

Spatio-temporal analysis of water productivity of potato (*Solanum tuberosum* L.) under different bioclimatic stages

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Abstract. Water scarcity is a major problem in Algeria. This shortage is set to worsen in the coming years as a result of both climate change and the growth in socio-economic activities, leading to an increasing demand for water. Market gardening, in particular potato cultivation - the second most important crop after cereals - is booming throughout the country, year-round. The aim of this study is to assess the water productivity of strategic potato crops in the regions of Algiers, Tiaret and El Oued, which have temperate, semi-arid and desert climates, respectively. The approach is based on calculating the water requirements of the potato crop (*Solanum tuberosum* L.), using the CropWat model (V 8.0) and the yields recorded by the Ministry of Agriculture and Sustainable Development, over a 23-year study period (2000–2022). The results obtained showed that the values of irrigation water requirements for potato cultivation in the three regions studied are 542.3 mm, 452.7 mm and 712.5 mm, respectively. On the other hand, the water productivity figures are around 6.1, 5.8 and 4.2 kg m⁻³. This analysis could be further used by irrigation system managers and potato growers, to help them use water resources efficiently.

Key words: climate, CropWat, irrigation, potatoes, water deficit.

INTRODUCTION

In the years to come, agricultural production will face a double challenge, meeting the growing needs of the world's population while preserving the environment and natural resources. However, the benefits of the agricultural sector for growth in general may be hampered by the limited availability of water resources and the increasing pressure on them, due to the rapid expansion of water demand (FAO, 2021).

According to the FAO, 20% of the world's cultivated land is affected by drought, which can reduce crop yields by up to 50% (Seabex, 2023). In Algeria, water resources are limited, over-exploited and vulnerable. The agricultural sector consumes a lot of water, so rational irrigation water management is essential for sustainable agriculture.

Irrigation sector stakeholders require tools to assess irrigation efficiency and water use efficiency in order to develop sustainable strategies for water resources management (Kambou et al., 2014)

According to the FAO (2021), by 2030, developing countries will increase their irrigated land by 34%, while the amount of water used by agriculture will increase by only 14%. Water use efficiency is crucial to meeting the challenges of water use in agriculture. In this respect, a great deal of scientific research has been carried out worldwide to assess and analyze water productivity for different types of strategic crops and under various environmental conditions.

Among crops that are sensitive to water availability, the potato (*Solanum tuberosum* L.) occupies a strategic position due to its high nutritional value and economic importance in several regions of the world, including semi-arid and desert areas. Several studies have highlighted the decisive impact of water management on potato yield. Indeed, this crop, characterised by shallow roots and high moisture requirements, is susceptible to water stress, particularly during the critical stages of tuberisation and tuber enlargement. Teshome et al. (2024) studied the effects of deficit irrigation on potatoes in northern Ethiopia. They showed that a 25% deficit at the beginning and end of the cycle optimised water productivity and agricultural income. Yields remained stable overall, with no statistically significant differences. This strategy is a cost-effective and sustainable solution in the context of water stress. In Turkey, Ayas (2025) modelled the relationship between potato yield and water consumption using five production functions (Stewart, Jensen, Minhas, Blank and Rao), evaluating their performance over two seasons in Turkey. The study revealed that the yield formation phase is the most sensitive to water stress. The Minhas model proved to be the most relevant for predicting yields under water deficit conditions. El Mokh et al. (2024) conducted a long-term study (2002–2020) in Tunisia, in the arid region of Médenine (southern Tunisia), on the response of potatoes (cv. Spunta) to different levels of irrigation with saline water. The application of the soil water balance (SWB) method made it possible to increase yields (up to +37%), reduce water consumption (15–22%) and limit soil salinisation. Irrigation covering between 70 and 100% of ET_c proved to be optimal in this arid context. Wu et al. (2022) conducted a study in China, in the Inner Mongolia region, to optimise irrigation management for potatoes, taking root distribution into account. By adjusting the depth of the wet zone to cover 80% of the root system, the authors observed a significant improvement in tuber yield, water productivity and nitrogen use efficiency. This method is an effective alternative to uniform irrigation, particularly suitable for areas with limited water resources. Djaman et al. (2022) published a scientific review analysing irrigation management in potato cultivation, a plant that is highly sensitive to water stress due to its shallow root system. The study highlights that optimising water efficiency requires the adoption of differentiated strategies according to environments, varieties and cultivation methods. The authors emphasise the importance of managing water by taking into account factors such as fertilisation, diseases and tuber quality to meet the economic and environmental challenges of irrigated agriculture. Misgina et al. (2025) conducted a study in the semi-arid areas of Tigray, northern Ethiopia, to evaluate the performance of five potato genotypes under supplemental irrigation and without irrigation. The results showed

significant differences in marketable yield, total yield and water productivity, depending on the genotype and type of irrigation. The genotypes CIP-3960478.90 (under irrigation) and CIP-394611.112 (without irrigation) stood out for their high performance, highlighting the importance of adapting irrigation strategies to the genotype in order to sustainably improve production.

Market gardening is a strategic sector in Algeria, having experienced remarkable growth over the last few decades. The area dedicated to these crops has increased from approximately 320,100 hectares in 2003 to 533,060 hectares in 2019 (MADR, 2020a). Potatoes occupy a strategic position in the vegetable sector. They are the second most important vegetable crop in the country, covering nearly 150,000 hectares cultivated annually, which represents about 30% of the national vegetable-growing area (MADR, 2020a). They are grown in most of the country's agricultural regions and are cultivated intensively in three production cycles: early, seasonal and late, which allows for a continuous supply throughout the year.

