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Evaluation and analysis of the water footprint of agricultural crop production in the Timahdite region (Ifrane, Morocco)

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ABSTRACT

Water is an essential resource and a critical factor for agricultural production, particularly in water-scarce regions such as the Timahdite area (Morocco). The water footprint (WF) concept is extensively used as an indicator to evaluate water use in agricultural crop production and better managing water resources. Drawing on this concept, the objective of this research is to evaluate and analyze the water footprint of the eight major crops cultivated in the Timahdite region over the 2020–2025 periods, and the influence of several factors (e.g. climatic condition). The typology of relationships among variables (WF and crop-types) was analyzed using principal component anlysis (PCA) and Pearson correlation analysis. The analysis of the major climatic factors in Timahdite revealed pronounced interannual variability, accompanied by a notable decline in precipitation in recent years. The results indicate that the mean total water footprint of all analyzed crops during the study period reached 1019.6 m^3/ton of production (48% green, 45% blue, and 7% grey WF) and wheat and other cereal exhibit the highest WF among all crops categories. A comparatively, stone fruit crops (plums, apple and cherries) exhibited relatively elevated total blue WF, which was significantly larger than root and bulb vegetables (onions, garlic, and potatoes), indicating a greater dependence on irrigation water. Several crops exhibit the most substantial percentage deviation in WF when compared to the global average benchmark established by FAO. The PCA provides a typological and clustering framework that elucidates the relationships between crops-types and WF, explaining 92% of the total variance. The analysis identifies five principal groups characterized by distinct water-use patterns. The clusters results indicate that apples and carrots exhibit the highest levels of blue water consumption. In contrast, onion and garlic exert comparatively lower pressure on local blue water resources. The WF components enables evaluation of both the origins of water resources mobilized in agricultural crop production in the Timahdite region and volume required to produce a given product.The findings of this study underscore the relevance of the water footprint concept as an innovative analytical framework, offering an effective tool for assessing agricultural water use and contributing to the sustainable management of water resources.

Keywords: water footprint, crops production, PCA analysis, Timahdite, Morocco.

INTRODUCTION

Water is a fundamental resource for agricultural production, and the increasing pressure exerted by farming activities necessitates the implementation of effective water-management strategies. The water footprint concept offers a holistic view, which account for both direct and indirect water use, and offers a comprehensive assessment of water associated with crop production (Mekonnen & Hoekstra, 2011). Agriculture constitutes the primary consumer of freshwater resources worldwide, accounting for approximately 80% global water use (Crovella et al., 2016 ; Attar et al., 2025). Water resources are indispensable for sustaining both societal livelihoods and productive activities

(Balata et al. 2022). However, the rapid global population growth, evolving human lifestyles, unsustainable methods of water utilization, and the impacts of climate change, are placing mounting pressure on global water resources (Hssaisoune et al., 2022). The scarcity of available water resources not only restricts sustainable socio-economic development but also poses a significant threat to environmental security (ESEC, 2020). The global water resources crisis has emerged as one of the most critical environmental and resource-related challenges worldwide (Ait-elkadi et al., 2025). Achieving and maintaining high levels of water-use efficiency is essential for meeting the United Nations Sustainable Development Goals (SDGs) for 2030 and also supports other interrelated goals, including foods security under SDG 2 and the protection of environmental and health under SDG 14 and SDG 15 (UN-General Assembly, 2015). Limited freshwater resources are facing increasing pressure worldwide as result of climate change and socio-economic development (Jàgermeyr et al., 2017; Baldassarre et al., 2018). Situated in a semi-arid region and increasingly impacted by climate change, Morocco faces persistent water stress. This structural vulnerability intensifies pressure on the country's water resources (Elkouk et al., 2022). In this context, the water footprint (WF) is a widely recognized concept in research and water resource management discourse. It can be used to improve the management and sustainability of water resources, particularity in arid and semi-arid regions where water scarcity poses significant challenges (Makate et al., 2018; Burszta et al., 2018; Bianbian et al., 2021).

In 2014, the water footprint index was standardized through the international standard (ISO-14046, 2014), which establishes the principals, and guidelines for assessing the water footprint of products, processes based on life cycle assessment (LCA) approach. Since the introduction of the WF as an environmental indicator, considerable research has been conducted on blue, green, and grey water use in crop production, along with corresponding water footprint assessments (Garrido et al., 2024). The water footprint methodology is a robust global tool for managing limited freshwater resources and to promoting sustainable and well-governed water use. Accordingly, the WF serves as a key indicator for assessing the impact of agricultural practices on freshwater resources. It should be noted, the water footprint concept consists of three components: green, blue, and grey water footprint. The green WF represents rainwater stored in the soil and used by plants, with any excess lost through evapotranspiration. The blue WF refers to the volume of surface and groundwater consumed during crop production. The grey WF is the theoretical volume of freshwater required to diluting pollutants to concentrations that comply with established water quality standards (Hoekstra & Mekonnen, 2014). Despite sustained efforts to safeguard Morocco's water resources, their reserves have declined sharply in recent years due to multiple factors, including recurrent droughts, rapid population growth and intensive exploitation by various economic sectors, particularly agriculture (Attar et al., 2025).

The study aims to: (1) evaluate and analyzed the water footprint of major crops in the Timahdite region (Morocco) over the 2020–2025 period; (2) elucidate the relationships between crop-types and their water consumption patterns by analyzing the statistical typology (PCA); (3) identify current shortcoming and outline future pathways for sustainability development in the region.

