EREM 82/1
Journal of Environmental Research, Engineering and Management
Vol. 82 / No. 1 / 2026
pp. 21–33
10.5755/j01.erem.82.1.43508

Governance Failures and Agricultural Water Scarcity in the Mediterranean Basin: Case of the Safsaf Irrigated Perimeter from 1992 to 2018 (Skikda, North-Eastern Algeria)

Received 2025/11 | Accepted after revisions 2026/02

https://doi.org/10.5755/j01.erem.82.1.43508

Governance Failures and Agricultural Water Scarcity in the Mediterranean Basin: Case of the Safsaf Irrigated Perimeter from 1992 to 2018 (Skikda, North-Eastern Algeria)

Naila Khochmane[1,2*], Siham Agaguenia[3,4], Abdelhak Acidi[1,2]

[1] Faculty of Earth Sciences, Department of Planning, Badji Mokhtar–Annaba University, Algeria
[2] Laboratory of Natural Resources and Planning, Badji Mokhtar–Annaba University, Algeria
[3] Institute of Urban Techniques Management, Larbi Ben M'hidi–Oum El Bouaghi University, Algeria
[4] Laboratory of Urban and Environmental Analysis (LUEA), Badji Mokhtar–Annaba University, Algeria

***Corresponding author:** naila.khochmane@univ-annaba.dz

The present study contributes to the understanding of agricultural water stress in the southern Mediterranean basin. Despite the effectiveness of dynamic multivariate analysis using principal component analysis (PCA) for identifying the potential causes of agricultural water scarcity, its application in this context has received limited attention in the existing literature. By applying this methodology to the Safsaf irrigated perimeter (North-Eastern Algeria) from 1992 to 2018, our research aims to investigate the causes driving irrigation deficits, which are typically attributed to climatic constraints. The results reveal a strong association between institutional failures and agricultural water scarcity, where institutional governance factors (52.33%) and management dysfunctions (24.38%) together explain approximately 76% of the observed irrigation deficits. This study demonstrates the value of dynamic multivariate analysis as a powerful tool for deconstructing the multidimensional temporal aspects of this composite issue. The challenge is not merely in implementing solutions that address physical water scarcity in agriculture, but in diagnosing its systemic accumulated root causes in order to achieve sustainable management and develop comprehensive, effective strategies.

Keywords: PCA, dynamic multivariate analysis, water scarcity, Safsaf irrigated system, Algeria.

Introduction

The Mediterranean basin is among the world's regions most vulnerable to climate change (IPCC, 2023). Recent decades have witnessed a marked increase in drought frequency and a sustained decline in precipitation, especially in the southern basin (FAO, 2023). These climatic trends have intensified water scarcity, a situation compounded by the high concentration of urban settlements and industrial activities, which place additional pressure on limited water resources (Noto et al., 2023; IPCC, 2023). Since the early 2000s, North African countries like Algeria, Egypt, Morocco, and Tunisia have experienced significant increases in irrigation water demand (IPCC, 2023). Agriculture remains the dominant water-consuming sector, accounting for approximately 70% of global water consumption and 80–90% of total water withdrawals in arid to semi-arid regions where competition for freshwater is intense (FAO, 2023). This scale of use underscores a deeper reality: agriculture's fundamental dependence on water makes securing its reliable supply a vital priority for global food security. Yet, this critical dependence coincides with persistently low irrigation efficiency, often due to outdated infrastructure and climate stress (MedECC, 2020).

The understanding of water scarcity is increasingly framed not only as a physical limitation but also as a governance challenge, stemming from institutional fragmentation, inadequate meta-governance, and weak adaptation mechanisms. Comparative studies illustrate this paradigm across diverse contexts: in England and Wales, scarcity reflects failures of ecological modernity and meta-governance despite shifts toward economic efficiency (Walker, 2014); in the United States, institutional responses emphasize adaptive governance to build greater resilience (Saleth, 2014); and in China, severe northern shortages stem from resource constraints, pollution, and the need for stronger institutions and market instruments (Jiang, 2009). Despite the complex, multidimensional nature of agricultural water scarcity, the majority of studies from 2010 to 2025 have focused on isolated factors, such as climate indicators (e.g., the Standardized Precipitation Index) (Noto et al., 2023), physical-economic determinants (Laoubi and Yamao, 2009), or specific institutional aspects including, poor coordination, lack of participatory governance (Feola, 2015; Mvongo et al., 2022; OECD, 2014), and infrastructure degradation (MedECC, 2020; Jamin et al., 2011). This fragmented approach, often reliant on univariate methods, has largely overlooked critical interactions among hydroclimatic, agricultural, and demographic variables, as well as their temporal dynamics. Consequently, findings often remain static, yielding fragmented solutions, such as promoting water-saving crops or isolated climate policies, that fail to address the systemic roots of scarcity.

