average monthly maximum temperature is around 35°C in July and the lowest monthly average temperature is around 6°C in January [34]. The geological formation in Msaken is dominated by quaternary system and the Early Pleistocene. Soil is classified into two classes according to the French soil classification : Poorly developed soil and Isohumic soils [34]. Due to its nature, the soil is considered light soil. Texture varies with depth.Sandy clay texture is dominant. The main rivers obsersed in the study area are Oued Melah, Oued Joubi and Oued Manar [34]. The main productions of the perimeter are olive trees and fodders for livestock. The area of this perimeter is approximately 178 km^2. WWTP of Msaken which is managed by the National Sanitation Utility (ONAS) serves for treated wastewater supply. The local water user association (GDA) is in charge of water distribution to local farmers through a volume-based cost process [34].

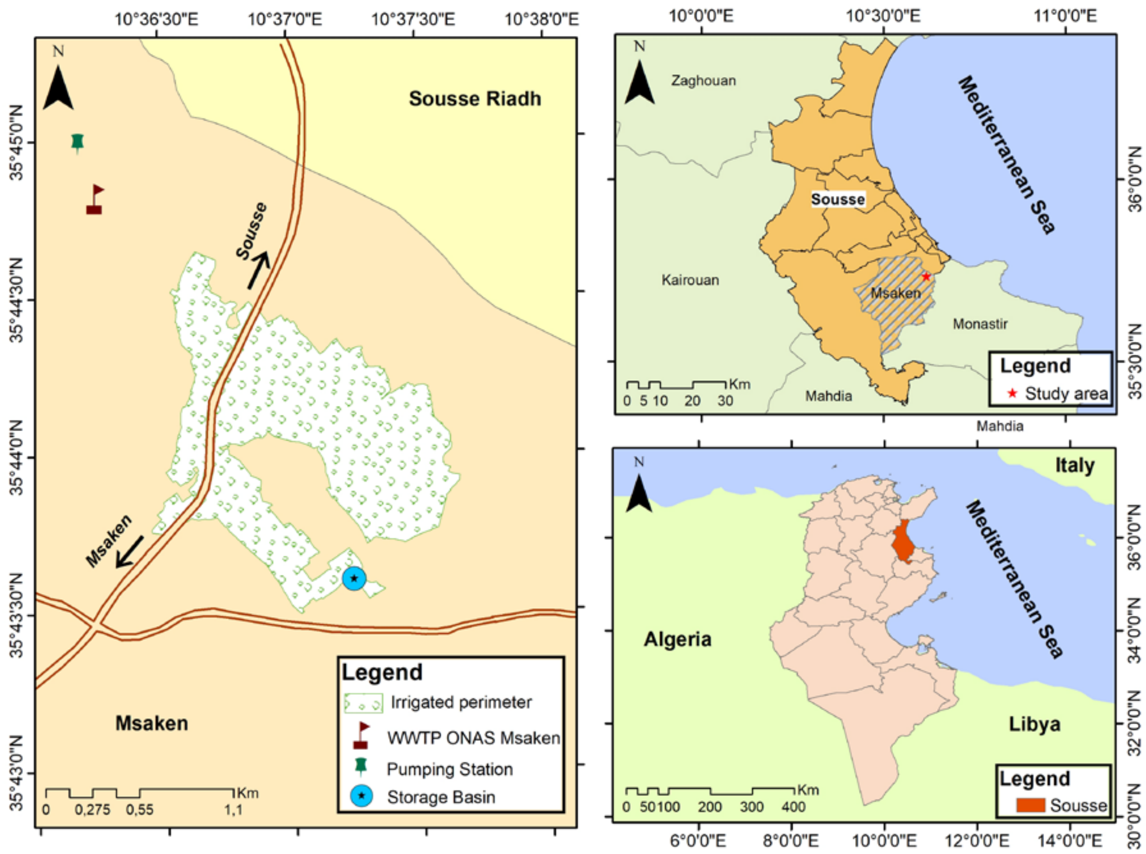


Figure 2. Study area location

2.3 Description of the applied approach

2.3.1 Treated wastewater reuse value chain

The concept of value chain is defined as all activities required to take a product from the initial input-supply phase, through numerous stages of production, to its final market destination [35]. In addition, value chain analysis is a process of breaking a chain into its component parts to understand its structure and operation in detail [35] . In the case of treated wastewater reuse, value chain was required to (i) identify the main actors involved in the process from the wastewater collection to reuse; (ii) describe the main components of the wastewater treatment system; (iii) monitor the water quality and quantity used; (iv) identify local farmers' perceptions of treated wastewater. The value chain analysis was useful in providing a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis for reuse in our study area. Moreover, SWOT analysis was conducted to identify the main gap of reuse.

2.3.2 Crop Simulation model

- Crop model description: Crop models are an important tool for optimizing irrigation and fertilization strategies to maximize yields. In this context, a dynamic system, based on the "ToyCrop" model [30] and the model of Pelak et al. [29] , was developed to describe the interaction of three main components: Soil moisture $S(t)$, total soil nitrogen content $N(t)$ and olive biomass production $B(t)$. The model is interpreted on the daily timescale and applied over the course of a single growing season.

- Soil water balance: The relative soil humidity in the root zone (dimensionless between 0 and 1) is modeled as a balance between gains from rainfall (R) and irrigation (I) and losses mainly due to soil evaporation (E), crop transpiration (T) and the combined run off and percolation rate (Q_p) as indicated in equation 1 [30]:

$$\frac{dS}{dt} = \frac{1}{\alpha\ Z}(R(t) + I(t) - T(t,S) - E(t,S) - Q_p(t,S)) \quad (1)$$

Where $\alpha\ Z$ is the field capacity with α is soil porosity and Z is the root depth. Transpiration rate (T) and evaporation (E), are given by equation 2 and 3 [30]:

$$T(t,S) = K_S\ (S)\ \phi(t)\ ET_0(t) \quad (2)$$

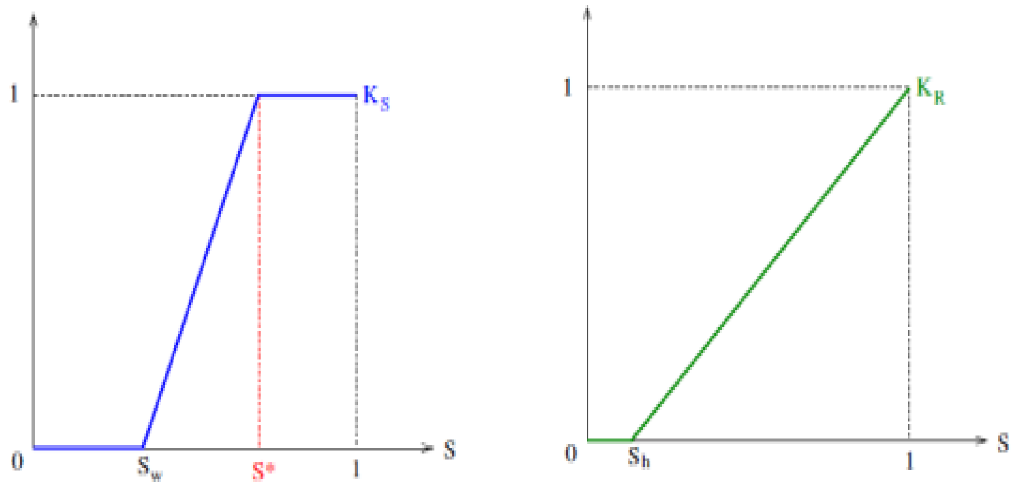
$$E(t,S) = K_R\ (S)\ \left(1 - \phi(t)\right)\ ET_0\ (t) \quad (3)$$

The function K_S is used to capture the plant stomatal response to soil moisture condition, as given by equation 4 [30]:

$$K_S = \begin{cases} 0, & S \leq S_w \\ \dfrac{S - S_w}{S^* - S_W}, & S_w < S \leq S^* \\ 1, & S > S^* \end{cases} \quad (4)$$

where S_w is the wilting point and S^* is the point at which stomata closure starts.
A similar function, K_R, is used to module evaporation, depending on the hygroscopic point of soil, S_h, below which no soil moisture losses occur (equation 5).
A diagram of K_S and K_R as a function of S is shown in Figure 3 [30]:.

$$K_R = \begin{cases} 0, & S \leq S_h \\ \dfrac{S - S_h}{1 - S_h}, & S > S_h \end{cases} \quad (5)$$



(**a**) (**b**)