MATERAILS AND METHODS

Study area

Morocco, located in Northwestern Africa, is distinguished by its great geographical diversity (Figure 1). The country's water resources are characterized by strong spatio-temporal variability and a marked dependence on irregular rainfall, unevenly distributed and often prone by episodes of severe droughts or flooding (Benabdelouahab et al., 2020). The municipality of Timahdite (33°14'13"N, 5°03'36"W) is located in Ifrane Province Morocco. It lies within the Fez-Meknes region in the central Middle Atlas an altitude of approximately 1800 m and covers an area of 452,8 km^2 (PWFS-Ifrane, 2014). The region is characterized by a harsh climatic regime and constitutes an important part of the tributary system of the Sebou River Basin, particularly through the Gigou Valley.

The spatio-temporal distribution of agricultural land and crop types in Morocco is mainly determined by the country's diverse geomorphological features and climatic conditions. The hydrogeological framework of the Timahdite area in the Middle Atlas is marked by considerable geological diversity, encompassing formations of various ages (Primary to Quaternary). The Timahdite area is characterized by important water

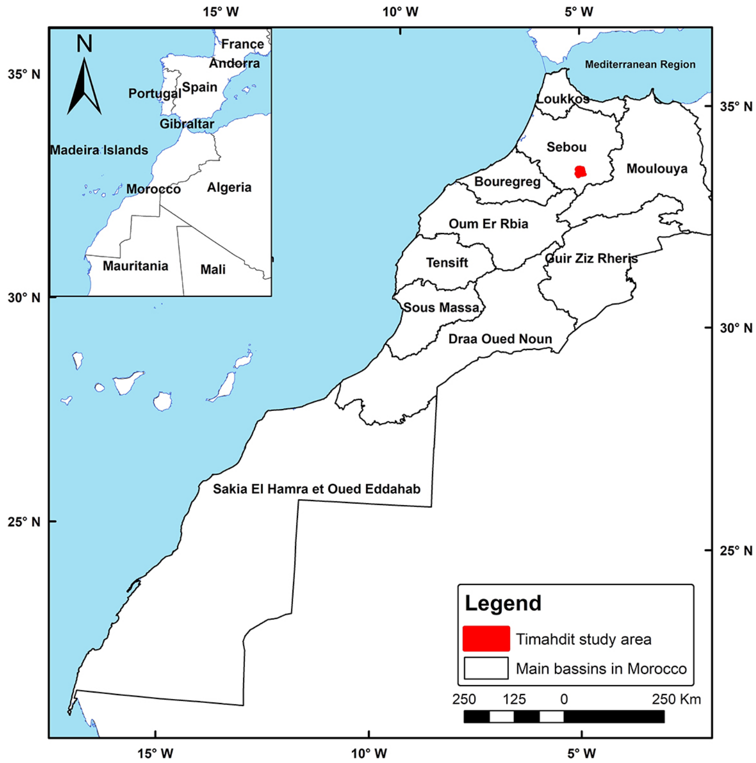

Figure 1. Map of Morocco and location of the study area (Timahdite, Ifrane). Disclaimer: the basins boundaries depicted, they are included solely for illustrative purposes

resources, which have earned it the designation of the "water tower'' of the Middle Atlas in Morocco. However, the region's predominantly mountainous topography poses significant challenges to groundwater availability an long-term sustainability, particularly during drought seasons. Accurate quantification of the water footprint (WF) is essential for effective management of regional agricultural water resources. Its magnitude is strongly influenced by climatic conditions, soil properties, and water management practices, leanding to significant spatio-temporal variability (Zhao et al., 2024).

Methodological framework

The International Water Footprint Network has developed a standardized methodology for assessing the water footprint in agricultural systems. In accordance with the water footprint assessment manual (Hoekstra et al., 2011), the approach adopted in this study involved the analysis of agricultural records collected over the period 2020–2025 to quantify, and evaluate the water footprint of crops in the Timahdite area. Crop water requirements and local climatic conditions were calculated using the CROPWAT software developed by the Food and Agriculture Organization. The data were obtained by Center Provincial Directorate of Agriculture in Timahdite (Ifrane, Morocco). The total water footprint of a crop, defined as the annual volume of water consumed per tonne of agricultural product, is calculated using Equation (1):

$$WF_{Total} = WF_{t,Gn} + WF_{t,B} + WF_{t,Gy} \quad (1)$$

where: $WF_{t,Gn}$ – green water footprint; $WF_{t,B}$ – blue water footprint; $WF_{t,Gy}$ – grey water footprint.

The green water footprint refers to rainwater stored in the soil and consumed by crops, the blue WF represents water withdrawn from surface and groundwater resources, and the grey WF denotes the volume of water required to dilute pollutants to meet water quality standards (Aldaya et al., 2011; Zhao et al., 2024). The grey water footprint is estimated using the following Equation (2):

$$WF_{Gy} = (L/Y)/(C_{max} - C_{nat}) \quad (2)$$

where: L – nitrogen load from leached/runoff fertilizers (kg), Y – crops yield (kg), C_{max} – the maximum permissible concentration of nitrogen in water ($kg \cdot m^{-3}$), C_{nat} – natural background concentration of nitrogen in water ($kg \cdot m^{-3}$).

The WF was evaluated for wheat and other cereals, potatoes, onions, garlic, carrots and turnips, apples, cherries, and plums, which together represent approximately 95% of the total sowing area. Agricultural water use is typically quantified on the basis of the harvested by evaluating the volume of water required for the annual crop cycle. The average specific water footprint was calculated separately for each crop type using the obtained data and subsequently compared with the FAO global average water footprint benchmark.