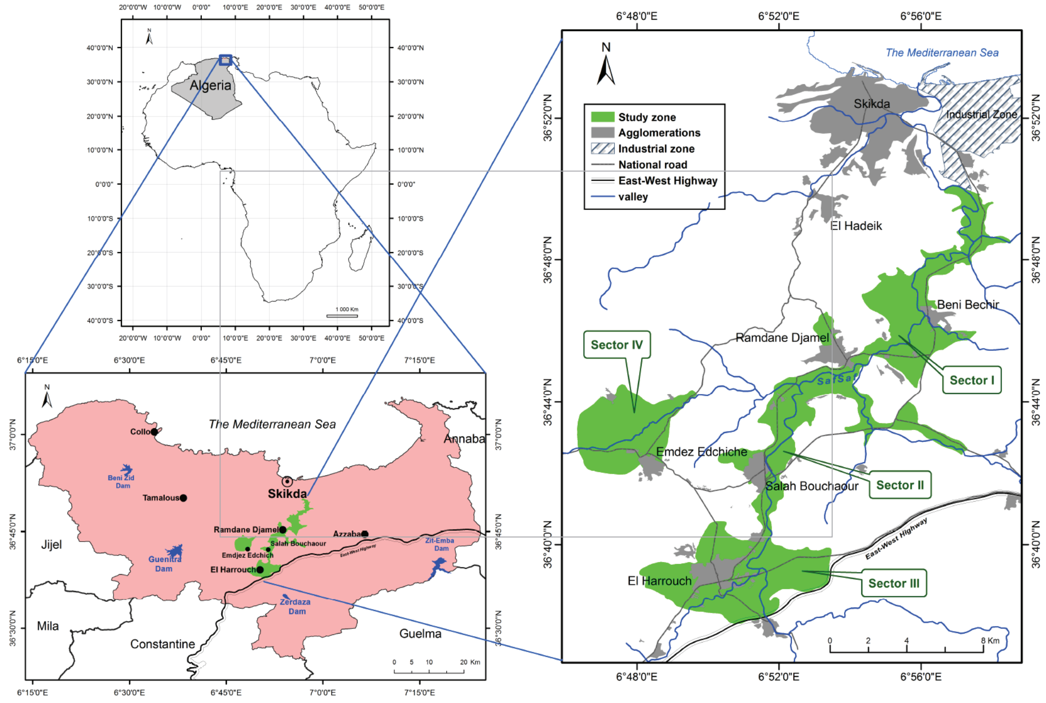
To address this gap, this study advances a dynamic analytical framework using Principal Component Analysis (PCA) to trace the temporal evolution of key drivers of irrigation water scarcity. By reducing dimensionality, PCA reveals underlying, interacting factors that static models fail to detect. Applied to the Safsaf irrigated perimeter in North-Eastern Algeria (1992–2018) across 16 hydroclimatic, agricultural, and demographic variables, this method identifies not only the root causes of water scarcity but also how these drivers have shifted over time. This study underscores the critical value of multidimensional temporal analysis for diagnosing cumulative failures in the irrigation systems, identifying key factors, and providing a robust foundation for sustainable management strategies.

Materials and Methods

The study area

The Safsaf irrigated system is located in the Skikda region, North-Eastern Algeria (*Fig. 1*). The perimeter extends over more than 56.54 km^2 and is divided into four sectors: I (Ramdane Djamel, currently non-operational), II (Salah Bouchaour), III (El Harrouch), and IV (Emdjez Edchiche). The study area is characterised by a Mediterranean climate; defined by hot, dry summers and mild, wet winters. The average annual rainfall is approximately 731.90 mm in the northern coastal zone and 564.77 mm in the southern inland zone of the province. The hot and dry season typically lasts from late May to late September, although it can occasionally extend to November or December. The Safsaf irrigated perimeter was designed to support intensive agricultural production and was placed under the supervision of the Office of Irrigated Perimeter (OIP) in 1992. In 2005, its management was transferred to the National Office of Irrigation and Drainage (NOID) for Large Irrigation System (LIS).

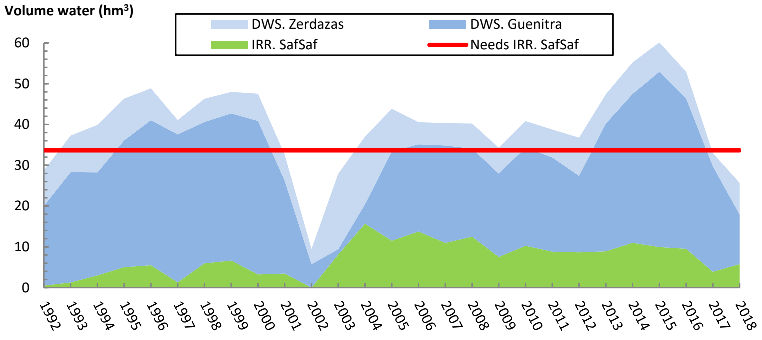
Fig. 1. *The location of the Safsaf irrigated system*



The irrigated system operates on a flat rate "on demand" regime, where the amount of water is determined by the crop type. However, the volume of irrigation water that is allocated remains significantly lower than the theoretical requirements.

The processing of drinking water consumption and supply in the Safsaf irrigated system, demonstrates a substantial increase in potable water withdrawals from the Guenitra and Zerdaza reservoirs compared with agricultural irrigation withdrawals (*Fig. 2*). A growing competition for resources is emerging as urban demand for potable and domestic use increasingly outpaces agricultural requirements. Although the Guenitra dam serves as the primary supply, supplemented marginally by the Zerdaza dam, these trends reveal a chronic structural deficit in water supply. This imbalance highlights the urgent need for integrated water resource management to reconcile conflicting sector demands. Accordingly, the Safsaf irrigation system provides a highly representative case study for investigating these dynamics.

Fig. 2. *Drinking water consumption and supply in the Safsaf irrigated system*



This study used empirical data collected from official institutions in the study area.