Figure 3. (a) Transpiration limitation function, (b) Evaporation limitation function

$ET_0(t)$ is the reference evapotranspiration, which is calculated from meteorological data. There are several methods of estimating ET_0 but for our work we used the Blaney-Criddle formula, given by equation 6.

$$ET_0(\mathrm{t}) = K_t\ (45.7\ T_m\ + 813)\ p/100 \tag{6}$$

Where $\mathrm{K_t}$ is a climatic coefficient, $\mathrm{T_m}$ is the mean monthly temperature (°C) and p is the mean daily percentage of annual daytime hours. The transpiration of olive is assumed to be proportional to the crop radiation interception efficiency ϕ(t), which is a function between 0 and 1 that reflects the plant cover, as mentioned in equation 7.

$$\phi(t) = \ \phi\_olive\ \ (t) + \phi\_olive\_tree\ \ (t) \tag{7}$$

The soil evaporation is considered proportional to the uncovered part of the soil (1- $\phi(t)$). Deep percolation occurs through the water table, which is assumed to be deep enough not to intersect with the root zone. Water leakage Q_p calculation is based on formulation given by Pelak et al. [20], where k_L is the saturated hydraulic conductivity [m/d], d_L [Dimensionless] is leakage parameter and S is the soil moisture (equation 8).

$$Q_p = k_L . S^{d_L} \tag{8}$$

- Soil nitrogen balance: The soil nitrogen balance estimates the full range of nutrient inputs to and removals (offtakes) from soils. The input source is from fertigation, which in the context of reuse irrigation, is taken as the product of the irrigation flow rate I and the nitrogen concentration of the irrigation water C_N. The main removal sources are leaching and plant uptake U for crop production, as presented in equation 9 [29].

$$\frac{dN}{dt} = C_N^{in}(t)I(t) - U(t,N,S) - L_N(t,N,S) \tag{9}$$

where N is the total mineral nitrogen content per unit area of soil. The plant uptake of nitrogen U is taken as the product of transpiration and a nitrogen uptake limitation function $f\left(\frac{N}{S}\right)$, which limits the nitrogen uptake above a certain critical concentration η_c (equation 10) [29]

$$U(t,S) = \frac{1}{\alpha\ Z} T(t,S)\, f\left(\frac{N}{S}\right) \tag{10}$$

The function of nitrogen uptake limitation is given by equation 11 [29].

$$\mathrm{f}\left(\frac{N}{S}\right) = \begin{cases} \dfrac{N}{\eta_c\ S}, & \dfrac{N}{S} \epsilon [0, \eta_c] \\ 1, & \dfrac{N}{S} \geq \eta_c \end{cases} \tag{11}$$

The nitrogen leaching L_N is proportional to the water percolation, Q_p, and the nitrogen concentration N/S as indicated in equation 12 [29].

$$L_N = Q_p \frac{N}{\alpha\ Z\ S} \tag{12}$$

- Crop biomass: The model assumes that the biomass production is proportional to olive transpiration T_{olive}, with growth restriction in the case of water and nitrogen limitations (equation 13)

$$\frac{dB}{dt} = W^*\ T_{olive}(t,S)\ f\left(\frac{N}{S}\right) \tag{13}$$

Where W^* is the normalized daily water productivity and olive transpiration is given by equation 14.

$$T_{olive}(t,S) = K_S\ (S)\ \varphi_{olive}(t)\ ET_0(t) \tag{14}$$

2.3.3 The sensitivity analysis

All mathematical models are approximate and their usefulness depends on the understanding of the uncertainty associated with the predictions [36]. Uncertainty can affect the accuracy of the results at every calculation stage [36]. Sensitivity analysis can determine how variability in inputs leads to variability in outputs. In other words, it is an approach to determine which parameters have the most or least impact on the output solution. It quantifies the ratio of output disturbances to input disturbances.

A sensitivity analysis was conducted to investigate the behavior of the crop model response with respect to the uncertainty of the model parameters. A random bias of ± 10% was introduced in the calibrated parameters in order to generate a set of disturbed systems. Then, the percentage of deviation from the error value using the parameters of the nominal system is calculated according to the equation 15

$$Error\ \ on\ \ J\ \ (\%) = \frac{J_{nominal} - J_{pert}}{J_{nominal}} \tag{15}$$

where $J_{nominal}$ is the quadratic error for the calibrated model and J_{pert} is the quadratic error resulting from parameter perturbation.

2.3.4 The viability analysis

When dealing with decision support for irrigation, decision making faces the dilemma of nitrogen concentration. While water supply is beneficial for crops, it can also dilute the nitrogen concentration in soil which is penalizing for the plant to satisfy its nitrogen needs. This dilemma needs to be reconsidered, especially in the context of reused water, since additional nitrogen can be provided by the irrigated water. To better understand this new water/nitrogen trade-off, we propose an approach based on the viability theory [37] rather than pure optimization. The idea is to first formulate based on a model, the constraints to be satisfied over the time season -in terms of soil humidity and nitrogen concentration- to ensure the best biomass production at harvest. Then, the viability analysis consists in studying the conditions under which it is possible for the system to meet these constraints at any time with three manipulated variables:

1. The initial fertilization i.e., the amount of nitrogen at the time of seeding
2. The nitrogen concentration in the irrigation water
3. The maximal flow rate of the irrigation water

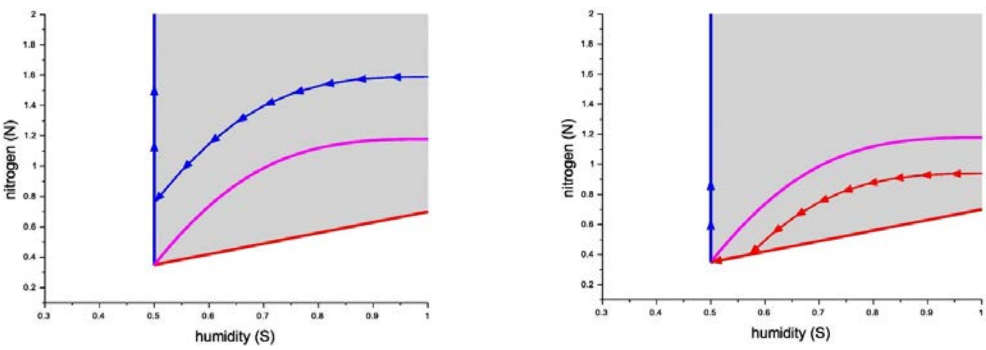
We considered the crop model described in section 2.3.2 for which the state vector at time t is composed of three variables: soil humidity S(t) (in percent), nitrogen quantity N(t) (in mass per hectare), and biomass produced B(t) (in mass per hectare). The dynamics of these variables are given by Eq.1, Eq.9 and Eq.13. Equation.13 indicates that biomass production is maximum when its derivative is maximum at any time t, which means that the following two conditions are satisfied:

- S(t) is above the threshold S* for any t. This means that there is no hydric stress
- The ratio N(t)/S(t) is above the threshold η_c at any t. This means that there is no nitrogen stress

Therefore, the viability problem is to investigate how to maintain the state (S(t), N(t)) in the constraint's domain defined as follows:

$$K := \left\{(S, N) \ ; \quad S \geq S^* \ \ and \quad \frac{N}{S} \geq \eta_c\right\} \tag{16}$$

at any time t ∈ [0,tf] with a control function I(.), depending on the initial state (where by convention t=0 and t= tf are the seeding and harvesting dates). In particular, the maximum value of the irrigation flow rate Imax plays an important role in forcing the trajectory solution (S(.), N(.)) not to exceed the limits S=S* and N=η_c S of the constraints set K. A geometric condition to stay within this domain is to find a value of control I everywhere on the boundaries of K such that the velocity vector is within this set at all times. From the equations, this implies a condition on Imax, that is called a "viability condition". For a given initial condition (S0, N0), one can consider the null control I=0 (i.e., no irrigation) from the initial date and determine by integration whether it first touches the boundary S=S* or the boundary N/S=η_c. Depending on which boundary is touched first, we determine that hydric stress or nitrogen stress dominates. We can then distinguish initial conditions for which the hydric or the nitrogen stress is dominant (Figure 4 as an example).