According to the Institute of Technical Research for Vegetable and Industrial Crops (ITCMI 2022), more than 120 varieties of potatoes are currently approved in Algeria. Among them, white-skinned varieties dominate national production, with references such as Spunta, Fabula, Nicola, Diamant, Timate and Atlas. Red-skinned varieties, such as Bartina, Désirée and Kondor, also occupy a notable place due to their increased resistance and ability to adapt to diverse soil and climate conditions. Potatoes are a staple food in the Algerian diet, with an estimated average availability of between 100 and 110 kg per capita per year (MADR, 2020a). Potatoes are a crop with high water requirements and are generally planted during dry periods, requiring regular irrigation. The El Oued region, located in the Sahara, is now the leading national production area, accounting for 25.67% of Algerian production (MADR, 2020b). Irrigation there relies mainly on traditional centre pivot systems. According to a study by the Agriculture and Finance Consultants (AFC, 2022), these systems can consume up to 27,500 m³ of water per 1 ha, a volume well above the average requirements estimated by the FAO, which are 5,000 to 7,000 m³ ha⁻¹ depending on the climate.

In a context of increasing pressure on water resources, exacerbated by the effects of climate change, the issue of water use efficiency (WUE) in this strategic crop is becoming crucial. Indeed, current irrigation practices, which are often intensive and poorly adapted to the actual needs of the plant and local characteristics, can lead to significant water waste and increase the risk of soil degradation, particularly through salinisation in arid and Saharan areas. However, few studies have examined the water performance of potato cultivation in different Algerian bioclimatic contexts in a comparative manner. In this context, the present study aims to evaluate the water productivity of potato cultivation in three contrasting environments, temperate, semi-arid and desert, in order to propose recommendations for more efficient and sustainable irrigation management. The objective is to formulate optimised agricultural practices that improve yields, reduce water consumption and strengthen the resilience of agricultural systems within a framework of sustainability.

MATERIALS AND METHODS

Presentation of the study area

The study covered three wilayas (Table 1; Fig. 1). **Algiers** is located in North-Central Algeria, covering an area of 809 km². To the North, it is limited by the Mediterranean Sea, Blida to the South, Tipaza to the West and Boumerdes to the East. It is part of the Mitidja plain, with fertile alluvial soils and an altitude of no more than 50 m. The high water table favours market gardening (ANIREF, 2020).

Tiaret is located in the West of the country; its area is 20,399.10 km² (Achir & Hellal, 2016). It borders the wilayas of Tissemsilt and Relizane to the North, Laghouat and El-Bayadh to the South, Mascara and Saida to the West, and Djelfa to the East.

Table 1. Geographical coordinates of study regions (Source: <https://dateandtime.info/>)

Region	Latitude	Longitude	Altitude (m)
Algiers	36.75° N	3.04° E	186
Tiaret	35.37° N	1.31° E	1,031
El Oued	33.35° N	6.86° E	84



Figure 1. Overview of study areas.

El Oued is located in southeastern Algeria, 650 km from the capital. It covers an area of 44,586 km², representing 1.87% of the national territory (ANDI, 2014). It is bordered to the north by the wilaya of Biskra, to the east by the wilayas of Khenchela and Tébessa as well as Tunisia, to the west by the regions of El M'Ghair and Touggourt, and to the south by the wilaya of Ouargla.

Climate and soil conditions

The three study regions are characterized by different climates:

Algiers. A moderate Mediterranean climate, the wilaya of Algiers has a low temperature range, with some frost. Average monthly minimum and maximum temperatures over the period 2000–2022 range from 5.20 °C to 31 °C, and an average monthly relative humidity ranges from 68.38% to 79.37%. Annual rainfall varies between 400 and 800 mm. Sunshine is highest in July (10.59 hours) and lowest in December (5.25 hours). The Algiers region is part of the Mitidja plain, which is characterized by very clay-rich soils.

Tiaret. The Tiaret region has a dry, semi-arid climate with two distinct seasons: dry and hot, and rainy and cold. According to Achir & Hellal (2016), in normal periods, the wilaya of Tiaret receives 300 to 400 mm of rain annually, with a fluctuation varying from 157 mm to 31 mm, in winter and summer, respectively. Average monthly temperatures range from -0.30 °C to 35.8 °C, and average relative humidity from 35.11% to 76.00%. Sunshine is highest in June (12.08 hours) and lowest in December (6.43 hours). The dominant soil is Vertisol, rich in clay, according to work carried out by the Pedology Department of the Tiaret Institute of Agronomic Sciences between 1990 and 1996 (Oulbachir, 2010).

El Oued. The El Oued region enjoys an arid Saharan desert climate, with annual precipitation averaging 62 mm and evaporation of around 6 mm per day. Average temperatures range from 8.10 °C to 42.90 °C between 2000 and 2022, and humidity varies from 31.03% to 66.57%. Insolation is high in the dry season (max: 12.27 hours in June) and low in the rainy season (min: 7.10 hours in December). According to Saccon (2014), the dominant soil unit in the El Oued region is classified as 'Yy1-1a' (Gypsic Yermosols of coarse texture class), which is characterised by the following texture: sand: 96%, silt: 2% and clay 2%.

To determine the bioclimatic stage of the regions studied, we used the Emberger quotient (Q_2), which is calculated as a function of mean maximum temperature (M), mean minimum temperature (m) and mean annual rainfall (P) in mm. This quotient is higher in regions with a wetter climate (Stewart, 1969). Table 2 shows the values of Emberger's quotient calculated for the regions studied, as well as the corresponding bioclimatic zone.