The National Office of Irrigation and Drainage (NOID), particularly the Safsaf operational service in the Skikda region, provided annual reports detailing hydro-agricultural management, irrigated areas, water distribution volumes, network losses, and operational constraints.

The dam authorities for Zerdaza and Guenitra provided annual hydraulic balance sheets, containing data on inflow, release, consumption, loss, filling rate, rainfall, and evaporation. Missing data for the Guenitra dam in the 1990s were retrieved from archival records.

The Agricultural Hydraulic Department of the Water Resources Directorate of Skikda contributed data related to Small and Medium Hydraulics (SMH).

The Directorate of the Agricultural Sector in Skikda furnished statistical data on regional agricultural production, while the demographic data for the municipalities within the Safsaf perimeter were obtained from the Directorate of Programming and Budget to track population trends.

The analysis is based on a longitudinal dataset from 1992 to 2018, comprising 16 variables categorized as hydroclimatic, agricultural, or demographic. After systematic processing and quality verification, the data were analysed using Principal Component Analysis (PCA) in XLSTAT 2025. This method was employed to conduct a comprehensive assessment of the causes of irrigation water scarcity.

Selection and definition of variables

Sixteen variables were selected based on the availability of authoritative data and the completeness of their time series over the study period. These variables are fundamentally linked to the annual agricultural water quota established by the ministerial committee responsible for allocating water across drinking, agricultural, and industrial sectors in the Safsaf basin. The performance of the irrigation water quota is measured using three variables: the irrigated area (IRR. area), dam water withdrawals (IRR. Zerd, IRR. Gueni), and the volume of water distributed to farmers (Vol. IRR).

Table 1. *The main and supplementary variables used in study*

Variables		Variable description	Unit
Main variables	IRR. area	Total irrigated area recorded annually by the managing institution	m^2
	IRR. Zerd	Annual volume of water withdrawn from the Zerdaza dam for irrigation	hm^3
	IRR. Gueni	Annual volume of water withdrawn from the Guenitra dam for irrigation	hm^3
	Trib. Gueni	Total inflow/tributaries recorded at the Guenitra Dam	hm^3
	Ws. Zerd	Average annual end-of-month water storage at the Zerdaza dam	hm^3
	Pop.	Population of the municipalities in the Safsaf Valley	Number of inhabitants (hab)
	Yield I	Vegetable crop yield for Ramdane Djamel municipality	kg/m^2
	Yield II	Vegetable crop yield for Salah Bouchaour municipality	kg/m^2
	Yield III	Vegetable crop yield for El Harrouche municipality	kg/m^2
	Yield IV	Vegetable crop yield for Emdjez Edchiche municipality	kg/m^2
Supplementary variables	Fill. R. Dams	Average filling rates of Zerdaza and Guenitra dams	%
	% DWS. Zerd	Proportion of water allocated for Drinking Water Supply (DWS) relative to total consumption from Zerdaza dam	%
	% DWS. Gueni	Proportion of water allocated for Drinking Water Supply (DWS) relative to total consumption from Guenitra dam	%
	Vol. IRR	Volume of water distributed to Irrigators during the agricultural year	hm^3
	Aver. Pro	Average annual vegetable Production in Safsaf Valley municipalities (Ramdane Djamel, Salah Bouchaour, El Harrouche, Emdjez Edchiche)	kg
	Wet, Dry, and Severely dry year	Qualitative variable determined by the Standardised Precipitation Index (SPI)	/

Based on the current state of water management, allocation decisions are fundamentally dictated by two core principles: resource availability and the national priority of meeting domestic drinking water demand.

The first criterion was measured using precise indicators derived from the annual hydraulic balance of the watershed. These indicators include water flow into the Guenitra dam (Trib. Gueni), the average annual reserve in the Zerdaza dam (Ws. Zerd), and average reservoir filling rates for the Zerdaza and Guenitra dams (Fill. R.Dams). Additionally, the Standardised Precipitation Index (SPI), a qualitative variable representing climatic variability, was incorporated into the analysis.

The second criterion integrates variables such as population (Pop) and the proportion of drinking water supply within total dam withdrawals (% DWS. Zerd and % DWS. Gueni) to evaluate the escalation in domestic demand.

Furthermore, indicators for vegetable crop yields (Yield I, II, III, and IV) and average production in the Safsaf Valley (Aver. Pro) are employed to assess agricultural productivity in regions characterised by intensive vegetable cultivation. These variables provide a framework for assessing the impacts of water scarcity on groundwater and surface water systems and sustaining production levels. The analytical procedure commenced with an initial examination of the database. This was followed by descriptive statistical analysis and tests to verify PCA suitability. Ten variables designated as active were included in PCA, and six variables were treated as supplementary and projected onto PCA space post-analysis to support result interpretation, *Table 1*.

The Standardised Precipitation Index (SPI) was calculated for the period from 1992 to 2018 using precipitation data from the Zerdaza and Guenitra stations. The average of these two indices was adopted to determine the SPI for the study area. The SPI formula (1) is as follows:

$$SPI = \frac{(Pi - Pm)}{\sigma} \tag{1}$$

where Pi – is the interannual average precipitation (mm); Pm – is the average precipitation series (mm); σ is the standard deviation of the precipitation series (mm).

For clarity, the SPI was categorised into three groups of values by year, as shown in *Table 2*.