(**a**) (**b**)

Figure 4. (a) Water stress dominant trajectory; (b) Nitrogen stress dominant trajectory

Once on the boundary of the constraint set, a control I(.) can be considered to keep the trajectory solution on the boundary up to the final state. The grey area in Figure 4 is the domain K where biomass is maximum. The vertical line in blue is the water stress defined by the constraint S=S*, and the horizontal line in red is the nitrogen stress given by N/S=η_c. The magenta curve represents the separation between the hydric and nitrogen stress. If we assume a waterlogged soil (S=1) and a high nitrogen stock at t=0 (Figure 4.a), the trajectory (blue line with arrows) is toward water stress. At this point, irrigation is required to stay at S=S*. On the other hand, if we assume S=1 and a low nitrogen stock at t=0 (Figure 4.b), the trajectory (red line with arrows) first hits nitrogen stress. Finally, by integrating the control I(.) over time, we obtain the quantity of water required by this strategy to ensure that it remains in the K region, that is to ensure maximum biomass production at the harvesting date. This analysis was performed for the parameters of the model calibrated for the case study of Msaken olive trees.

2.3.5 Data used and processing

Several data are used and generated for this research. A comprehensive literature review was conducted to obtain the useful documents related to the irrigated perimeter of Msaken. In addition, a field survey is managed in the study area to gather detailed information on the functioning and structures of the sewage treatment system. Two-level interviews were coordinated to make reliable diagnoses of reuse situations and their impact, and to assess appropriate variables useful for mathematical simulation. A representative sample of decision makers and end-users was selected based on the implication to treated wastewater, reuse level and olive production. The two levels are described below:

- Level 1: Local decision makers. The main targets of the discussion were (i) to identify the role of each stakeholder involved in major process of reuse in the study area; (ii) to collect historical records related to monitoring the quantity and quality of treated water ; (iii) to distinguish between the main steps of processing, treatment, distribution and reuse; (iv) to indicate principal obstacles and barriers of reuse.
- Level 2: Farmers at the olive growing farms. Farmers surveyed were selected based on water reuse and agriculture production. The main questions are about reuse, land use, crops characteristics, agricultural practices and farmer’s perceptions and behaviors towards reuse.

Data required for the estimation of variables in each equation of the mathematical simulation were obtained from the field survey and laboratory experiments. For this purpose, soil and water sampling campaigns were carried out and appropriate laboratory analysis were conducted. Data related to the characteristics of treated wastewater and volumes used for irrigation are obtained from local partners GDA, CRDA and ONAS. We used data of 2020 in particular. We focused on the concentration of chemical properties of treated wastewater such as conductivity, Biochemical Oxygen Demand (BOD5), Chemical Oxygen Demand (COD) and Total Suspended Solids (TSS). Several guidelines and standards are developed for wastewater reuse. At the local level, Tunisian standard NT 106-03 refers to wastewater reuse in agriculture [38]. At the international level, FAO has provided specific guideline and recommendations regarding to the use of wastewater in agriculture [39] . Recently, the European Parliament and of the Council adopted Regulation n° 2020/741 on minimum requirements for water reuse [40]. In this study, water quality parameters were subsequently compared with Tunisian standards and guidelines to evaluate the performance efficiency of wastewater treatment. Specific techniques and methods are used to measure the parameters. Conductivity is measured by conductivity meter. TSS is obtained by flitration, DCO is measured by titration[41] and DBO5 is developed by Dilution and seeding method[42].

Data related to rainfall was collected from the rainfall station of Msaken.

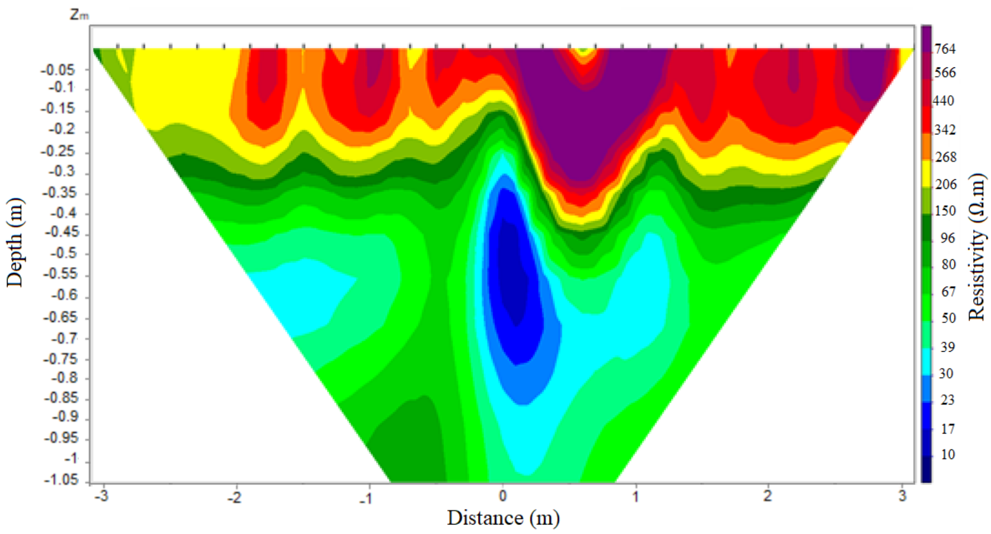
The required data for soil are soil texture, physicochemical parameters, root depth, soil nitrogen, soil humidity and permanent wilting point.

A soil sampling campaign was conducted in January 2022 to determine the impact of treated wastewater, focusing on changes in soil nitrogen and phosphorus concentrations. The plots were selected according to the degree of irrigation. For each plot, Three soil samples were collected at three depths (Depth 1: 0-20 cm; Depth 2: 20 – 40 cm; Depth 3: 40 – 60 cm)

- ✓ Plot 1: No irrigation for more than 3 years
- ✓ Plot 2: Moderate irrigation schedule and only olive trees were irrigated
- ✓ Plot 3: Substantial irrigation. Crops system is based on olive trees intercropped with fodder

As Nitrogen is an important factor for plant growth and it is aslo included in the simulation, we focus on the nitrogen in the soil. In this context, six additional soil samples were taken at a selected farm from May to October 2022, to monitor the temporal variation of soil Nitrogen. this nutrient was determined using the Kjeldhal method[43].

Moreover, the root depth estimation was performed using Electrical resistivity tomography (ERT) method. This method is applied to measure electrical resistivity which can lead to identify potential freshwater and groundwater [44], [45]. However, the resistivity can be affected by several factors such as soil water content, groundwater level, geological structure and other causes [46]. In our study, ERT survey and prospecting was conducted by using ABEM SAS4000 multi-electrode Earth Resistivity Meter and 32 electrodes chain with a 0.2 m inter-electrode spacing. A Wenner-Schlumberger array was adopted. Based on this approach and considering the value of resistivity (localization of a prominent elongated low resistivity beneath the tree), it was detected that the average root depth in the selected olive growing farm is about 0,8 m. Figure 5 shows the ERT profile related to the analysis.



3. **Figure 5. ERT profile to assess root depth** Results and discussion

In this section, the results of value chain analysis were presented and the SWOT was also elaborated. Then, the optimal irrigation and nitrogen plan is developed through the mathematical simulation.

3.1 Value Chain of Treated wastewater reuse

The value chain analysis framework is illustrated by Figure 6. Three phases were determined.

- Phase 1: Wastewater collection and treatment. ONAS is the main actor involved in this phase. It has the responsibility to collect raw water and to do the appropriate treatment in WWTP of Msaken. This WWTP was constructed in 1996. The treated plant includes a secondary treatment based on activated sludge process. The daily treatment capacity of domestic and industrial sewage is 7844 m3. The final effluent is reused in olive tree irrigation but the major portion of effluent is discharged in the environment.
- Phase 2: Reuse. Several actors are involved in this action at local (Farmers/GDA), regional (CRDA) and central (DGGREE) level. Farmers are the users of treated wastewater. The role of GDA is to distribute water for the registered end-users with adequate pricing schemes to encourage water reuse schemes. The fixed price is 0,035 DT/m3. The Msaken irrigated perimeter is created in 2022. The total area of the perimeter is 178 hectares. The registered farmers in the GDA are about 77. Additionally, the main role of CRDA is to supervise the functioning of the irrigated perimeter and water distribution. CRDA Staff has also the responsibility to implement extension services programs for farmers. However, the main activities of DGGREE are to implement the national strategies of reuse.
- Phase 3: Control authorities. The main role of these institutions is to control the quality of treated wastewater considering the Tunisian standard and guidelines. NT 106.03 of 1989 is the national standard for reuse for agriculture purposes. NT106.02 of 1989 and the updated version of the Ministerial decree of 2018 were produced for the control of effluent loaded in the environment.