Statistical analysis

Statistical analysis were conducted to evaluate correlations between crop yields and water footprint using XLSTAT software (version 2025.2.0). To establish a typology of the study area, multivariate analysis were performed using this software, including principal component analysis (PCA), correlation heatmaps to assess relationships among water footprint variables, Scatterplot analysis, and descriptive statistical analysis. In environmental and agrico-ecological research, these methods have been extensively applied to elucidate relationships among individuals and/or variabales, as well as to identify seasonal and climatic influences on en environmental, agricultural systems and environment-health (Essahale et al. 2015; Zhuo et al., 2016c; Bianbian et al., 2021; Essahale et al., 2024). The Person's correlation analysis was used to evaluate associations between crops and water footprint (WF) variables, and t-tests were performed to compare WF parameters between the different study periods (2020–2025).

RESULTS AND DISCUSSION

Temporal fluctuation of climatic factors

Climate variability exerts a direct influence on crop water requirements and yield per unit area. Consequently, it indirectly affects the WF associated with crop production. Figure 2 highlights the strong seasonal changes in the average variation of principal climate factors in Timahdite region.

The maximum and minimum temperatures recorded during thchili e study period were respectively 35°C and -10°C. It should be noted that this city Timahdite is localed in a region with a very cold climate that records the lowest temperatures in Africa (following the significant snowfall by the region). Annual rainfall in Timahdite exhibited marked interannual variability, ranging from a minimum of 161 mm in 2022 to a maximum of 611 mm in 2025. The years 2023 and 2024 recorded 273 mm and 346 mm, respectively. A particularly, dry season was recorded in 2021, with only 110 mm of rainfall between Sepembre to April and merely 4 mm in August. The spatial distribution of agricultural land in Morocco is primarily shaped by the country's diverse geomorphological factures, climatic conditions and availability of water resources (Fathian et al.,

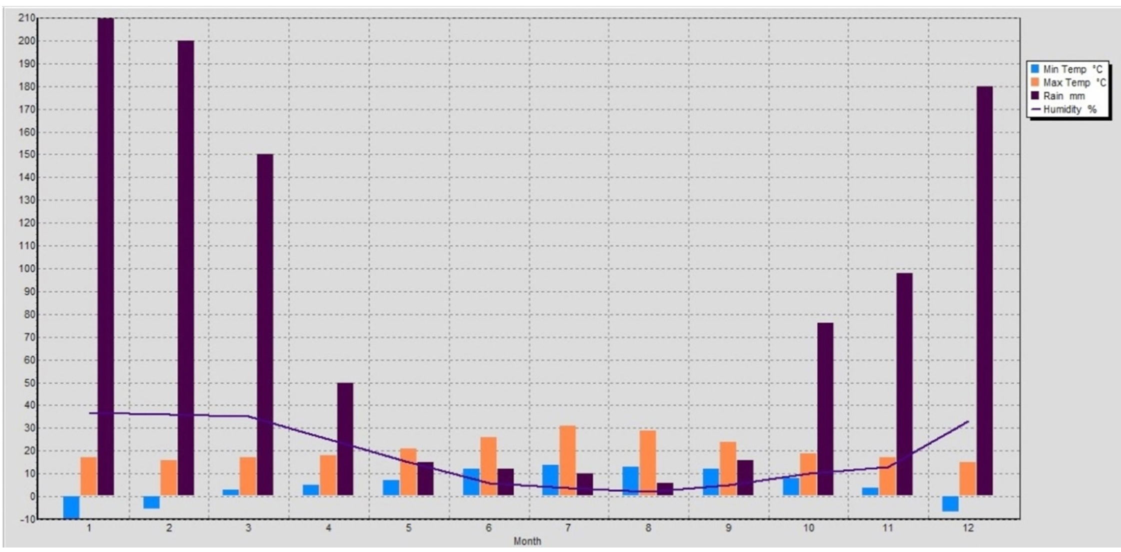

Figure 2. Average variation annual of major climatic factors (study period 2020–2025) in Timahdite. Data-source: Provincial Direction of Equipment and Water of Ifrane (DGH-2025). Data processed by the software FaoCropWat.8.0.water climate

2023). This seasonality is typical of the climate in the Middle Atlas region. The climate is Mediterranean, characterised by rigorous winters and moderate summers, with a bioclimatic succession from humid, to semi-arid and arid. Rainfall varies annually between 150 mm (southwest) and 780 mm (northeast) (Bouizrou et al., 2022). Snow occurs sporadically from November to April with variable heights ranging from 20 to 60 cm (Tuel & Moçayd, 2023; GDA, 2024).

Crop-specific water footprint analysis

The water consumption associated with eight major agricultural products in the Timahdite region was evaluated using WF assessments conducted over the period 2020–2025. For each crop, they were ranked based on their average sown area percentage from largest to smallest and the predominance of vegetable and bulb crops (onion, potato, garlic), which constitute more than 70% of the area (GDA, 2024). Minor crops with a very low cumulative percentage were grouped under "other cereals". The annual water footprint of agricultural production in Timahdite (green, blue, and grey WF), is summarized in Figure 3. The results reveal a rise in the blue WF over the years of study, reflecting increased reliance on irrigation water for crop production. Analysis using the FaoCropWat.8.0. Software reveals that in the Timahdite region, the period of low rainfall and high temperatures (May through August) coincides wiht the key growth stages of many crops, such as potato, onions, garlic, carrot, and apple.