Table 2. *Categories of SPI values*

SPI values	Group
0 to 1.49	Wet year
0 to –1.49	Dry year
–1.5 to –1.99	Severely dry year

Descriptive analysis, tests of PCA adequacy and K-Means clustering procedure

Descriptive statistics, including the mean, median, standard deviation, minimum, and maximum values, were calculated to characterise the variables and assess their nature, comparability, and suitability for further analyses.

Skewness and kurtosis coefficients were used to evaluate the shapes of the statistical distributions. The results of this descriptive analysis were essential in selecting the most appropriate method for the principal component analysis of this study.

The database consists of quantitative variables with non-normal distributions. Consequently, Principal Component Analysis (PCA) was performed on the Spearman correlation matrix, which is based on centred and normalised ranks, making variable standardisation unnecessary. Data suitability for PCA was confirmed by a significant Bartlett's test of sphericity ($p < 0.0001$) and the Kaiser-Meyer-Olkin (KMO) test. Following the classification of the KMO, values above 0.5 are acceptable, with values of 0.5–0.7 considered averages, 0.7–0.8 good, 0.8–0.9 very good, and > 0.9 excellent (Naseer et al., 2019). The period from 1992 to 2018 was analysed to track the long-term shifts in water management challenges within the Safsaf irrigation system. This was achieved by applying the K-means clustering technique to the PCA scores, specifically the coordinates of the observations following a Varimax rotation.

The typology reconstructs key periods of crisis and transition within the perimeter, providing valuable insights into the dynamic nature of hydro-agricultural conditions over time (Apollin and Eberhart, 2012). The multivariate statistical approach allows for a comprehensive analysis of the complex interrelationships among multiple variables (Tabachnick and Fidell, 2019). PCA was explicitly chosen for its ability to reduce the dimensionality of large datasets while preserving the most significant sources of variation (Abdi and Williams, 2010; Wold et al., 1987; Lever et al., 2017). This reduction enhances the interpretation of patterns and trends by grouping correlated variables and identifying the principal components that explain the variability within the system (Abdi and Cadima, 2016; Abdi and Williams, 2010).

Results and Discussion

Descriptive statistics results and (PCA) adequacy tests

The descriptive statistical analysis indicates that for most variables, the marked disparity between the mean and median suggests a non-normal distribution as detailed in *Table 3*.

Table 3. *Descriptive statistics results of main variables*

Main variables 'enter PCA'	Mean	Median	Standard deviation	Kurtosis	Skewness	Minimum	Maximum
IRR. area (m^2)	8,978,892.59	9,173,400	3,968,635.98	–0.29	-0.70	0.00	14,120,000
IRR. Zerd (hm^3)	1.79	1.68	1.32	–0.25	0.48	0.00	4.45
IRR. Gueni (hm^3)	5.34	5.78	3.50	–0.81	0.14	0.00	13.18
Trib. Gueni (hm^3)	40.53	36.74	21.12	0.03	0.69	3.04	86.28
Res. Zerd (hm^3)	9.44	9.41	2.81	0.17	-0.56	3.26	14.43
Pop. (hab)	131,385.26	130,384	19,437.09	–1.05	0.04	98,535	164,773
Yield. I (kg/m^2)	1.60	1.26	0.75	–1.21	0.57	0.73	2.96
Yield.II (kg/m^2)	1.48	1.40	0.44	–1.10	0.16	0.81	2.17
Yield.III (kg/m^2)	1.88	1.66	1.01	–0.35	0.68	0.39	4.03
Yield.IV (kg/m^2)	2.33	2.00	0.93	–0.13	0.77	1.18	4.48

Furthermore, non-zero Skewness values and negative kurtosis coefficients indicate asymmetric and non-normal distributions. While Pearson's correlation coefficient assumes symmetrical distributions and a linear relationship, Spearman's correlation coefficient was chosen because it is more appropriate as it is not affected by the asymmetry of the distribution and is based on ranks rather than raw values. The suitability of the data for factor analysis was validated by a significant Bartlett's test of sphericity ($p < 0.0001$) and a Kaiser-Meyer-Olkin (KMO) measure of 0.82, indicating 'very good' sampling adequacy. The first three principal components cumulatively explained 86.81% of the total variance, achieving the objective of data reduction. For this study, the interpretation focused on the first two axis only.

Principal component analysis (PCA) results

The PCA applied to hydroclimatic, agricultural, and demographic variables in the Safsaf irrigated system reveals the following results:

Correlation matrix

The monotonic relationships among the ten variables used in the PCA are illustrated in the Spearman correlation matrix in *Table 4*, which highlights the intricate and interdependent relationships among demographic growth, water resource use, and agricultural productivity.

A notable finding showed the strong positive correlation observed between population size and the four variables of vegetable crop productivity ($r = 0.90$ for Pop, Yield I and II, and $r = 0.95$ for Pop, Yield III). These results suggest that as the population grew, vegetable production increased accordingly. This strong correlation indicates that agricultural activity was likely driven by both rising demand and the increased availability of labour. Among the hydroclimatic variables, the volume of water withdrawn from the Guenitra dam (IRR. Gueni) had a strong positive impact and correlation with agricultural crop variables ($r = 0.71$ for Yield II) and population ($r = 0.68$), underscoring its central role in sustaining local agricultural activity.