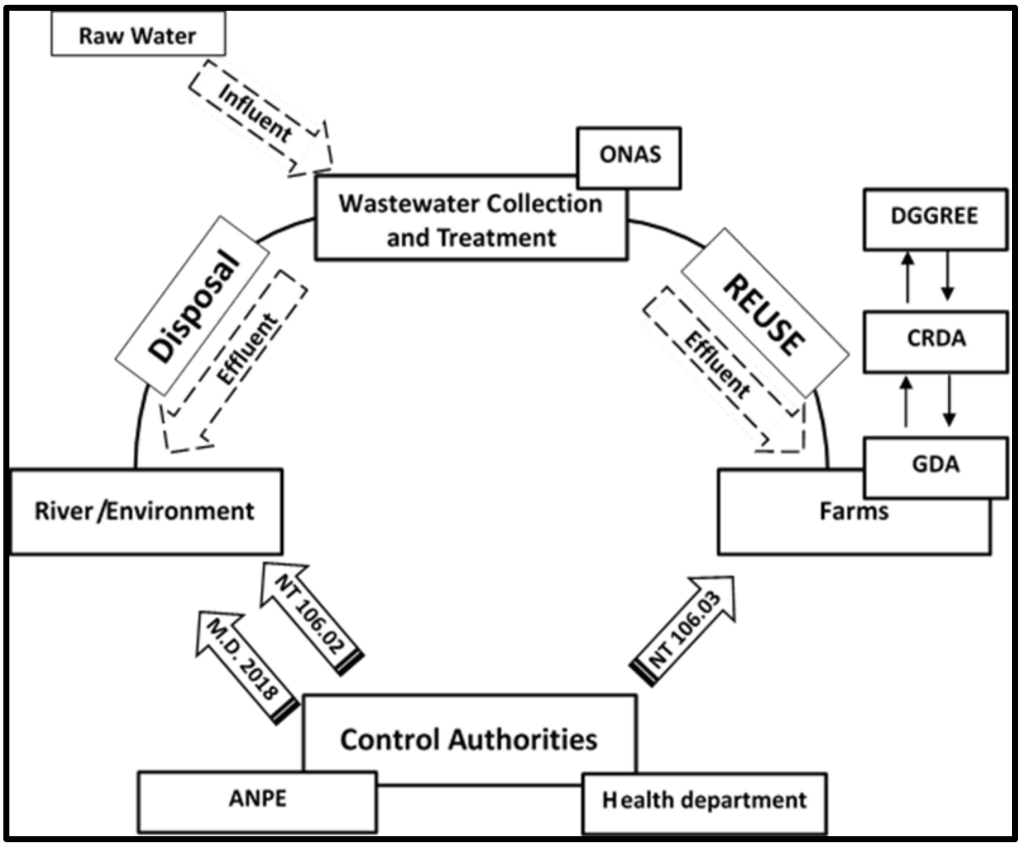


Figure 6. Framework of Value Chain of treated wastewater

ONAS : National Sanitation Utility ; DGGREE : General Directorate of Rural Engineering and Water Exploitation ; CRDA : Regional Office for Agricultural Development ; GDA : Water User Association ; ANPE : National Environment Protection Agency ; M.D.: Ministerial Decree

3.2 *Monitoring of treated wastewater reuse*

The reuse was assessed based on water volume and water quality.

3.2.1 Volume of effluent reused

Figure 7 shows the variation of the volume of effluent consumed by the farmers. We found that the amount of treated wastewater that farmers consume varies. The annual average from 2012 and 2020 is 185 277 m3. The highest usage was in 2016 and the lowest is in 2020. The volume in 2020 was estimated to be 69650 m3. This volume is only about 2% of overall treated wastewater provided by WWTP of Msaken. Based on the survey and discussions with local users and managers, we found that farmers mainly used TWW to irrigate their olive growing farms, and the main cultivar is Chemlali olive (Olea europaea L.). The irrigation scheme depends on rainfall and the amount of TWW provided by ONAS. In fact, olive trees can grow in difficult climatic conditions and with poor water quality [47]. Additionally,olive trees are an alternate bearing species which is characterized by low-yield "off-year" followed by a high-yield "on-year" [48]. This situation can explain the fluctuations in water consumption in 2014, 2019 and 2020. However, water usage in 2016 was exceptional. This is because in the past, several local farmers were dairy producers and they irrigated their land to grow pastures for their livestock. However, due to various reasons such as livestock insecurity and declining subsidies for seeds, many farmers stopped this activity and focused solely in irrigating their olive trees in appropriate period. In fact, supplemental irrigation of the Chemlali olive cultivar helps ensure and maintain olive yields [49]. As it was presented in figure 8 ((a);(b)), few olive growing farms were irrigated. Indeed, there are only 32 farmers in 2019 and 22 farmers in 2020. Due to several problems such as high price of forage seeds, breakdown of pumping station or workers availability, the crop system in the irrigated farm is only based on olive trees and small plots of fodder for livestock. For this reason, local farmers have developed irrigation strategies based on a complementary irrigation schedules at appropriate times.