This climatic necessitates increased reliance on groundwater for irrigation, reflected in the high blue water footprint for these crops. In contrast, autumn-sown crops like wheat and other cereals align better with the rainy season, allowing them to depend primarily on precipitation, which indicated by higher green water footprint. Comparable patterns have been documented in multi-country and regional agricultural assessments across the North African and Mediterranean regions. For instance, Vanham et al. (2018) evaluated the water footprints of agricultural products across 365 European River basins. Their analysis identified several basins, notably the Ebro River (Spain) and the Po River basins (Italy), as major hotspots of agricultural water consumption, particularly of blue water use. In spain, DeMiguel et al. (2015) reported that blue water represents approximately 25% of the total crop water footprint. Despite, the blue water constitutes a critical component of agricultural water use, as its current consumption generates considerable water stress. This finding is particularly relevant for Morocco, which experiences comparable Mediterranean climatic conditions. Similarly, Attar et al. (2025) provided specific estimates of the blue water footprint and documented a marked increace in blue water scarcity after 2017, with the scarcity index reaching a peak value of 2.4 in 2019.

Table 1 presents the calculated water footprints for eight crops in the timahdite area, along with heir percentage deviation from the global average benchmark (FAOSTAT, 2011). The analysis is centered on crops that constitute approximately 95% of the cultivation area.

Wheat and other cereals exhibit the highest water footprint among all crops categories, with an average water requirement of 2253.84 m^3 per ton (WF_{total}=2252.84 $m^3.t^{-1}$), exceeding the global benchmark by +23.25%. This of production relatively high value is consistent with observations reported in Mediterranean agro-climatic systems.

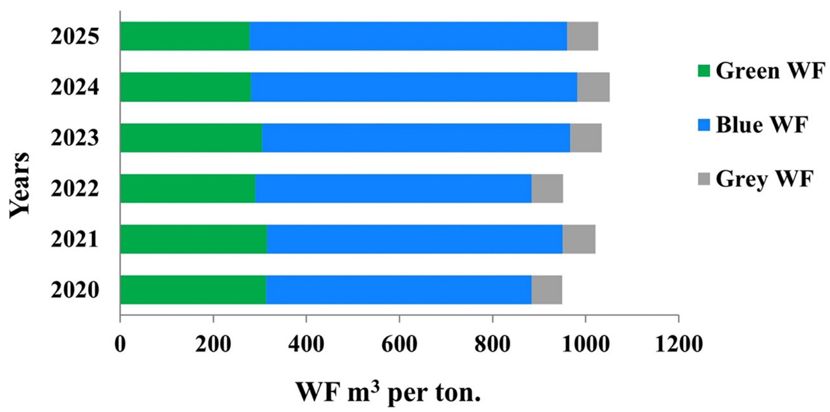

Figure 3. Average water footprint (green, blue, grey) per year in Timahdite region (m^3/t)

Table 1. Average water footprint of crop production during the period 2020–2025 of product per year (m^3/ton), and the percentage deviation from the FAOSTAT2011 benchmark

Crop or sector	Water footprint per ton of product [m^3/ton]			Total WF [m^3/ton]	Average total WF [m^3/ton]	Global average WF benchmark [m^3/ton] FAOSTAT2011	Deviation from benchmark, %	Average area sown [ha]	Average harvest [ton/ha]
	Green WF	Blue WF	Grey WF						
Wheat and other cereals	1281	289.5	81.33	1651.83	2253.84	1828	23.25	3314	1.9
Potatoes	139.67	295.81	58.34	493.82	494.5	287	72.3	4530	31
Carrrots and turnips	139.33	306	62.67	508	507.16	195	160.08	2450	17
Onions dray	131.5	289.5	49.84	470.84	470.83	345	36.48	4700	23
Garlic	133.5	257.67	37.34	428.51	428.5	569	-24.78	2355	15
Cherries	203.67	1111.34	89.66	1404.67	1404.66	1604	-12.45	750	5
Apple	189.2	926.67	54.66	1170.53	1170.5	822	42.4	1087	8
Plum	160.2	1102.3	89.5	1352	1351.83	2180	-38.02	906	7

For example, studies in Tunisia reported wheat water footprint ranging from 2000 to 2400 m^3/ton (Schyns & Hoekstra, 2014b), while similar values between 1800 and 2300 m^3/ton have been documented in Spain and Turkey (Katerji et al., 2008). These comparable ranges highlight the strong influence of Mediterranean climatic conditions on cereal water requirements. This pattern can be attributed by the strong reliance of grain production on rainfall (hight level green WF), the extensive area devoted to grain cultivation, and its higher water footprint per unit of output (per ton) compared to vegetables and fruits. Market gardening crops (e.g., onion, potatoes and garlic) generally require less water than fruit trees. In contrast, the total water footprint of fruit trees like cherries (1404.46 m^3/t) and plums (1351.81 m^3/t) is similar to that of cereal crops. Generally, stone fruits (e.g., plum and cherries) have a significantly higher water footprint (in m^3 per ton) than root vegetables and bulbs, such as onions dry, garlic and potatoes (Mialyk et al., 2024). The carrot-turnips and potatoes showed the largest deviation (d.b =+160%) and (d.b=+72.3%) respectively, relative to the reference value (Global average WF benchmark FAOSTAT2011), reflecting the highest levels of water consumption in the Timahdite area, mainly blue water use. In addition to the rainfall provides water to plants throughout the growing season and plays a crucial role in determining crop yields (Papadopoulou et al., 2016; Paula et al., 2024). Elevated green water footprint levels indicate significant reliance on rainfall for crop cereal growth, highlighting the role of renewable water resources in replenishing surface and groundwater systems (Ewaid et al., 2019).