Table 2. Emberger rainfall-thermal quotient (Q_2) calculated for the study regions and corresponding bioclimatic stage

Region	Rainfall (mm)	M (C°)	m (C°)	Q_2	Bioclimatic Stage
Algiers	611.44	31	5.2	81.9	Temperate
Tiaret	394.37	35.8	-0.3	39.7	Semi-arid
El oued	62.21	42.9	8.1	6.1	Desert

$$Q_2 = 3.34 \cdot P / (M - m) \quad (1)$$

Q_2 : the Emberger's rainfall quotient; Humid for $Q_2 > 100$; Temperate for $100 > Q_2 > 50$; Semi-arid for $50 > Q_2 > 25$; Arid for $25 > Q_2 > 10$; Desert for $Q_2 < 10$.

Calculation methodology

According to the FAO (1986), the determination of irrigation water requirements (IWR) for field crops follows the FAO method, which is based on several steps that allow for an accurate estimate adapted to the local agroclimatic context. The process begins with the calculation of reference evapotranspiration (ET_0) based on local climate data: temperature, humidity, wind, sunshine and solar radiation. Crop coefficients (K_c), which vary according to the stage of plant development, are then applied to calculate actual evapotranspiration (ET_c). The effective rainfall (R_{eff}) is then estimated, which represents the portion of precipitation that is actually usable by plants. The net irrigation water requirements are finally obtained by subtracting this effective rainfall from the actual evapotranspiration.

CropWat, developed by the FAO, is a calculation tool for evapotranspiration, crop water requirements and irrigation. It is also used to estimate crop yields (Langlois, 2006). Determining a crop's water requirements requires knowledge of various parameters, such as climatic conditions, soil and data on the crop itself (Table 3).

Table 3. Input parameters required by CropWat

Modules	Parameters		
Climate	Rainfall (mm)		
	Minimum and maximum temperature (C°)		
	Relative humidity (%)		
	Wind speed (m s ⁻¹) and Insolation (hours)		
Crop (Potatoes)	Planting (February 15) and harvesting (June 15) dates		
	Phenological stages : Initial (25 days); Middle (65 days); Late (30 days)		
	Rooting depth (60 cm)		
	Cultural coefficient: $Kc_{initial} = 0.50$; $Kc_{medium} = 1.15$; $Kc_{tardif} = 0.75$		
	Crop height (60 cm)		
	Crop cycle (120 days)		
Soil		Algiers and Tiaret (Clay)	El Oued (Sand)
	Total available soil moisture (FC-WP) mm meter ⁻¹	200	60
	Initial soil moisture depletion (%)	0	0
	Initial available soil moisture mm day ⁻¹	200	60

FC: Field Capacity; WP: Wilting Point.

Calculation ET₀

To evaluate reference evapotranspiration, CropWat uses the FAO-approved Penman-Monteith method. this method requires as input data: average temperatures, relative humidity, wind and insolation. These data were collected over 23 years (2000–2022) at a monthly time step from National Meteorological Office (NMO) bulletins and meteorological sites.

$$ET_0 = \frac{0.408 \Delta (R_n - G) + \gamma \left(\frac{900}{T + 273} \right) u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)} \quad (2)$$

ET₀: Reference evapotranspiration (mm day⁻¹); R_n: Net radiation at the crop surface (MJ m⁻² day⁻¹); G: Soil heat flux density (MJ m⁻² day⁻¹); T: Mean daily air temperature at 2 m height (°C); u₂ : Wind speed at 2 m height (m s⁻¹); e_s: Saturation vapour pressure (kPa); e_a: Actual vapour pressure (kPa); e_s-e_a : Saturation vapour pressure deficit (kPa); Δ: Slope of vapour pressure curve (kPa °C⁻¹); γ: Psychometric constant (kPa °C⁻¹).

Effective rainfall

In agriculture, effective precipitation refers to the fraction of total precipitation that is actually usable by plants, as it contributes to the recharge of soil water reserves. A simple and widely used method for estimating this usable fraction was developed by the USDA-SCS and is commonly used in irrigation studies and projects (Guyot, 1998).

$$R_{eff} = R_{month} \cdot (125 - 0.2 \cdot R_{eff}) \text{ for } R_{month} < 250\text{mm} \quad (3)$$

$$R_{\text{eff}} = 125 + 0.1 R_{\text{month}} \text{ for } R_{\text{month}} > 250\text{mm} \quad (4)$$

where R_{month} = Monthly rainfall mm and R_{eff} = Effective rainfall mm.

Crop Water Requirement (ETc)

The Crop water requirements for potato cultivation (ETc) were estimated by multiplying the reference evapotranspiration (ETo) by the crop coefficients (Kc) specific to each stage of plant development (Allen et al., 1998). The general expression is as follows:

$$ETc = Kc \cdot ETo \quad (5)$$

where ETc represents actual crop evapotranspiration (mm day^{-1}), represents reference evapotranspiration (mm day^{-1}), and Kc represents the crop coefficient, which varies according to the crop species and its stage of development. This method, widely used in irrigation planning, allows for accurate estimation of crop water requirements based on local agroclimatic conditions.

Calculation of the irrigation water needs (IWR)

In irrigated agricultural systems, part of the water requirements of crops can be naturally covered by rainfall, while the rest must be met by irrigation. The net irrigation water requirement (IWR) is therefore the difference between crop evapotranspiration (ETc) and the proportion of rainfall that can actually be used by the plant (Pe) (FAO, 1986). This relationship can be expressed as follows:

$$IWR = ETc - R_{\text{eff}} \quad (6)$$

Crop water productivity (WP)

Water productivity is defined as the ratio between the output obtained (biomass, agricultural yield or income) and the amount of water used or consumed during the production process (Kijne et al., 2003; Molden et al., 2010). It is a key indicator of water use efficiency in agriculture, making it possible to assess how much production is generated per cubic metre of water consumed. According to Kambou et al. (2014), this measure makes it possible to assess improvements in agricultural yield in relation to the water used and is a strategic tool for sustainable water resource management.

$$WP = Ya/ETc \quad (7)$$

where Ya is the actual crop yield achieved (kg ha^{-1}) and ETc: crop evapotranspiration ($\text{m}^3 \text{ ha}^{-1}$).