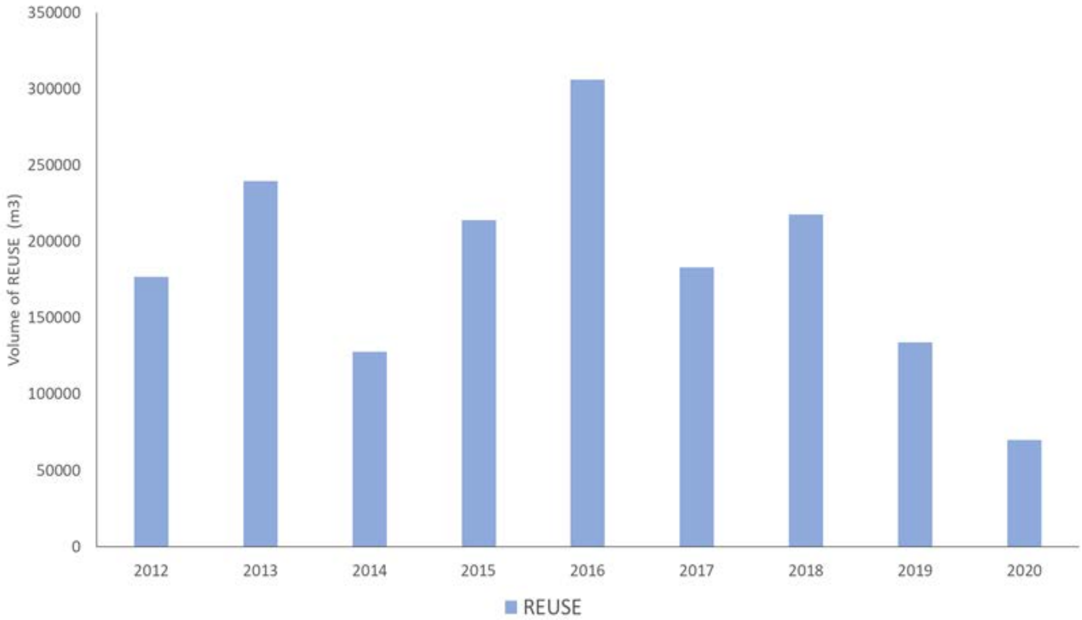


Figure 7. Volume of reuse treated wastewater by year

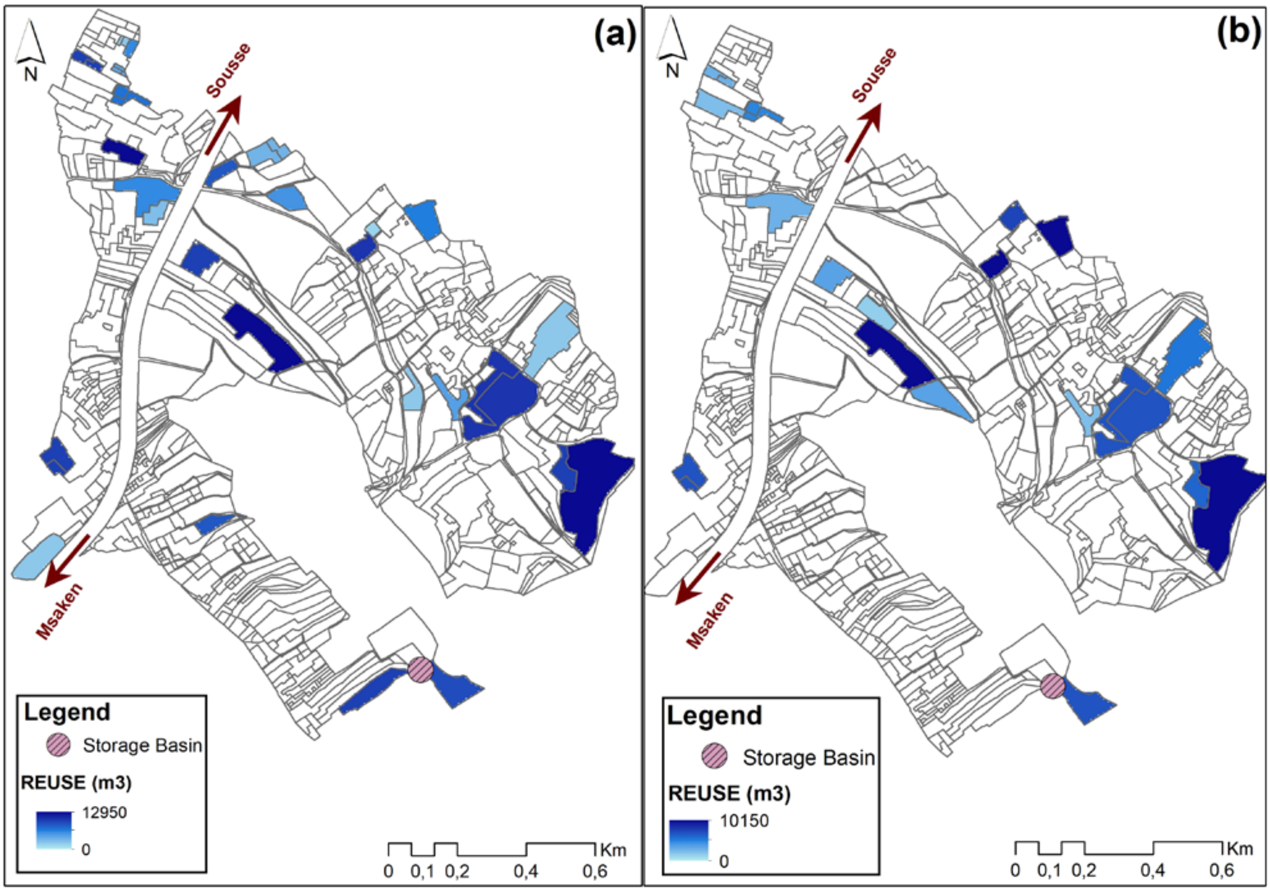


Figure 8. Spatial distribution of treated wastewater in (a) 2019 and (b) 2020

3.2.2 Quality of effluent reused

The treated wastewater used on this irrigated perimeter was monitored for the year 2020 to evaluate the efficiency of the treatment plant of Msaken and its appropriateness for use on agricultural irrigation. In this study, we focused on the 4 important parameters (Conductivity, Total Suspended Solids (TSS), BOD5 and COD). It was observed that the concentrations of these parameters were high before treatment and they reduced after treatment as described in Figure 9. The conductivity is varied from 2830 to 3365 µS/cm before treatment and after treatment, the conductivity of treated wastewater is from 2839 to 3104 µS/cm. The removal efficiency of conductivity is 4%. For the case of TSS, the amount is varied from 274 to 579 mg/L before treatment but the concentration decreases after treatment and it is ranged from 16 to 27 mg/L. The removal efficiency of TSS is 95%. However, BOD5 before treatment is varied from 344 to 660 mg/L. After treatment, the value of BOD5 is from 9 to 30 mg/L. The performance of the BOD5 treatment is high, about 96%. In addition, the amount of COD before treatment varies from 414 to 1377 mg/L. This value has decreased drastically: COD ranges from 50 to 86 mg/L after treatment. The removal efficiency is about 93%. The high efficiency of the treated plant is in accordance with the Tunisian standard (NT 106-03) for reuse in agriculture, as shown in Table 1. We can confirm that the quality of treated wastewater is suitable for irrigation and does not pose any risk to human health. However, the salinity of the soil must be monitored because the conductivity value is high. In this context, the impact of treated wastewater on soil properties is also important.

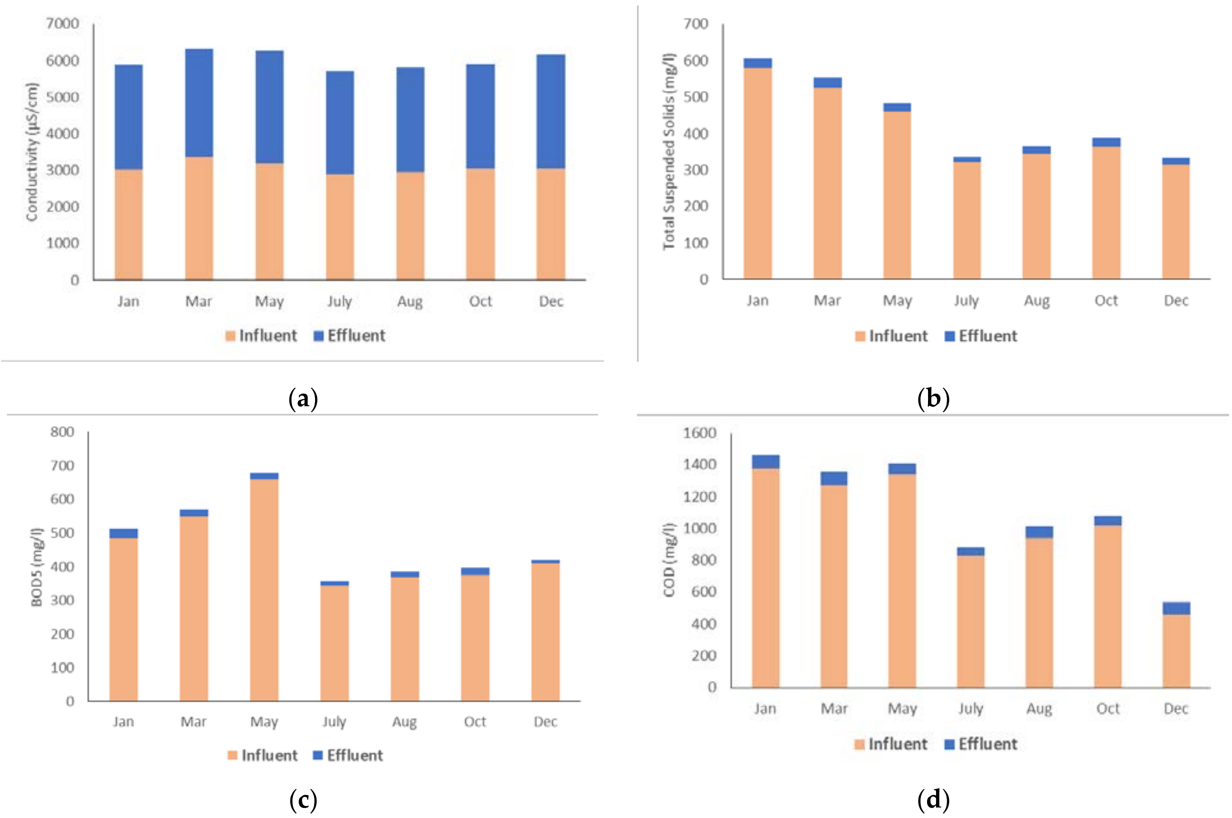


Figure 9. Monitoring influent and effluent flow of WWTP (a) Conductivity; (b) Total Suspended Solids (TSS); (c) DBO5 ; (d) COD

Table 1. Treated wastewater effluent used for irrigation

Parameter	Unit	Min	Max	Mean	Std. Deviation	Tunisia Standards NT 106-03
Conductivity	µS/cm	2839	3104	2919	90.84	7000
TSS	mg/l	16	27	22	3.36	30
DBO5	mg/l	9	30	20.08	6.52	30
COD	mg/l	50	89	69.45	14.02	90

3.2.3 Soil properties

Nitrogen and phosphorus are two important and basic natural components for the growth of living organisms [50]. Additionally, in the case of soil nutrients deficiency, the use of synthetic fertilizers is a significant factor in securing and increasing global food production[51]. Moreover, the high potentials of the recuperated nutrient for reuse as fertilizer in agriculture is recognized[52]. In our research, we focus on the variation of Total Nitrogen (N) and Phosphorus (**P_2O_5)**in soil as a function of irrigation with TWW. The results presented in Table 2 show that the nutrients concentration increased under the effect of irrigation. It is found that the total Nitrogen content at 0-20 cm depth in plot 1 (without irrigation) is 440 mg/kg, while in the most irrigated plot it was 1120 mg/kg. The same tendency is observed for phosphorus. The highest concentration was obtained in plot 3 compared to the amounts in plots 2 and 1. Similar results were found in the research work of Hidri et al. [53]. The authors confirmed the impact of treated wastewater reuse for irrigation and the increase in the amount of nutrients in the soil after irrigation. Moreover, the application of excess amounts of nitrogen and phosphorus in the soil can lead to groundwater contamination and eutrophication of surface water[54]. The optimal use of treated wastewater can be a solution to reduce soil and water pollution. For this reason, the simulation of nitrogen supply based on an optimal fertigation schedule can ensure olive yields and protect the environment.