Figure 4 illustrates the mean total water footprint (green, blue, and grey WF), over the study period. The results reveal a predominant dependence on groundwater and surface water resources for crop production, with the blue WF representing approximately 64% of the total water footprint. Fruits

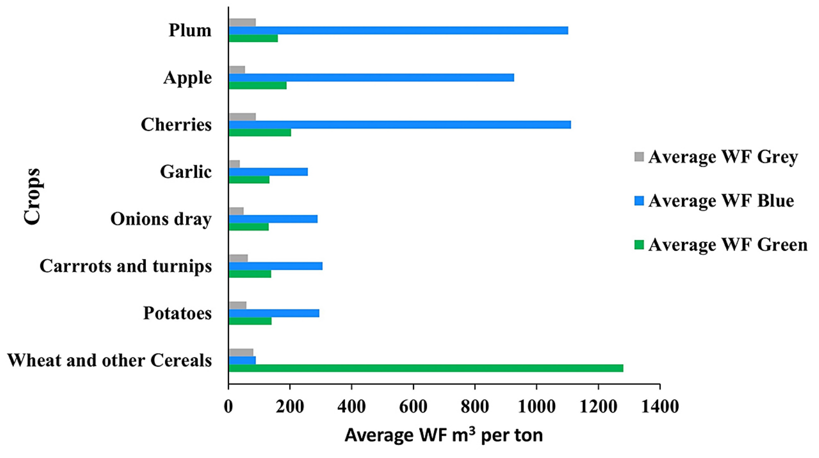

Figure 4. Distribution of average water footprint (green, blue, and grey) by crop during the study period (2020–2025) (m^3/ton)

and vegetable crops represent the lowest contributors to the green WF in the study area.

This is largely because their growth cycle coincide with the low-precipitation period (June-August), and the predominant use of groundwater for irrigation, leading to a high contribution of blue water to the total footprint (high level blue WF). The growing season for the majority of crops in Timahdite (Ifrane, Morocco) extends from mid-April to the end of September, reaching maximum water consumption in Jun and August. This accounts for the elevated blue water footprint observed during this period, caused by low precipitation and increased excessive groundwater use for crop irrigation. The water footprint assessment of vegetable and bulb crops reveals that the blue water footprint of carrots and potatoes is considerably higher than that of onions and garlic, indicating a greater reliance on groundwater resources for the production of these crops.

Statistical analysis

Statistical metrics were applied to characterize the dataset, and the results of the descriptive statistical analysis are summarized in Table 2.

The relatively high standard deviation observed for most variables indicates substantial dispersion in their distributions**.** This variability can be attributed to temporal and seasonal fluctuations in climatic conditions associated with climate change, as well as to anthropogenic factors, particularly inefficient irrigation water management practices (Sun et al., 2013; Achli et al., 2022).

An evaluation of the individual water footprint components indicates that the blue WF constitues the predominant contributor to crop production in the Timahdite area. Since 2020, the blue WF has shown a consistent upward trend systematically, reaching a peak value of 701.25 m^3/ton in 2024 (Figure 5).

This magnitude generally exceeds the green WF by several fold, highlighting the strong dependence of local agricultural production on irrigation water resources. On the other hand, green WF shows a decreasing trend since 2022 due to drought and low precipitation. The average blue water footprint values indicate that blue water is becoming an increasingly important component of the total water footprint. This trend is primarily attributable to the intensive reliance on groundwater resources for crop irrigation. Crop quality and yield remain highly dependent on prevailing rainfall patterns throughout the year. In recent years, prolonged periods without precipitation

Table 2. Results of descriptive statistical analysis

Statistical variable	Nb. of observations	Minimum	Maximum	Average	Variance (n-1)	Standard deviation (n)	Asymmetry (Pearson)
Green WF	48	113.00	1370.00	297.29	143470.5	±308.77	2.25
Blue WF	48	187.00	1276.00	644.89	142951.07	±378.08	0.21
Grey WF	48	20.00	115.00	68.04	624.21	±24.98	0.03

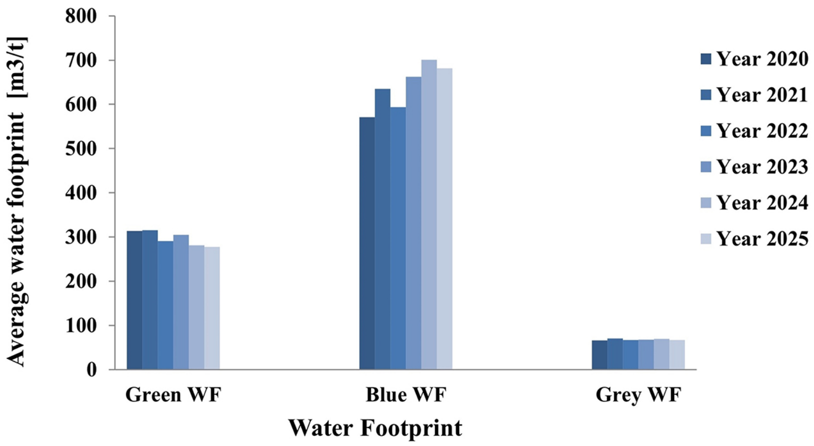

Figure 5. Components of the water footprint indicators for the Timahdite area. Consecutive bars within each group represent the values recorded from 2020 to 2025 (from left to right)

suggest that crops are becoming more frequently exposed to condition of water scarcity. This dynamic situation may lead to increased pressure on available water resources, as crop water demand exceeded precipitation inputs (Tuninetti et al., 2019; Hatami et al., 2025). In 2025, conditions improved slight, with a greater contribution of rainfall to meeting crop water demand (i.e. in relatively balanced recovery for groundwater). Desite that, the increasing risk of water deficits, together with the limited water reserves of the Timahdite region, presents new challenges that could affect both water availability and agricultural water demand. This underscores the need for actions aimed at improving water-use efficiency.

The relationship between water footprint variables was modeled using an exponential function (Table 3). All three components exhibited statistically significant positive correlations, with Pearson correlation coefficients of r = 0.275 for $WF_{Green-Blue}$, r = 0.563 for $WF_{Green-Grey}$ and r = 0.632 for $WF_{Blue-Grey}$.