Baseline Scenario

Table 4. *Descriptive statistics results of main variables*

	Variables	IRR. area	IRR. Zerd	IRR. Gueni	Trib. Gueni	Res. Zerd	Pop	Yield I	Yield.II	Yield. III	Yield. IV
Main	IRR. area	1									
	IRR. Zerd	0.58	1								
	IRR. Gueni	0.47	0.40	1							
	Trib. Gueni	0.18	0.35	0.41	1						
	Res. Zerd	0.16	0.55	0.23	0.53	1					
	Pop	0.17	–0.08	0.68	0.16	–0.19	1				
	Yield. I	0.22	–0.06	0.68	0.25	–0.08	0.90	1			
	Yield.II	0.20	–0.01	0.71	0.14	–0.15	0.90	0.82	1		
	Yield.III	0.14	–0.09	0.68	0.17	–0.23	0.95	0.89	0.87	1	
	Yield.IV	0.01	–0.08	0.61	0.09	–0.22	0.92	0.83	0.89	0.91	1
Supplementary	Fill. R. Dams	0.04	0.31	0.27	0.58	0.71	–0.22	–0.03	–0.21	–0.17	–0.22
	% DWS Zerd	–0.69	–0.87	–0.38	–0.17	–0.36	–0.03	–0.02	–0.11	0.00	–0.06
	% DWS Gueni	–0.18	–0.41	–0.81	–0.44	–0.43	–0.59	–0.57	–0.60	–0.59	–0.57
	Vol. IRR	0.81	0.68	0.72	0.25	0.20	0.40	0.42	0.48	0.39	0.33
	Aver. Pro	0.26	0.02	0.73	0.23	–0.15	0.96	0.94	0.88	0.94	0.90

The analysis revealed a moderate correlation was observed between variables pertaining to irrigated areas and agricultural water for dams (e.g., r = 0.58 for IRR. area, IRR. Zerd, r = 0.47 for IRR. area, IRR. Gueni). In contrast, the relationship between the irrigated area and the supplementary variable of agricultural water distribution was very strong (r = 0.81 for IRR. area – Vol. IRR). The most probable explanation for this discrepancy is a miscalculation of the irrigated area, as the recorded and declared areas by the farms do not correspond to reality. However, by wasting water through the main irrigation channels, according to NOID's weekly monitoring reports, the rate of water loss through the supply network reached 28% in 2014. Aging pipes and inefficiently used hydraulic equipment result in significant water losses within the distribution network, partly due to inadequate maintenance. This problem is further compounded by illegal withdrawals from the main pipeline. These taps compromise a system that must simultaneously meet both irrigation and drinking water demands.

The analysis showed moderate relationships between the agricultural water variables of dams and the variables regarding the condition of the water resource (e.g., r = 0.55 for IRR. Zerd, Res. Zerd; r = 0.41 for IRR. Gueni, Trib. Gueni). These findings suggest that hydraulic potential is not the sole determinant of water scarcity. Agricultural water use exists within a context of competing demands, where domestic water supply is prioritised over other sectors. This highlights the significant role of management and governance in shaping scarcity conditions. Furthermore, the results reveal significant inverse correlations (very strong negative associations) between irrigation water variables and drinking water supply indicators as additive variables (e.g., r = –0.87 for IRR. Zerd, %DWS. Zerd and r = –0.81 for IRR. Gueni, %DWS. Gueni). Conversely, the analysis shows a negligible to very weak association between irrigation water use and vegetable productivity yields (for example, r = 0. 01 for Yield. IV, IRR. Area; r = 0.22 for Yield. I– IRR. area). This indicates that the expansion of irrigated land is not governed solely by the volume of allocated water, but is influenced by a complex array of factors, including traditional irrigation methods and institutional inefficiencies.

Correlation circle

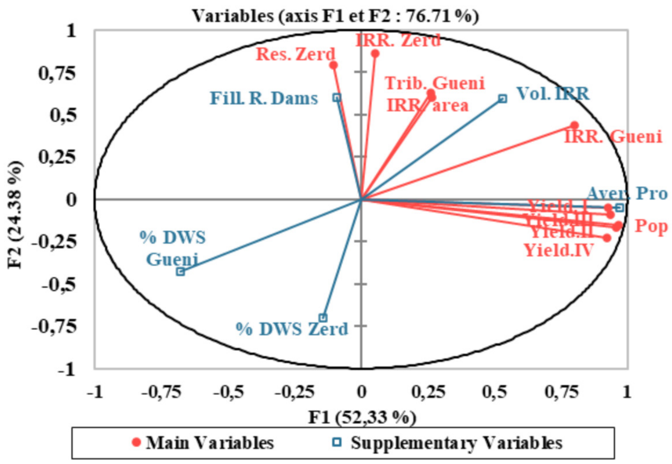
The principal component analysis (PCA) of the correlation circle revealed a clear two-dimensional structure that explained 76.71% of the total variance, *Fig. 3*.

Axis 1 (52.33%) reflects, 'agricultural productivity and demographic pressure'. This axis is strongly defined by a 92% cumulative contribution of agricultural yields (Yield.I, II, III, IV) population (Pop), and Guenitra dam irrigation (IRR. Gueni) clustering in the positive quadrant. Temporally, a clear shift is observed: the period from 1992 to 2003 and 2005 occupy the negative quadrant, characterised by a low production-water profile. Conversely, 2004 and 2006–2018 cluster in the positive quadrant, reflecting a significantly higher production-water profile and synchronised demographic growth. This represents a governance failure to regulate land use in alignment with water limits.