Table 2. Monitoring soil nutrients

	Plot 1 (No irrigation)		Plot 2 (Moderate irrigation)		Plot 3 (High Irrigation)	
Depth	N (mg/kg)	P_2O_5 (mg/kg)	N (mg/kg)	P_2O_5 (mg/kg)	N (mg/kg)	P_2O_5 (mg/kg)
0-20	440	3.2	710	3.2	1120	22.4
20-40	320	1.8	350	0.8	810	10.5
40-60	360	2.9	220	6.5	680	10.2

3.3 SWOT Analysis

The main outcomes of the SWOT analysis are presented in Table 3. The SWOT analysis pointed out several advantages and barriers to the development of the reuse in the irrigated perimeter of Msaken. Indeed, the application of reuse based on mathematical simulation can lead to ensuring sustainable irrigation and fertilization schedules.

Table 3. SWOT analysis

Strengths	Weaknesses
- High treatment efficiency of TWWP - Great collaboration between the actors involved in the reuse value chain - Experienced staffs and motivated farmers - High productivity of Olive growing farms - Appropriate regulations and standards procedures - Nutrients recovery benefit - Very Low price of treated wastewater	- Low Reuse rate - Land fragmentation - Crop system dominated by a monoculture practice, mainly olive trees - Breakdown of pumping station - Low level of youth participation in agriculture practice
Opportunities	**Threats**
- Reuse is an asset to develop various agriculture activities - Geographic location of Msaken irrigated perimeter between Sousse and Monastir can be an advantage to develop several markets - The location of Msaken perimeter can lead to implement a cluster of reuse which include research activities and extension services	- High proportion of abandoned and uncultivated lands - Increase of population in surrounded areas can affect the treatment performance of TWWP - Potential Environment impact issues

3.4 Crop model Simulation

3.4.1 Model calibration

In order to calibrate the crop model, the simulation time considered for our analysis is the annual development cycle of the olive tree. It was considered from 1st January 2022 to 30 November 2022. The data used related to soil parameters are summarized in Table 4.

Table 4. Soil parameters

Parameter	Name	Value	Units	Source
S*	Point of incipient stomatal closure	0.62	-	Soil analysis
Sw	Wilting point	0.02	-	Assumption
Sh	Hygroscopic point	0.02	-	Soil analysis
Z	Root Depth	0.8	m	ERT method
α	Soil porosity	0.21	-	Soil analysis

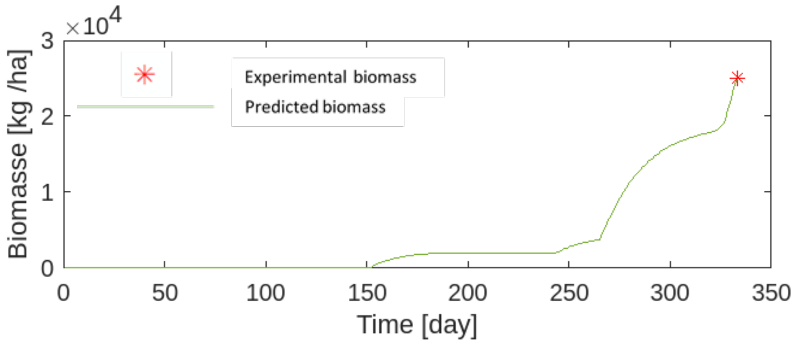
The parameters of the crop model shown in table 5 were estimated by the least-squares fitting to experimental data using the MATLAB optimization function "fminsearch". The experimental data used for the calibration of the model are mineral nitrogen content in the soil obtained by laboratory analysis and the biomass of olives at harvesting period.

Table 5. Estimated parameters

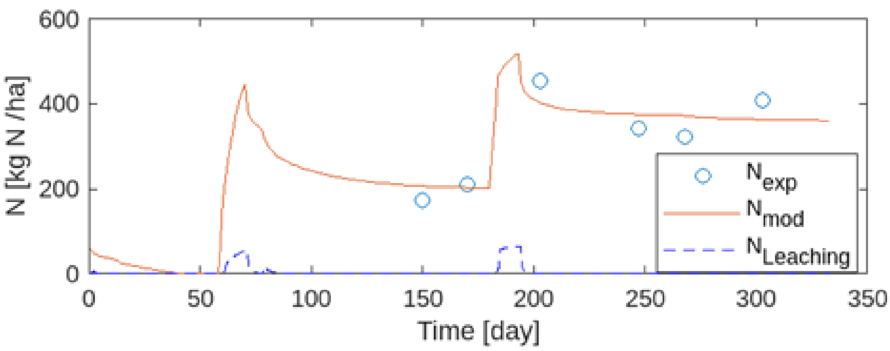
Parameter	Name	Value	Units
η_c	Maximum N concentration taken up	0.047	Kg N/m3
w^*	Normalized daily water productivity	5539.8	Kg B/m2/day

k_L	Saturated hydraulic conductivity	15.25	m/d
d_L	Leakage parameter	9.03	-

Figure 10 shows the results of the model compared to the data used. The results show a good fit of the model to the field data. In fact, the olive biomass production simulated by the model is quite similar to the field production. In addition, the soil nitrogen content determined in the laboratory is very close to the model results.



(**a**)



(**b**)

Figure 10. (a) Time series of olive's biomass production (Green solid line represent the modelled biomass and star point represent the experimental amount of biomass obtained at the harvesting time) ; (b) Time series mineral nitrogen content in the soil (circular markers is the measured nitrogen; solid line represents the modeled nitrogen content in the soil; dashed line represents the amount of nitrogen leached)

3.4.2 Soil Humidity simulation

The model is also applied to simulate soil moisture. Namely, this parameter is estimated based on water inputs from rainfall and irrigation, and losses from evaporation, transpiration, and deep percolation. The variation of soil humidity over time is illustrated in Figure 11. Due to the increase of drought period and rainfall deficit, the selected farmer applied two intensive rounds of irrigation with 350 m3 of TWW per day per hectare: 12 days for the first round and 13 days for the second one. According to the simulation results, the volumes brought by each irrigation overflow the soil and may induce to deep percolation of water. Soil evaporation and crop transpiration simulated by the model are shown in Figure 12.b. In this context, data on the reference evapotranspiration ET0 and the radiation interception efficiency of olive crop (that is the total $\phi\ \ (t)$) and the one specific to olive production $\phi_{olive}(t)$) are required (cf. Figure 12.a). However, the soil humidity being simulated by the model was not compared with real values due to the lack of experimental data. This is the subject of future work, where we will intend to s soil moisture sensors in the irrigated area of Msaken to improve the model calibration following the procedure proposed in [55].