The statistical differences were considered significant if $P<0.05$. The correlation matrix shows that the diagonal cells (e.g., greenWF versus green WF) appear in bright green, reflecting a perfect positive correlation (correlation coefficients=1), as expected when a variable is compared with itself. The blue WF exhibited a trend closely aligned with that of the grey WF, indicating a strong statistical association between these two components. This relationship suggests that crops with higher irrigation requirements often generate greater volumes of return flows or pollutant loads, which are reflected in the grey WF (Bianbian et al., 2021; Coman et al., 2025). Such a result is a fundamental property of correlation matrices and is commonly observed in statistical analyses used in environmental and agricultural studies (Betelhem et al., 2026).

Principal component analysis and typology

Figure 6 presents a point clouds and scatterplot matrix that enables the simultaneous examination of pairwise relationships among multiple variables while also displaying the univariate distribution of each variable.

This visualization technique is widely used in exploratory data analysis to identify patterns, correlations, and potential outliers (Wu et al., 2023). The off-diagonal cells contain scatterplot where each point represents an individual observation. A red line shows the linear regression fit, illustrating the overall trend or direction of the relationship between water variables. Additionally, a blue confidence ellipse surrounds the data points, illustrating the concentration and dispersion of the underlying bivariate distribution. The analysis of the distribution of data points reveals a pronounced association between blue-WF and grey-WF (3rd row, end column). The relationship is demonstrated by the close alignment of observation along the regression line, as well as the high concentration of points within the confidence ellipse, indicating a strong linear correlation. Principal Component Analysis (PCA) is a multivariate statistical method used to reduce data dimensionality while preserving the maximum amount of variability present in the dataset (Hastie et al., 2019).

Principal Component Analysis (PCA) was applied to all the quantitative variables considered in this study. The results (Figure 7) show that the first two principal components (PC1 and PC2) explain more than 92% of the total variance, indicating that these two factorial axes effetively capture majority of the variability within the dataset. In general, a higher proportion of inertia (≥75%) reflects a better representation of the point cloud within the factorial design (Jollifie & Cadima, 2016). We observe that the first principal component (PC1 – horizontal axis) is predominantly and exclusively associated with total water footprinte and the crop category.

These variables exhibit strong correlation coefficients and contribute significantly to the formation of the PC1 axis. In contrast, the second principal component (PC2-vertical axis) is primarily explained by the ratio between green and blue WF, derived from crop water footprint data for the Timahdite area during the 2020–2025

Table 3. Pearson correlation matrix of water footprint variables

Variables	Green WF	Blue WF	Grey WF
Green WF	1	0.275	0.563
Blue WF	0.275	1	0.631
Grey WF	0.563	0.631	1

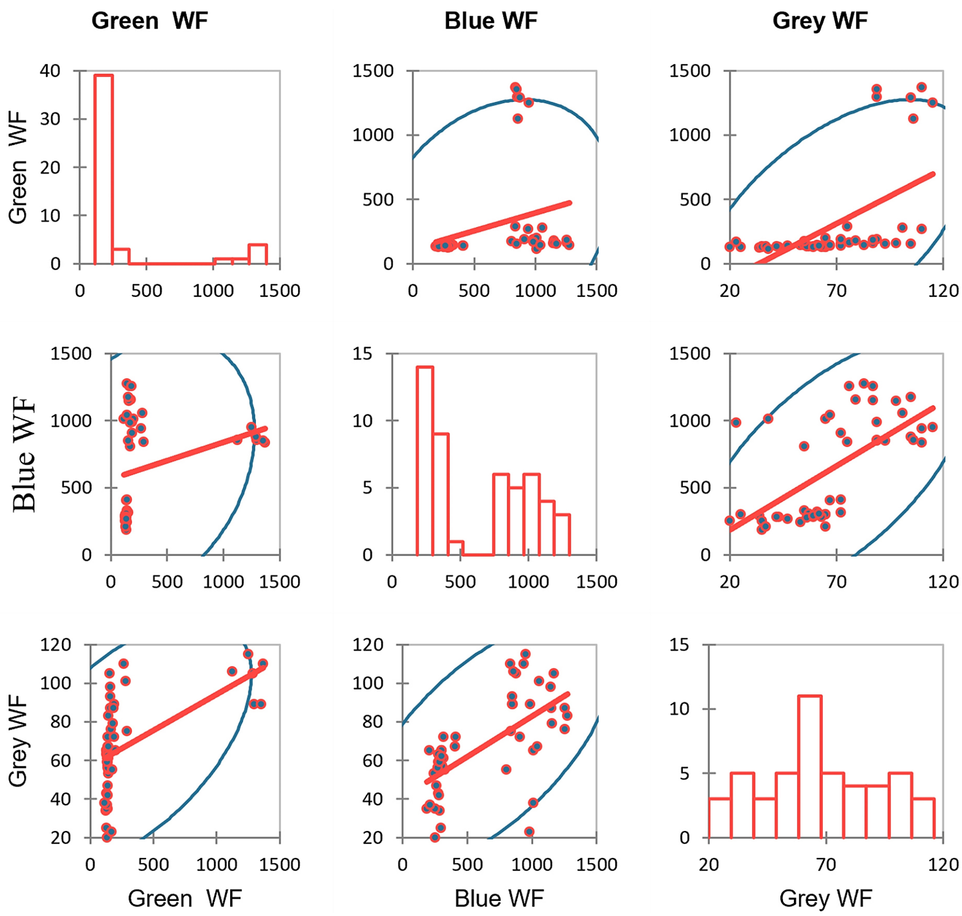

Figure 6. Point clouds and scatterplot matrix (relationships among WF components)