Axis 2 (24.38%) captures 'water resource management and dam potential' by placing domestic water supply allocations (% DWS. Zerd, % DWS. Gueni) in the negative quadrant and irrigation usage variables for Zerdaza dam (Res. Zerd, IRR. Zerd) and reservoir storage dam-filling with a 73% contribution rate (Fill. R. Dams) in the positive quadrant reflecting institutional management dysfunctions. Four distinct clusters emerged: Socio-Demographic and Yields, where this correlation indicates a reactive policy where agricultural output is driven by population demand rather than sustainable resource planning;Hydraulic infrastructure (Guenitra), where the 28% water loss in the Guenitra system serves as a direct ind icator of governance failure, resulting from inadequate maintenance and a lack of institutional accountability; Water availability (Zerdaza), where the Zerdaza dam demonstrates institutional inertia as a siltation escalates into crises due to fragmented management and a failure to act proactively; Urban priority, where the prioritisation during deficit periods reveals a centralised crisis-management model.

This approach prioritises short-term social stability over the equitable distribution of water to the agricultural sector.

Fig. 3. *PCA correlation circle*



Analysis of individuals projection

The factorial analysis revealed a two-dimensional framework structuring the regional hydroclimatic and agricultural systems over 26 years, *Fig. 4*.

The temporal analysis reveals three distinct phases in the evolution of the Safsaf irrigation system:

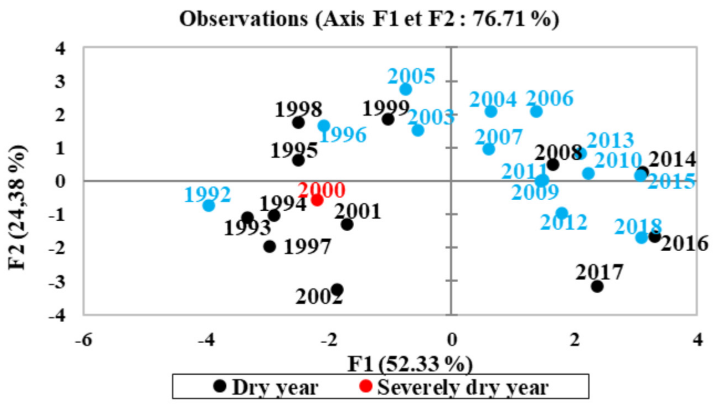
The group of years (1992–1999) positioned on the negative side of Axis 1, reflects a stage of lower agricultural productivity and smaller population centres before full infrastructural maturation.

The group of years (2000–2010) reveals increased dispersion with positive values on Axis 2. This distribution does not affect the favourable hydrological conditions characterising this period.

The group of years (2011–2018) is concentrated within positive Axis 1, demonstrating the maturation of Guenitra dam-supported agricultural intensification and demographic growth.

Climate stratification reveals systematic patterns: humid years align with positive Axis 2 values, while dry and

Fig. 4. *Individuals Projection on factorial Axis 1 and 2*



severe drought years correspond to negative Axis 1 and Axis 2 values, confirming the water scarcity impacts.

Critical years illustrate the system's vulnerability to hydroclimatic variability and the evolving balance between agricultural development and water resource sustainability: 2002 (severe water constraints, Axis 2 = −3.24), 2005 (exceptional water abundance, Axis 2 = +2.75), and 2017 (high productivity with emerging water stress).

PCA-based chronological typology

Based on the Elbow method shown in *Fig. 5*, the K-means analysis confirms an optimal cluster count of k = 5. This finding is further corroborated by the highest coefficient of variation of 0.54. The five groups of years represent the main periods of the evolution of agricultural water shortage in the Safsaf irrigated system. Based on the intra-class variance value, as shown in *Table 5* and the year clustering shown in *Fig. 5*.

Fig. 5. *The curve of the Elbow demonstrating the optimal number of principal components to retain*

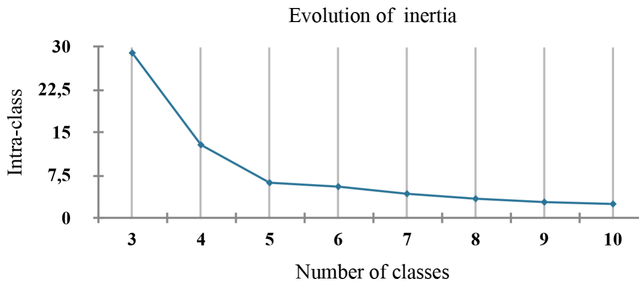


Table 5. *Barycentre of classes*

Class	Axis D1: Population-production dynamics	Axis D2: Water resource availability	Sum of weights (number of years)	Intra-class variance
1	−1.16	0.23	7	0.22
2	−0.83	−1.49	4	0.29
3	0.01	1.59	4	0.37
4	0.89	0.20	9	0.26
5	1.13	−1.28	3	0.40

Class 1 (1992–1999) is highly homogeneous, characterised by low agricultural productivity and restricted irrigated areas, with a heavy reliance on rainfed farming. This stagnation was a directly result of inadequate investment in hydraulic infrastructure and protracted delays in completing the irrigation networks for Sectors I and II. Consequently, the perimeter experienced economic water scarcity during this period.