Statistical analysis: The data obtained were statistically analysed to assess the effect of the bioclimatic zone on irrigation water requirements and water productivity for potato cultivation. To this end, a one-way analysis of variance (ANOVA) was performed using Excelstat software. This method was used to test the significance of differences between the means of the three regions representing the humid, semi-arid and arid zones. When ANOVA revealed a significant effect ($p < 0.05$), a post-hoc analysis was conducted using Tukey's HSD (Honest Significant Difference) test to identify pairs of regions with statistically significant differences. This approach allowed for a rigorous interpretation of regional climatic effects on the parameters studied.

RESULTS AND DISCUSSIONS

Rainfall analysis

The variations in precipitation between the regions of Algiers, Tiaret and El Oued over the period from 2000 to 2022, shown in Fig. 2, reveal a marked disparity in the spatial and temporal distribution of rainfall. Algiers has the highest average annual rainfall with 616.27 mm, followed by Tiaret with 394.37 mm, while El Oued, with its desert climate, has a very low average of 62.21 mm. This distribution highlights a north-south gradient, typical of the Algerian climate, with decreasing humidity towards the interior and south of the country.

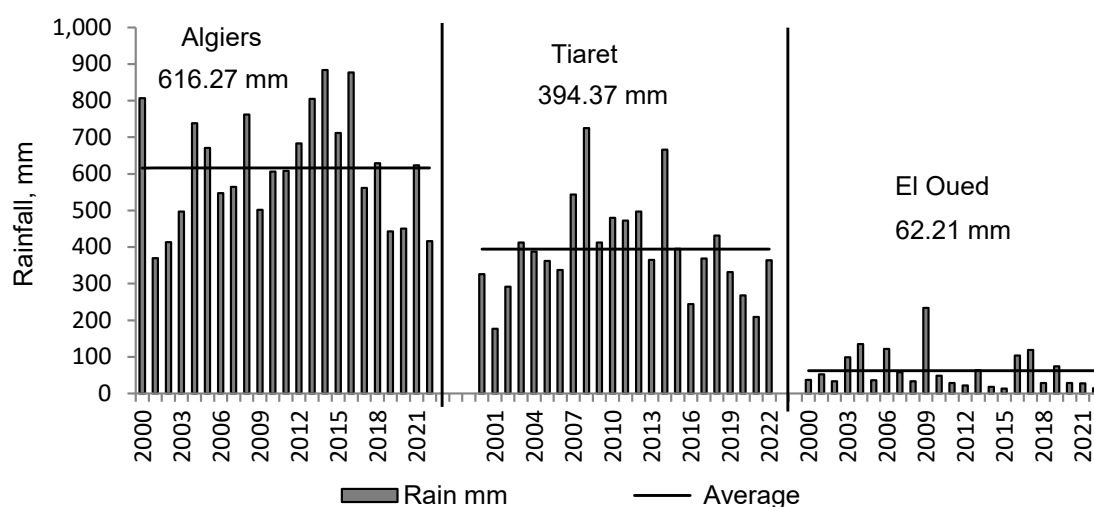


Figure 2. Annual rainfall (period: 2000–2022).

The interannual analysis also shows high variability, both in humid and arid areas. The wettest years were 2014 in Algiers (884.3 mm), 2008 in Tiaret (724.8 mm) and 2009 in El Oued (233.7 mm), while the driest years were 2001 in Algiers (369.3 mm), 2001 in Tiaret (177.3 mm) and 2015 in El Oued (13 mm). This interannual irregularity in rainfall highlights the climate vulnerability of certain regions, particularly El Oued, where dependence on irrigation is almost permanent. Such fluctuations directly influence agricultural planning and sustainable water resource management, making it imperative to adopt strategies adapted to local climate specificities.

Reference Evapotranspiration (ET₀)

The analysis of changes in reference evapotranspiration (ET₀), illustrated in Fig. 3, highlights significant geographical contrasts between the northern areas (stations Algiers and Tiaret) and the southern region (station El Oued). ET₀ follows a clearly marked seasonal pattern, with maximum values in summer and minimum values in winter. In July, peaks reach 5.9 mm day⁻¹ at Algiers, 7.9 mm day⁻¹ at Tiaret, and a high of 10.6 mm day⁻¹ at El Oued. In contrast, the lowest values are observed in December: 1.5 mm day⁻¹ (Algiers), 1.4 mm/day (Tiaret) and 2 mm day⁻¹ (El Oued), reflecting a strong influence of temperature, humidity and solar radiation.

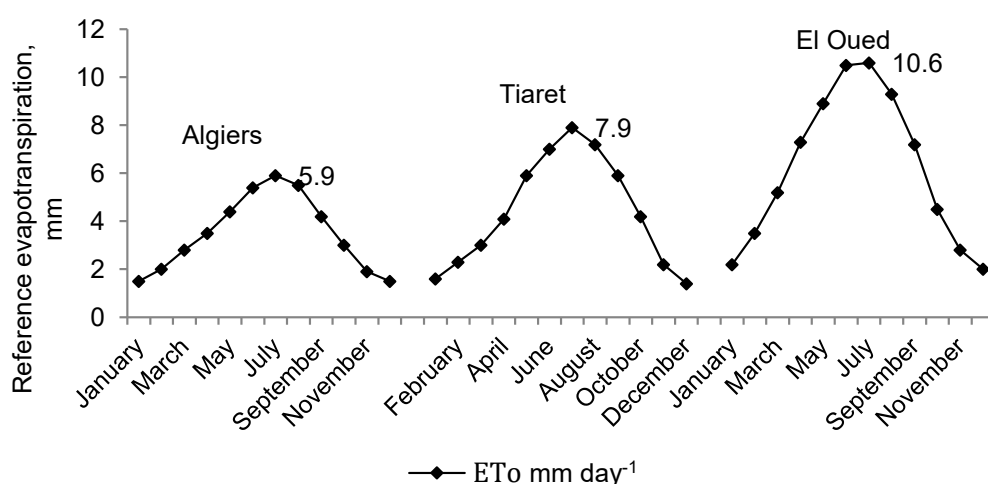


Figure 3. Monthly mean of reference evapotranspiration mm day⁻¹ (period 2000–2022).