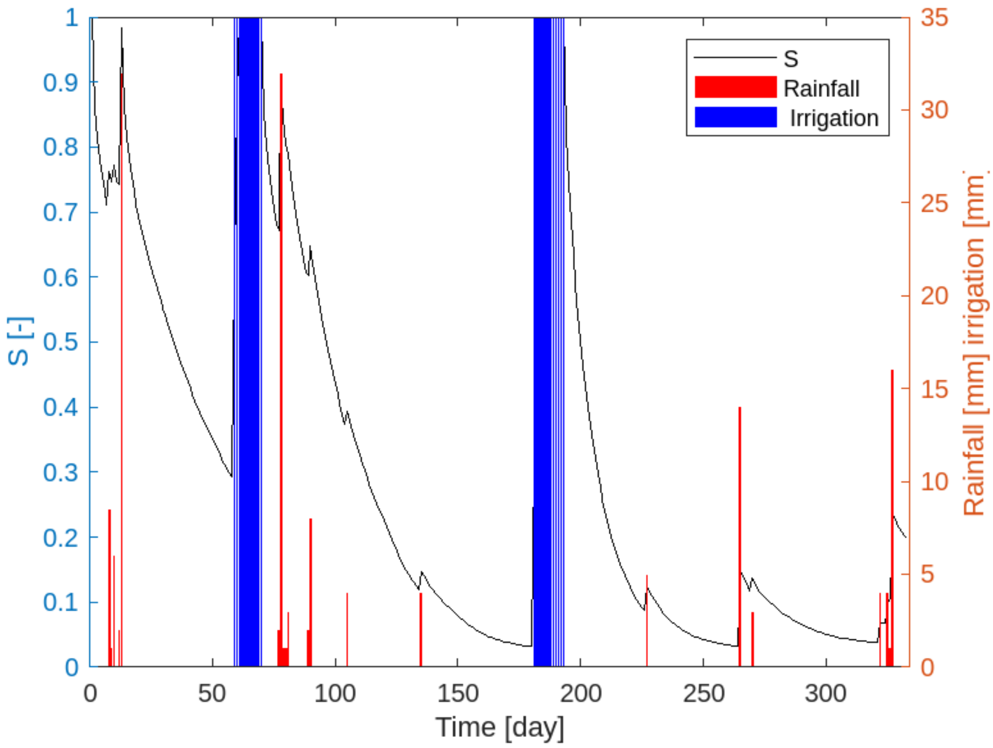
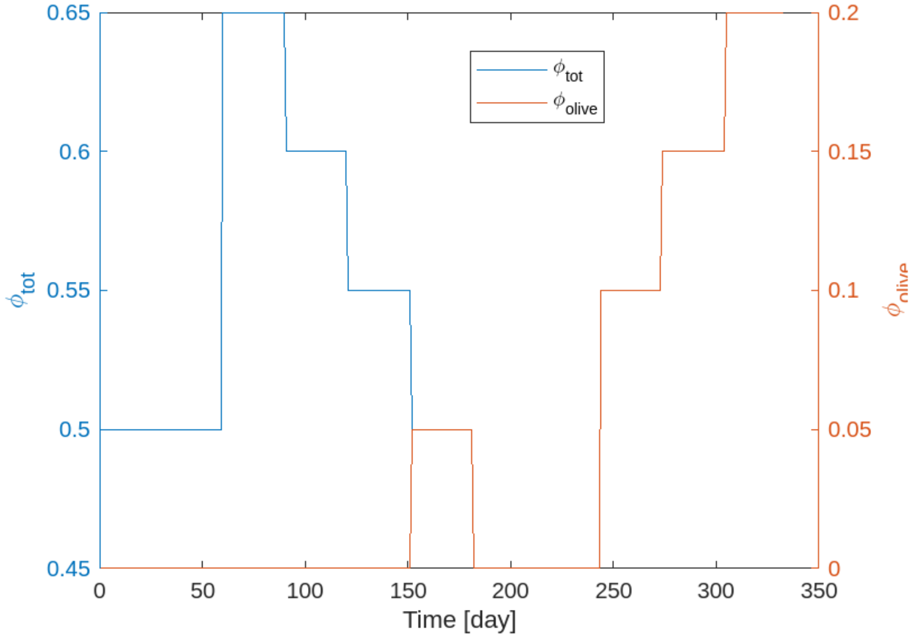
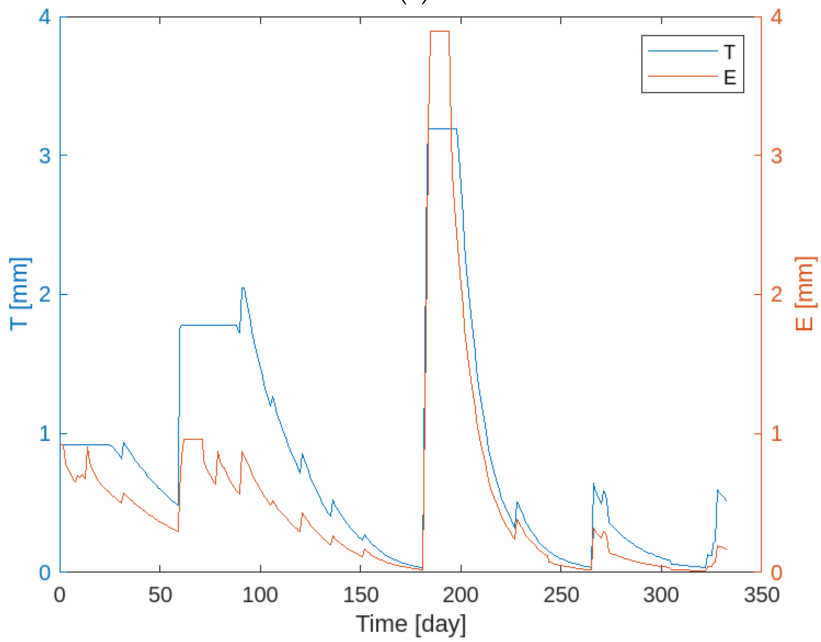


Figure 11. Soil humidity (black color), Rain (red color) and irrigation (blue color) over the olive farming season



(**a**)



(**b**)

Figure 12. (a) Olive crop and olive radiation interception efficiency over time ;
(b) Time series of transpiration and evaporation of olive crop

3.4.3 Soil Nitrogen content simulation

The nitrogen content of the soil was also increased by fertigation (cf. Figure 10.b). The treated wastewater used for irrigation is rich in mineral nitrogen. In fact, water analysis shows that the average concentration of mineral nitrogen is about 0.2 kg N/ha. Over-irrigation with TWW leads to nitrogen leaching, especially when the nitrogen concentration in the TWW exceeds the uptake capacity of olive trees. The amount of mineral nitrogen uptake of very productive olive trees in a year is estimated to be 60 -70 kg/ha [56].

However, simulation results show that the total amount of nitrogen leached into the soil during an agricultural year is estimated at 1209 kg N/ha/year, which may be a source of soil and groundwater pollution. Efficient and sustainable management of nitrogen in wastewater is very complex. The use of TWW can be considered as a "natural" fertilizer source which may provide specific elements necessary for plant growth, without excess or deficits. In addition, the use of treated wastewater for irrigation should always consider the evaluation of environmental risks versus the benefits of nitrogen for crop growth.

3.4.4 Sensitivity analysis results

From 100 iterations, the results shown in figure 13 reveal that the biomass is sensitive to the normalized daily water productivity (W*). However, the nitrogen response is sensitive to both parameters of the nitrogen leaching function (d_L and k_L). On the other hand, a perturbation of the initial soil N concentration or of the plant N uptake limit does not affect the model output.