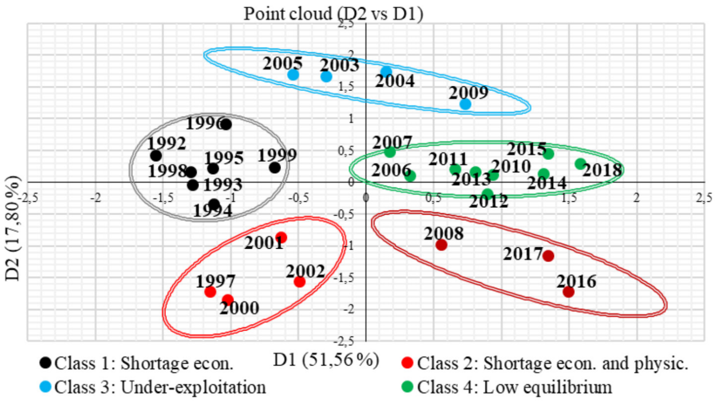
Class 2 (1997, 2000, 2001, and 2002) reflects a period of increasing drought events resulting from physical water scarcity in the study area. During this period, domestic drinking water supply became the priority for regional authorities. This reallocation was driven by severe water deficits, which effectively sidelined agricultural requirements during the partial operation of the irrigation perimeter. This class represents a trend toward domestic prioritization under extreme scarcity.

Class 3 (2003, 2004, 2005, and 2009) is moderately homogeneous. This class shows a trend of favourable water resource conditions. The commissioning of the Zit Emba dam from 2003 to 2005 contributed to the replenishment of the Zerdaza and Guenitra reservoirs. However, irrigation expansion remained limited due to institutional restructuring in 2005, which replaced the OIP with the National Office of Irrigation and Drainage (NOID), requiring time and methodological adjustments. In 2009, rainfall and the establishment of the Skikda desalination plant supported partial reservoir recovery; however, irrigation activity remained weak.

Class 4 is the most homogeneous group. It contains the largest number of years (2006, 2007, 2010, 2011, 2012, 2013, 2014, 2015, and 2018). This period is characterised by a dynamic equilibrium cycle.

Class 5 (2008, 2016, and 2017) is heterogeneous class corresponds critical drought years and severe depletion of the Zerdaza dam reserves.

Fig. 6. *Clustering of scores (PCA) after a Varimax rotation*



Discussion

This study demonstrates that agricultural water scarcity in the Safsaf irrigated perimeter is a composite phenomenon resulting from the interplay between institutional governance failures and hydroclimatic constraints. The results indicate that the deficit cannot be attributed exclusively to climate variability; instead, it is compounded by existing management frameworks.

Multivariate analysis reveals that the correlation matrix exposes critical institutional failures. Specifically, the moderate correlation between irrigated areas and dam withdrawals (r = 0.58 for Zerdaza dam, r = 0.47 for Guenitra dam) contrasts sharply with the strong relationship observed in distributed volumes (r = 0.81). This discrepancy highlights systematic losses, corroborated by National Office for Irrigation and Drainage (NOID) reports indicating network leakage of 28%. Climatic variability functions as an amplifying factor; while SPI analysis identifies extremes, ranging from severe drought in 2002 (Axis 2 = −3.24) to water abundance in 2005 (Axis 2 = +2.75), these factors account for only a secondary portion (24.38%) of the total variance.

Institutional dysfunction is further exemplified by the Zerdaza dam siltation crisis and a distorted pricing structure (2.5 DA/m^3 ≈ 0.0138 €/m^3), which creates perverse incentives for inefficient water use. This systemic failure is corroborated by the strong correlation between crop yield and Guenitra withdrawals ($r = 0.71$ for Yield II), which contrasts sharply with the negligible correlation found in irrigated areas ($r = 0.01 – 0.22$).

Resolving this crisis requires a suite of integrated measures. These include the rehabilitation of the Zerdaza dam (Toumi and Remini, 2020) and the reclamation of treated wastewater from the Skikda plant, which offers up to 42,000 m^3/day, enough to irrigate approximately 10 km^2. Additionally, the physical decoupling of potable and irrigation networks is essential to ensure system efficiency. Furthermore, the expansion of desalination capacity may provide indirect relief by meeting industrial and domestic demand, thereby mitigating intersectoral water competition. However, the long-term economic viability of these capital-intensive solutions remains uncertain. Protracted implementation delays have exacerbated the saturation crisis, eroding farmer confidence in the reliability of the National Office for Irrigation and Drainage (NOID). While these measures may offer short-term relief, they lack inherent sustainability; they primarily reflect a supply-side management paradigm that overlooks critical demand-side strategies.

The analysis indicates that failures in water governance institutions have contributed to the composite scarcity shaped by the interaction between institutional constraints and climatic pressures. Centralised decision-making, institutional fragmentation, and the lack of participatory mechanisms (e.g., functional Water User Associations) have impeded the integrated management of surface and groundwater resources. This factor has fostered irrational water use, putting pressure on ecosystems and intensified threats of water pollution and salinisation. Furthermore, the financial instability of the National Office for Irrigation and Drainage (NOID) and the disparity between official pricing and real distribution costs undermine the transition toward sustainable water management. This misalignment discourages efficient usage and hinders the adoption of environmentally and rational agricultural practices within the Safsaf Basin."