The southern region is characterised by much higher evaporative demand due to its Saharan climate, which is characterised by high temperatures, strong sunshine and low relative humidity. Xu & Chen (2005) points out that evaporation is mainly governed by temperature, but also by complex interactions with wind and atmospheric humidity. These factors determine the atmosphere's ability to extract water available at ground level and from plants. Mokhtari et al. (2016) report that the ETo of the Oued Righ region (South East) is around 9.7 mm day⁻¹ (in July) over a 30-year climatic period (1984–2013), which is adjacent to the El Oued region.

Effective rainfall

Effective rainfall represents the amount of rainfall that can actually be used by plants. It is important to note that not all precipitation is directly available for potato cultivation, as some is lost through runoff and/or deep infiltration. Fig. 4 and 5 show variations in effective precipitation on an annual (January to December) and seasonal (February to June) basis.

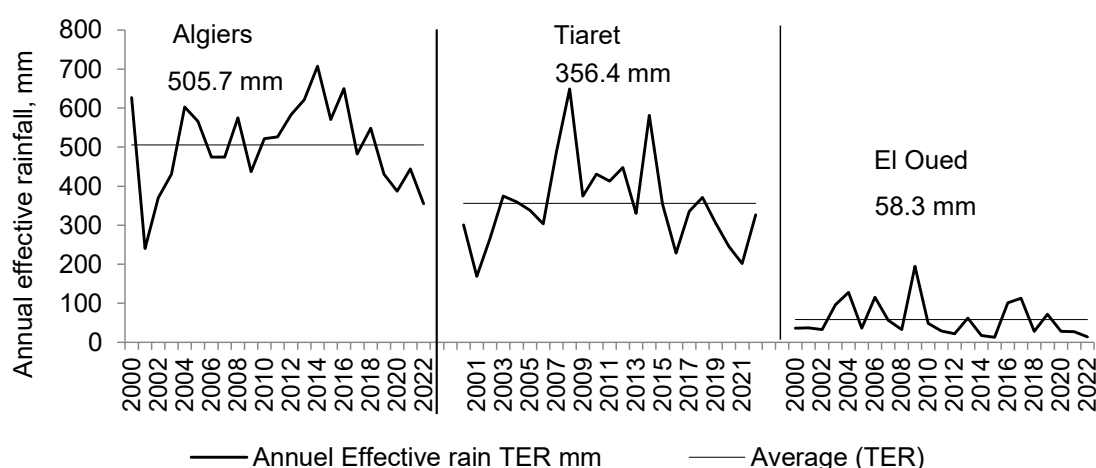


Figure 4. Interannual variation of annual effective rainfall.

The annual values of effective precipitation (Fig. 4) recorded are higher in the northern regions (Algiers and Tiaret), with figures of 505.7 mm (Algiers), 356.4 mm (Tiaret) and 58.3 mm (El Oued). This disparity is explained by the different bioclimatic zones to which they belong. The effective rainfall for the potato growing season shows that the Tiaret region has the highest value with 157 mm, representing 44.05% of the annual effective rainfall. The Algiers region, on the other hand, has a value of 129.7 mm, or 25.65% of annual effective rainfall (Fig. 5).

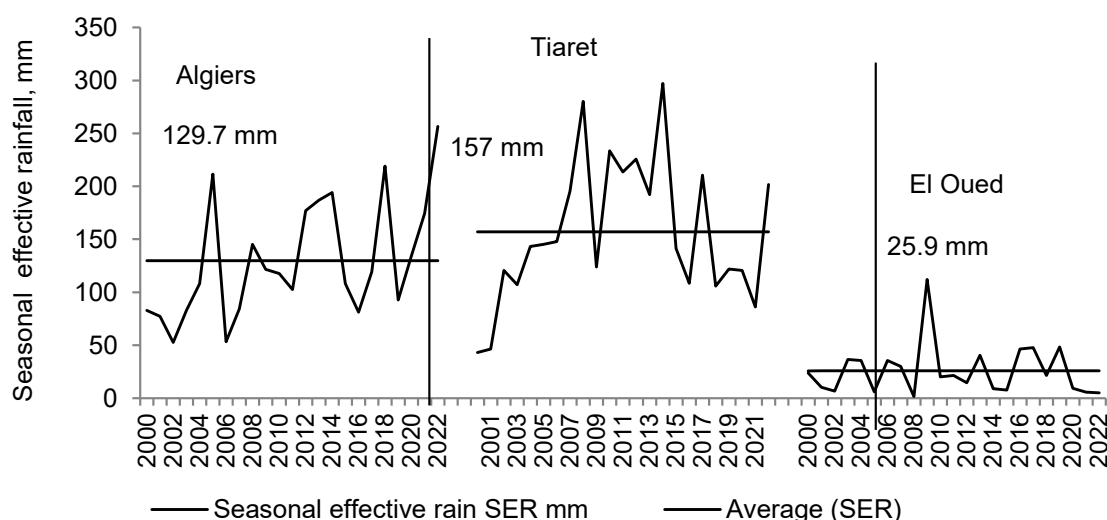


Figure 5. Interannual variation of seasonal effective rainfall.