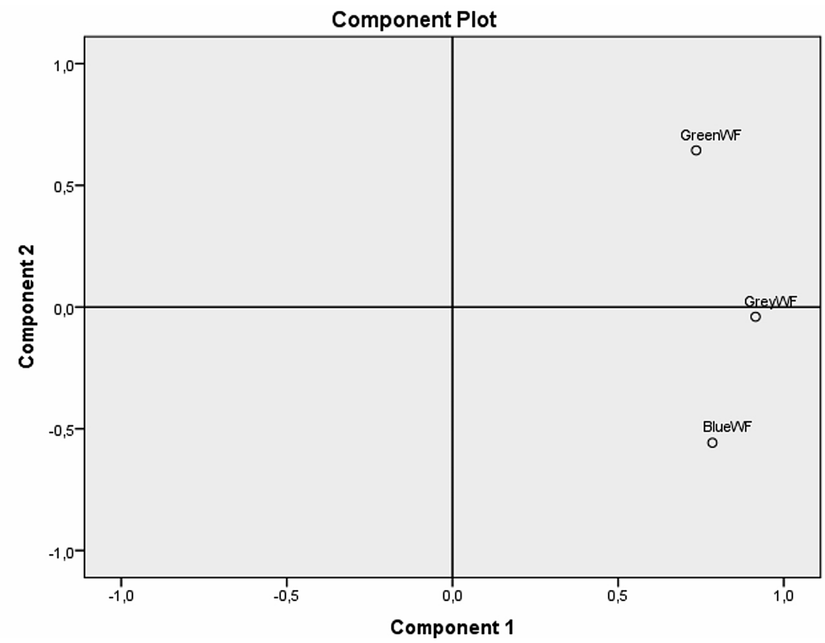

Figure 7. Typology of crops and water footprint averages in Timahdite area

period. The loadings associated wiht the first principal component (PC1) indicate that the green water footprint makes a substantial positive contribution. The blue water footprint also contributes positively, although its influence is comparatively moderate. In contrast, the grey water footprint displays only a weak positive loading on this axis. They showed that in the Sebou basin (while includes Timahdite, Ifrane), blue water footprint are concentrated in irrigated perimeters, while green water footprint dominate rain-fed cereal zone (Schyns & Hoekstra, 2014a). The negative correlation between green and blue component observed in our PCA matches their nationwide assessment.

Principal component analysis was performed on eight major crops cultivated in the Timahdite area (Ifrane, Middle Atlas, Morocco) in order to explore underlying patterns, assess similarities among crops, andexamine the relationships between thier water footprint component. The PCA is a multivariate statistical technique that transforms complex, high-dimensional datasets into asmaller set of orthogonal (uncorrelated) component while retaining most of the original variance (Zhuo et al., 2016; Wang et al., 2023). In this study, the first principal component (PC1 and PC2) summarize the dominant patterns of water use variability among different crop. Accordingly, Figure 8 presents a synthesized typological and cluster analysis illustrating the relationships between water footprint variables and crop production. The first two principal components (PC2 and PC2) explain the majority of the total variance observed among the original water-footprint variables, thereby revealing the dominant underlying structure of the dataset. Their combined explanatory power enables the identification of a distinct crop typology based on similarities and contrasts in water footprint component. This dimensionality reduction highlightsa distinct typology, the scores reveal five main groups, reflecting differentiated water use patterns and water footprint types dependance characteristics.

The PCA distinguishes five major groups based on their water-use-haractristics:

- Group 1 – high water demand/high green water footprint (mainly rainfed): wheat and other cereals (PC1 = 2, PC2 = 1.45) display high positive scores on both principal components. This positioning reflects a large total water footprint and a predominance of green water (rainfall contribution). As a staple crop cultivated primarily under rainfed conditions in the region, wheat is consistent with this profile.
- Group 2 – high water demand/high blue water footprint: cherries (PC1 = 0.80, PC2 = -1. 25] and plums (PC1 = 0.70, PC2 = -1.35) are characterized by substantial irrigation requirements, particularly during the summer season. Their negative PC2 scores indicate a strong dependence on blue water resources.
- Group 3 – intermediate water demand/Intermediate blue water footprint (mixed sources): apple (PC1 = - 0.10, PC2 = -0.70) occupies an intermediate irrigation position, suggesting moderate overall water demand and partial reliance on irrigation, with contribution from both green and blue water.

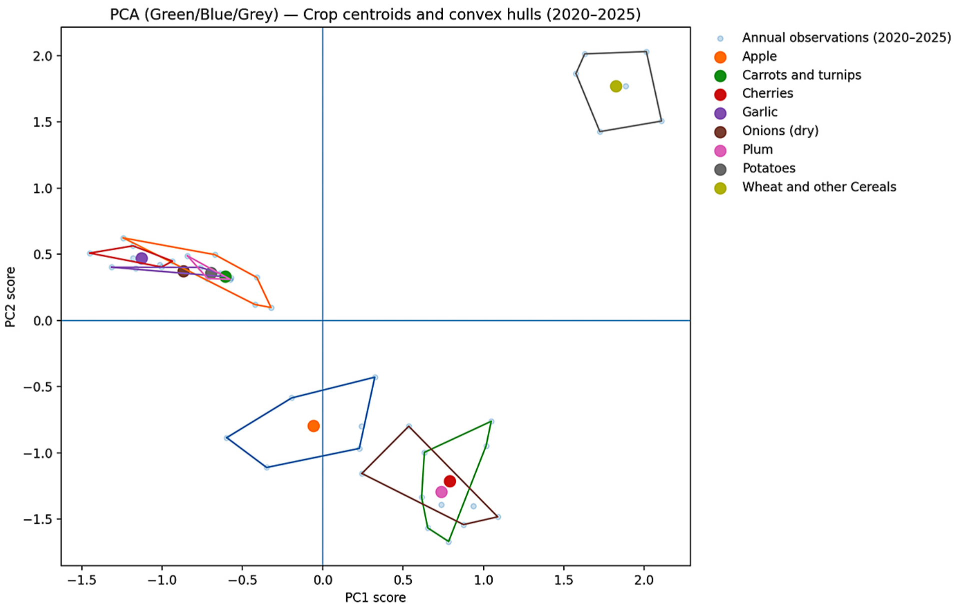

Figure 8. The typology and multivariate (PCA) clustering model describing the relationships between crop-type and water footprint component