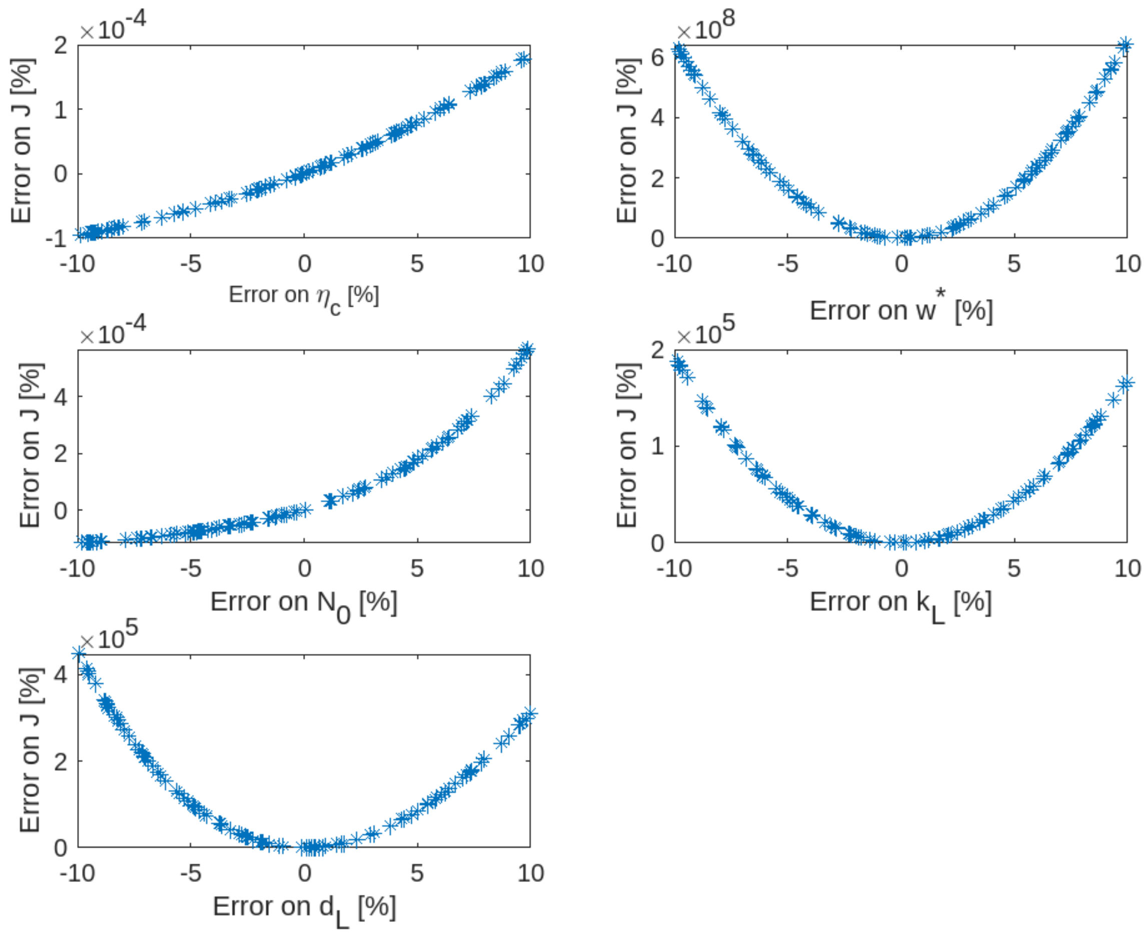


Figure 13. Sensitivity analysis. The deviation of the *sum of squared errors J of the calibrated model* based on 100 iterations for different biased values of parameters of the model

3.4.4 Viability analysis

For the analysis of viability, we found that nitrogen stress is always largely overcome by water stress, which is then the only limiting factor for biomass production. Figure 14 shows the domain K of maximum biomass production in grey and two boundaries: the red boundary for nitrogen stress and the blue for hydric stress. The finding indicates that the magenta curve representing the separation between the hydric and nitrogen stresses, does not belong to the domain K. Therefore, any trajectory of the system depicted in the (S,N) plane that starts in the domain K will only touch the S=S* boundary of the hydric stress and never the S/N= ηc boundary of the nitrogen stress. Moreover, due to the fertigation, we can observe that the trajectory which remains on the S=S* boundary goes upward. This means that the amount of nitrogen increases with irrigation, which implies that irrigation with TWW can stay away from the nitrogen stress. This result is corrobored by Fernández-Escobar et al., [57]

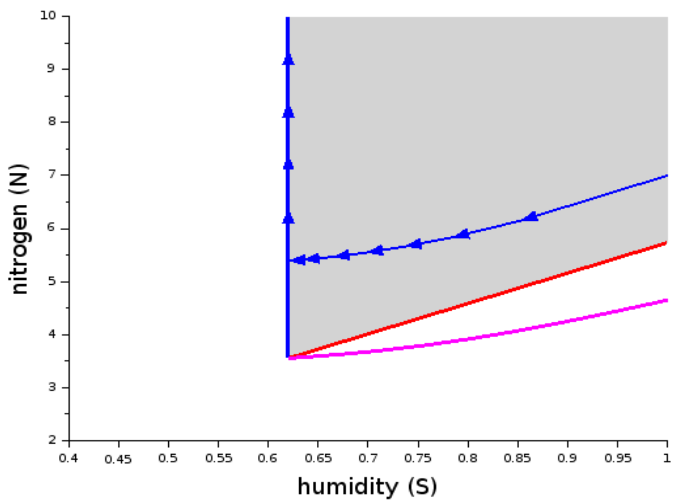


Figure 14. Result of the Viability analysis:
Viable trajectories may only touch the water stress boundary (blue)

From the humidity and nitrogen assessment, we deduced that only the hydric stress needs attention and we should adopt the minimum irrigation strategy to remain in the domain K. It consists in two successive phases:

- ✓ Phase 1 : No irrigation until the trajectory touches (or is very close) the boundary of the domain S=S*
- ✓ Phase 2 : Minimum irrigation strategy to keep the trajectory on the blue boundary S=S*, which is determined such that $\frac{dS}{dt} = 0$ with S=S*.

In order to suggest some recommendations for local farmers, we developed the Figure 15, which presents the strategy at the initial condition S0=1 and N0=57.1 kgN/ha. These theoretical trajectories shown in Figure 15 are determined without rain precipitations and for the chronicle of the function (.) that has been identified previously (and that we assume to be representative of the usual climate for the considered farm), and serve as reference values. From this simulation, the theoretical recommended values for irrigation were the maximum flow rate Imax = 5.77 m3/day/ha and the total water required per year V_{tot} = 1240 m3/ha. These values intend to help practitioners for designing the irrigation system (maximum flow rate Imax) and determining the total quantity of water for the season (V_{tot}).

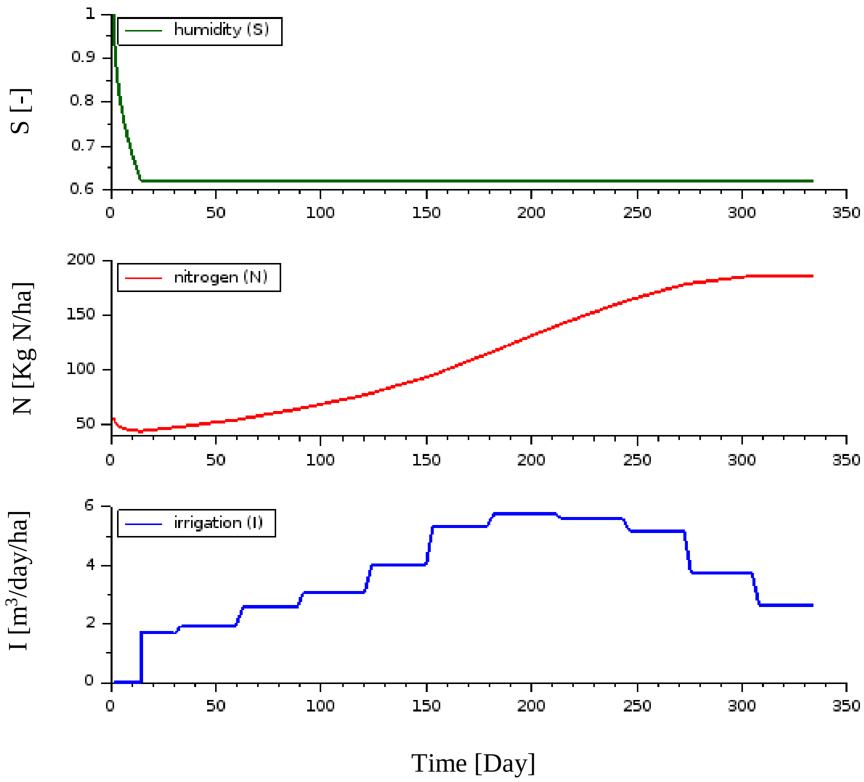


Figure 15. Simulation of the viable trajectory with the minimal irrigation strategy

4. Conclusions

Wastewater reuse is a sustainable solution for water resource management to cope with water scarcity. In addition, treated wastewater is also considered as a fertilizer source that can provide necessary inputs for plant growth. This study investigated local farmers'perceptions of the use of treated wastewater in agriculture in irrigated perimeter of Msaken. We also applied a crop model and mathematical simulations to identify optimal and safe conditions for wastewater reuse.

Results related to the reuse value chain show that the quality of TWW is suitable for irrigation and does not have a risk to human health. However, local farmers only focus on supplemental irrigation to ensure the olive production. Moreorer, the viability analysis indicates that nitrogen is not a limiting factor for olive production in the Msaken irrigated area. In addition, in this study, we have identified a theoretical minimum irrigation scheme that could guarantee maximum olive production, taking into account soil and water reuse characteristics. We found that maximum irrigation is 5.77 m^3/day/ha and the total water required per year is 1240 m^3/ha.

Further viability analysis can be elaborated in the future studies to investigate the minimal total quantity of water or total supplied nitrogen to ensure a given biomass production and to consider phosporus needs.

The next step of the research is to calculate in real conditions optimal trajectories that maximize olive production (both in terms of water and nutrient content), taking into account weather effects. It could even be interesting to intervene in the reuse chain (water treatment system) and act at that level to irrigate olive trees with optimal quality water. In other words, it would be possible to treat water so that it exactly meets the needs of olive trees.

Finally, this study could be improved with additional experimental data. For example, the use of appropriate sensors could provide more accurate estimation of soil moisture and thus, model calibration and prediction.

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