Crop Water Requirement (ET_c)

Potato cultivation has water requirements that vary according to regional climatic conditions. A comparison was therefore made between three areas with contrasting bioclimatic profiles: Algiers (humid), Tiaret (semi-arid) and El Oued (arid), highlighting significant differences in irrigation needs, as shown in Fig. 6. The results show that these requirements vary significantly depending on the region, with estimated values of 542.3 mm for Algiers, 452.7 mm for Tiaret, and 712.5 mm for El Oued. These differences are mainly explained by the climatic differences between the regions: Algiers enjoys a temperate Mediterranean climate, Tiaret a semi-arid climate, while El Oued is subject to a desert climate, where high temperatures and intense evapotranspiration lead to significantly higher water demand.

Statistical analysis (Table 4) highlights significant differences between regions in terms of crop water requirements (ET_c), $F(2.66)=60.00$; $p < 0.001$. The Tukey HSD analysis shows that all pairwise comparisons are statistically significant, according to a clear gradient: El Oued (712.5 ± 108.2 mm) > Algiers (542.3 ± 67.8 mm) > Tiaret (452.7 ± 60.9 mm).

These results reflect a direct influence of climatic conditions on water demand, with maximum pressure in the arid context of El Oued and more moderate pressure in the temperate climate of Algiers. The Tiaret region, on the other hand, stands out for its

significantly lower water requirements, which is a considerable asset in terms of resilient agriculture. This water saving not only reduces pressure on water resources but also improves production sustainability and food security in semi-arid areas.

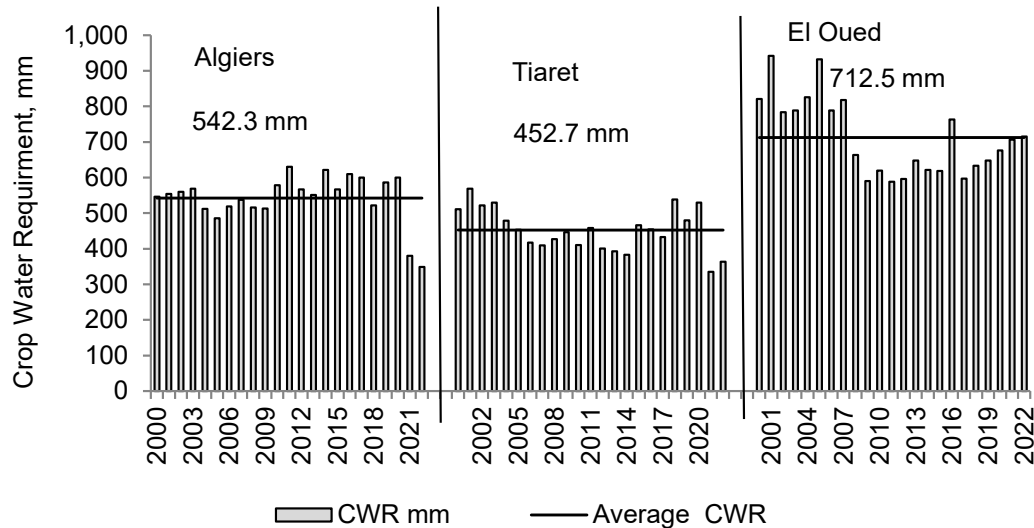


Figure 6. Water requirement for potato cultivation under different bioclimatic stages.

Thus, beyond a simple statistical comparison, the results suggest that Tiaret is an ideal environment for the development of potato cultivation, due to its combination of a favourable semi-arid climate and reduced water demand.

Furthermore, the values obtained are broadly in line with the ranges published by the FAO, which estimates that the water requirements of potatoes vary between 500 and 700 mm depending on climatic conditions and cultivation practices. The results for Tiaret are consistent with those reported by Amirouche et al. (2023), who simulated water requirements of 517.24 mm (CropWat) and 507.38 mm (AquaCrop) for the same region over a period of 31 years, confirming the reliability of the estimates obtained. The value recorded in Algiers (542.3 mm) is also within the limits set by previous studies such as that of Kassua et al. (2017), who estimated a requirement of 500.87 mm in the Husked region (Ethiopia), and that of Sood & Sharma (1993), who estimated requirements of between 350 and 550 mm depending on practices and climate. These variations demonstrate the importance of contextualising water requirements at the local level.

However, the high value observed in El Oued (712.5 mm) slightly exceeds the upper thresholds mentioned by the FAO, which is to be expected in an arid climate. This trend is consistent with the findings of Alataway et al. (2019), who recorded water requirements of 713 mm in eastern Saudi Arabia and up to 856.4 mm in the Al Jouf region, both of which have similar climatic conditions to those in El Oued. Such levels of water consumption reflect the high vulnerability of these areas to water scarcity and highlight the need for rigorous management strategies to optimise irrigation.

The results obtained confirm that potato water requirements are closely linked to regional climatic conditions. The Tiaret region, with moderate requirements, appears to be the most favourable for sustainable potato cultivation in terms of water efficiency,

while El Oued imposes a significant water load, requiring controlled and potentially costly irrigation. These findings reinforce the importance of appropriate agro-hydrological planning, taking into account regional climate variability and crop characteristics, to ensure efficient and sustainable water resource management.

Irrigation Water Requirement (IWR)

The results of the irrigation water requirement (IWR) simulation using the CropWat model (Fig. 7) reveal significant differences between the three regions studied: Algiers, Tiaret and El Oued. The wilaya of El Oued, characterised by a desert climate, has the highest irrigation requirements, with an average of 688.7 mm. Conversely, the simulated values for Algiers and Tiaret are significantly lower, at 438.2 mm and 315 mm respectively. This variation is mainly due to the specific climatic characteristics of each region. El Oued, exposed to extreme aridity and high temperatures, has higher evapotranspiration, which significantly increases crop water requirements. Algiers, on the other hand, with its Mediterranean climate, benefits from more regular rainfall, partially reducing its dependence on irrigation. As for Tiaret, its semi-arid climate, combined with moderate temperatures during the potato growing cycle, helps to limit water requirements.