- Group 4 – moderate water demand/high blue water footprint: potatoes (PC1 = -0.60, PC2= 0.35), and carrot-turnips (PC1 =-0.70, PC2 = 0.35) show moderate total water requirements but relatively high dependence on irrigation, especially during summer, indicating a significant blue water component.
- Group 5 – Moderate water demand/moderate blue water footprint: garlic (PC1=-1.2, PC2=0.5), and onions (PC1=-0.80, PC2=0.4) are classified together as crops with moderate demands on irrigation water. In the statistical used (PCA), they cluster closely together on the graph (both on the left side and upper half), indicating they have similar profiles regarding their water use and source. While they require irrigation (blue water), the volume is considered moderate compred to other, more water-intensive crops.

The identified typology (for Timahdite area) is consistent with the global assessment conducted by the water footprint network (Mekonnen & Hoekstra, 2011), which demonstrated clear differences in both total and component – specific water footprint among crops. For instance, although wheat generally exhibits a high total footprint (≈1650 m^3/ton), apples show substantial water requirements as well (≈1170 m^3/ton). More importantly, in Mediterranean climates, apples often derive more than ≈ 60% of their total water footprint from blue water resources, whereas wheat typically relies far less on blue water (rarely exceeding 30%), remaining largely dependent on green water (rainfall). In Morocco, similar patterns have been observed in the Sous-Massa and Houaz region of Marrakech, where fruit trees and vegetable crops are classified as intensive users of blue water resources, whereas cereal crops are predominantly sustained by green water derived from rainfall (Schyns & Hoekstra, 2014b, Choukr-Allah et al., 2017). It has been reported that approximately 84% of the cereal cultivation area in the Ifrane province is rain-fed, while the expansion of apple, cherry, and carrot production since 2021 has contributed to an estimated 12% increase in blue water consumption in the region (Benayad et al., 2024). This aligns with the strong blue WF vector and the hight PC1 scores of fruit crop. Accordingly, the PCA results for the Timahdite area provide a locally calibrated representation of these structural contrasts, offering valuable insights for sustainble water resource management and planning in the province of Ifrane. The PCA scores clearly highlight this local differentiation pattern. In a comparable climate context, Chouchane et al. (2015), in their study of Tunisian agriculture, reported that the first principal component (PC1) of the water footprint dataset exhibited a strong positive correlation with the total water footprint (r = 0.91), whereas the second principal component (PC2) was primarily associated with the blue-to-green water footprint ratio. The results obtained for the Timahdite area reveal a very similar structure, thereby confirming the robustness of principal component analysis (PCA) as an effective statistical approach for synthesizing crop water requirements and supporting the development of water-saving management strategies. Also global water footprint assessments guide critical water management decision (Betelhem et al., 2026). Finally, this water-use hierarchy in Timahdite region (Ifrane Morocco) aligns with global benchmark data, in semi-arid region, irrigated fruit crops and root vegetables generally exhibit higher water requirements, whereas rainfed cereals such as wheat tend to present a lower blue water footprint, particularly when winter rainfall contributes substantially to their green water supply. In the Middle Atlas, e.g. Ifrane, wheat is generally planted in autumn and harvested in spring, depending primarily on rainfall (green water) to meet its water requirements. In contrast, apple and carrot crops demand continuous irrigation during the summer season to ensure adequate growth and productivity (end of September). This situation intensifies the pressure associated with the overexploitation of blue water resources.

CONCLUSIONS

This study effectively applied the water footprint framework to quantify and analyze the WF associated with agricultural crop production in the Timahdite region. Overall, the following key conclusions can be drawn:

1. The study principal climatic factors in Timahdite region exhibited marked interannual variability, accompanied by a significant decline in rainfall in recent years, this seasonality is characteristic of the climatic regime of the Middle Atlas.
2. The analysis revealed that wheat and other cereal crops exhibit the highest total water footprint values in the Timahdite region, followed

by cherries. Apples and carrots are characterized by the highest levels of blue water consumption (reliance on irrigation). In contrast, garlic and onion crops are associated with comparatively lower overall WF values, suggesting that they exert relatively moderate pressure on water resources.

3. Elevated blue water footprint values reflect a strong reliance on surface and groundwater resources for agricultural production. Consequently, the increasing frequency and duration of precipitation deficits in recent years, particularly during crops growth periods (May–August), are likely to exacerbate water resources shortages.
4. Several crops demonstrate the largest percentage deviations in water footprint relative to the global benchmark values (established by the FOA). This disparity exacerbates pressures linked to the overexploitation of blue water resources, thereby undermining the sustainable management of water resources.
5. The statistical analysis (typological classification and multivariate techniques, PCA), show that the first two principal components (PC1 and PC2) explain more than 92% of the total variance of relationships between crop-types and WF components.The clustering identified five main groups of crops, categorized according to their water-use characteristics. Furthermore, the components of the water footprint facilitates a detailed assessment of both the sources of water utilized in crop production and the corresponding volume required to produce a given product.

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