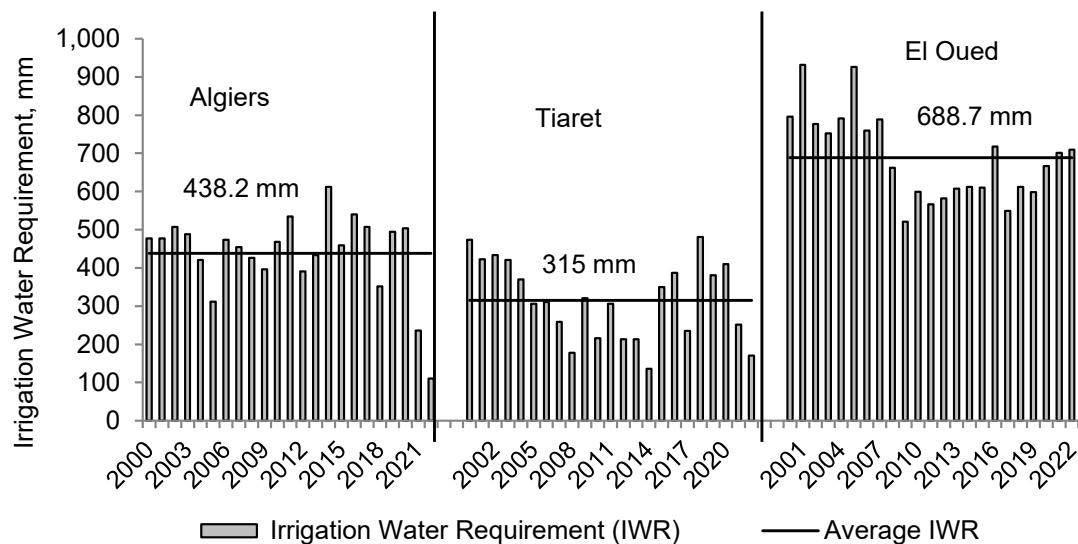


Figure 7. Irrigation water requirement (IWR) simulated by CropWat under different bioclimatic stages.

ANOVA conducted on irrigation water requirements (IWR) shows a highly significant effect of region $F(2.66) = 72.29$; $p < 0.001$, with a clear gradient $\text{El Oued} > \text{Algiers} > \text{Tiaret}$ (Table 4). The results of Tukey's post-hoc test confirm that all pairwise comparisons between the three regions are statistically significant. Thus, water requirements reach 688.7 ± 113.1 mm in El Oued, 438.2 ± 106.9 mm in Algiers and only 315.0 ± 101.9 mm in Tiaret.

These results highlight that Tiaret stands out as having the lowest irrigation volumes among the regions studied. This characteristic represents a major water advantage in a context of increasing water scarcity, since potatoes can be grown there with reduced water consumption without compromising yields. In comparison, Algiers requires greater inputs, and El Oued faces the most severe constraints due to its arid climate.

Thus, from the point of view of sustainable resource management, the Tiaret region appears particularly favourable for potato cultivation, offering an optimal compromise between water availability, semi-arid climate and productivity potential.

Water Productivity

To identify the yields of potato cultivation in the study regions, we used the 'B 1 series' of the Ministry of Agriculture and Rural Development. The analysis of water productivity for the different study regions is illustrated in Fig. 8. Potato water productivity obtained in the Algiers region fluctuates between a minimum of 2.8 kg m^{-3} and a maximum of 8.5 kg m^{-3} with an average of 6.1 kg m^{-3} . On the other hand, that of the Tiaret region, it fluctuates between 1.8 and 8 kg m^{-3} with an average of 5.8 kg m^{-3} . From this graph, it is clear that the water productivity values for the two regions (Algiers and Tiaret) followed the same trend despite belonging to different bioclimatic stages.

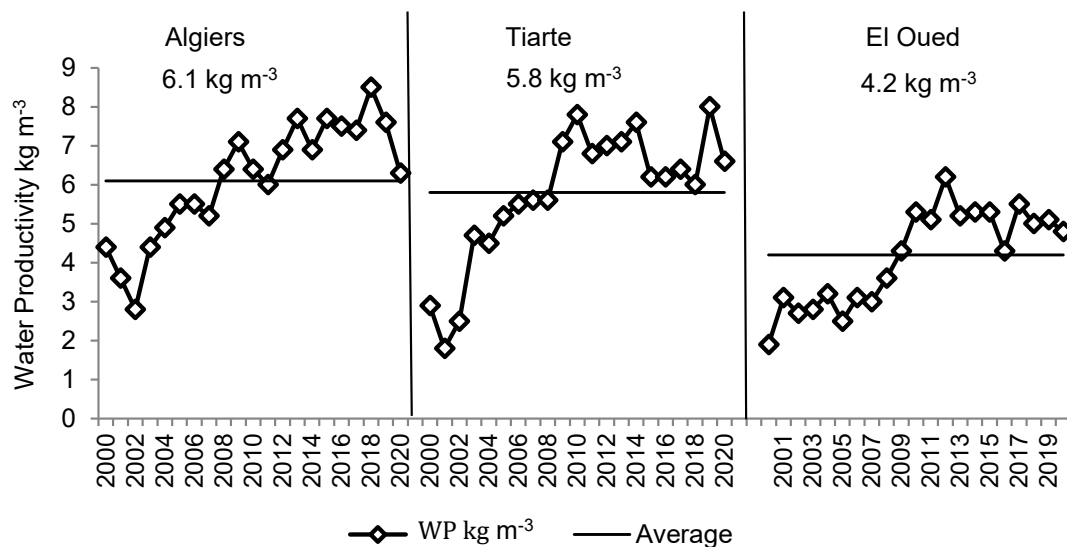


Figure 8. Water productivity for potato cultivation simulated under different bioclimatic stages.

ANOVA highlights a significant effect of region on water productivity, $F(2.60) = 9.22$, $p < 0.001$. On average, Algiers and Tiaret have higher values (6.00 ± 1.60 and $5.77 \pm 1.70 \text{ kg m}^{-3}$, respectively) compared to El Oued ($4.15 \pm 1.23 \text{ kg m}^{-3}$). Post-hoc comparisons (Tukey HSD) confirm that Algiers > El Oued and Tiaret > El Oued, while the difference between Algiers and Tiaret is not significant. These results highlight that, despite their contrasting climatic conditions (temperate in Algiers and semi-arid in Tiaret), both regions offer similar, high water efficiency, reflecting better use of each cubic metre of water used. Conversely, El Oued,

which has an arid climate, has significantly lower efficiency due to greater losses linked to high evaporation rates and low retention in sandy soils.

Table 4 presents the results of the analysis of variance (ANOVA) and Tukey's post hoc test for the three parameters studied (IWR, ETc and WP) in the different regions.

Table 4. ANOVA and Tukey's test results for IWR, ETc and WP in the three regions

Parameter	El Oued (Mean $\pm$ SD; Tukey)	Algiers (Mean $\pm$ SD; Tukey)	Tiaret (Mean $\pm$ SD; Tukey)	F (ddl)	p-value	Signif.
IWR (mm)	688.70 $\pm$ 113.10 (a)	438.20 $\pm$ 106.90 (b)	315.00 $\pm$ 101.90 (c)	72.29 (2.66)	1.00e-12	***
ETc (mm)	712.50 $\pm$ 108.20 (a)	542.30 $\pm$ 67.80 (b)	452.70 $\pm$ 60.90 (c)	60.00 (2.66)	1.41e-15	***
WP (kg·m ⁻³)	4.15 $\pm$ 1.23 (b)	6.00 $\pm$ 1.60 (a)	5.77 $\pm$ 1.70 (a)	9.22 (2.60)	3.23e-04	***

Notes: Tukey's letters indicate homogeneous groups; two regions sharing the same letter do not differ significantly ($\alpha = 0.05$). ANOVA significance codes: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns: not significant.

The lowest water productivity values were obtained in the El Oued region, which fluctuates between 1.9 and 6.2 kg m⁻³ with an average of 4.2 kg m⁻³. According to Sander et al. (2004), the variability in water productivity of a given crop can be attributed to climate, irrigation water management and soil (nutrient) management. According to the meta-analysis by Niu et al. (2025), water efficiency in potato cultivation depends on both irrigation practices and soil and climate conditions. Ahmadi et al. (2010) showed that the effects of irrigation strategies on potato yield and water productivity vary depending on soil type, with full irrigation being more effective in loamy soils, while water-saving strategies are more suitable for sandy and loamy soils in contexts where resources are limited.

The results obtained fall within the range highlighted by Wright & Stark (1990), who noted that the WP of potato crops varied between 5.4 and 12.0 kg m⁻³ depending on the region and management. irrigation. Amirouche et al. (2023) noted that the water productivity of potatoes (Tiaret region, Algeria) varies from 3.64 to 13.70 kg m⁻³ depending on climatic conditions.

Nagaz et al. (2007) reported that water use efficiency ranged from 6 to 14 kg m⁻³ for potatoes planted in fall, winter and spring. Cantore et al. (2014) evaluated the water use efficiency of potatoes (Apulia Regions, Southern Italy), carried out under three irrigation regimes I100, I50 and Pluvial (I0). They found that the values of water use efficiency are 10.73, 10.63 and 9.02 kg m⁻³, respectively. Hassanpanah (2010), comparing seven potato cultivars, observed that water stress increased water use efficiency (from average values of 6.65 kg m⁻³ for the well-watered crop to values of 7.9 kg m⁻³ for the crop grown under water stress).

Concerning the overall assessment of water productivity (WP), the graph shows two distinct periods, one (2000–2008) where the WP values are lower than the corresponding average for each region and the other (2008–2022) where these are higher than the corresponding average, this improvement could be explained by the mastery of technical routes by farmers.

CONCLUSIONS

This comparative study demonstrated the relevance and reliability of the CropWat model in estimating the water requirements of potato cultivation in various agroclimatic contexts. The results obtained in the three bioclimatic environments studied (temperate, semi-arid and desert) show that potato water productivity depends on both climatic conditions and local soil characteristics. These findings confirm that adapting irrigation practices to the regional context is a major lever for improving water use efficiency and the sustainability of production systems.

The CropWat model was used as a methodological tool to estimate crop water requirements. The results are broadly consistent with the international literature, confirming the relevance of this tool for accurately reproducing potato water requirements in various agroclimatic contexts.

The assessment of water productivity confirms these trends, with higher performance observed in Algiers and Tiaret (5.8 kg m^{-3}) compared to El Oued (4.2 kg m^{-3}), where irrigation efficiency remains limited due to extreme climatic conditions. These results suggest that it would be wise to promote the expansion of potato cultivation in temperate and semi-arid areas, where yields can be optimised with more rational water consumption. In arid areas, particular attention must be paid to the technical management of irrigation, the selection of appropriate equipment and the optimisation of cultivation practices to improve the value of each cubic metre of water.

Ultimately, the lessons learned from this study can be used by irrigation managers, farmers and public decision-makers to implement more sustainable agricultural strategies, reducing water vulnerability while ensuring food security. They also highlight the importance of developing a territorialised approach to water management, based on simulation, climate adaptation and water performance.

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