Addressing these systemic issues necessitates a paradigm shift towards decentralised governance frameworks that are inherently adaptive, inclusive, and participatory in nature. These measures should promote local co-management, establish transparent water rights, implement volumetric pricing aligned with ecological thresholds and delivery costs, and foster institutional collaboration that integrates environmental protection with agricultural development in the region. Comparative experiences from the Mediterranean region and other international contexts demonstrate the feasibility of these reforms. In Thailand, collaborative initiatives involving diverse local stakeholders, particularly farmers, have strengthened participatory irrigation governance (Donlatip and Somboon, 2023). Similarly, in Algeria's Setif Province, integrated strategic planning encompassing dam construction, water transfers, and desalination has yielded significant gains (Bouchareb and Morad, 2023). These cases illustrate that, while no universal solution exists, strengthening governance, enhancing data transparency, and integrating technology are essential for transitioning the Safsaf perimeter from a reactive crisis management model toward one of sustainable, ecologically responsible intensification.

Conclusion

This study of the Safsaf irrigated perimeter (Skikda, North-Eastern Algeria) from 1992 to 2018 demonstrates that water scarcity challenges in the southern Mediterranean basin constitute a multifaceted phenomenon. While traditional discourse often attributes scarcity to climatic and physical constraints, this research underscores deeper institutional dysfunctions and governance failures. To explore the root causes of the water scarcity crisis, this study employs a dynamic multivariate analysis across 16 hydro-climatic, agricultural, and demographic variables. By integrating Spearman correlation, Principal Component Analysis (PCA), and Varimax-rotated clustering, it identifies critical interdependencies that univariate methods fail to capture. This longitudinal approach provides a robust diagnostic framework for understanding the evolution of water scarcity in the region.

The main findings underscore the predominance of governance factors in explaining agricultural irrigation water scarcity. The institutional factors account for 52.33% of the total system variance, while climatic variability and management dysfunction contribute 24.38%. The analysis delineates three primary drivers of water scarcity in the Safsaf perimeter.

First, the temporal accumulation of failures as a primary driver of water scarcity in Safsaf, which evolved over three phases: economic scarcity in the 1990s due to incomplete infrastructure; physical scarcity in the early 2000s, exacerbated by droughts and limited storage; and a saturation crisis in the 2010s, when demand exceeded supply despite infrastructural improvements.

Second, rapid population growth and urban expansion have intensified socioeconomic competition for resources. This has led to a strategic shift favouring domestic water supply at the expense of agricultural needs.

Third, institutional and water management dysfunctions manifest through significant resource degradation, including the siltation of the Zerdaza dam and the unregulated expansion of Small and Medium Hydraulics (SMH). These factors exacerbate socioeconomic competition and drive unsustainable practices, such as informal groundwater extraction, as farmers seek to compensate for surface water shortages." Furthermore, these physical challenges are compounded by institutional fragmentation, centralised governance, and pricing inequities, all of which are sustained by a critical lack of participatory mechanisms that prevent local stakeholders from engaging in sustainable resource management.

These findings require a paradigm shift toward adaptive, decentralised, and participatory governance, sustainable water management and long-term climate projections together.

In the short term, investment in supply-side infrastructure is required to stabilise the system; however, ensuring long-term sustainability necessitates a shift toward demand-side management. These include transparent water rights, volumetric pricing, and the empowerment of Water User Associations through capacity-building programs, and promoting methodological approaches based on dynamic longitudinal multivariate analysis. Comparative experiences, such as integrated planning in Setif Province (Algeria) and participatory irrigation governance in Thailand, confirm that institutional reforms succeed when adapted to local conditions and supported by public investment. By addressing governance deficits in tandem with irrigation challenges, the Safsaf perimeter can transition toward ecologically responsible intensification, ensuring food security and resource sustainability in the face of climate change.

Acknowledgements

I acknowledge using Paperpal, an AI-based language editing tool, solely to improve the English language, grammar, and clarity of this manuscript. The scientific content, data analysis, and conclusions are entirely my own responsibility.

References

Abdi H. and Williams L. J. (2010) Principal component analysis. Wiley Interdisciplinary Reviews: Computational Statistics 2(4): 433–459. Available at: https://doi.org/10.1002/wics.101

Apollin F. and Eberhart C. (2012) Analysis and diagnosis of peasant irrigation systems (English ed.). AVSF (Agronomists and Veterinarians Without Borders).

Bouchareb N. and Morad I. (2023) Contribution of the Algerian water management strategy to the agricultural sector of the Setif Province. Journal of Innovations and Sustainability 7(2): 1–8. Available at: https://doi.org/10.51599/is.2023.07.02.08

Donlatip M. and Somboon S. (2023) Social capital and farmers' participation in multilevel irrigation governance in Thailand. Heliyon 8(9): e18793. Available at : https://doi.org/10.1016/j.heliyon.2023.e18793

El Jarari M. (2024) Analyse par composantes principales des déterminants de la résilience des petits exploitants agricoles de la Vallée du Souss [Principal Component Analysis of the determinants of resilienceamong smallholder farmers in the Souss Valley]. International Journal of Accounting, Finance, Auditing, Management and Economics. Available at: https://doi.org/10.5281/zenodo.13948487 (*in French*).

FAO (The state of food and agriculture) (2023) Revealing the true cost of food to transform agrifood systems. Rome. Available at: https://doi.org/10.4060/cc7724en

Feola G. (2015) Societal transformation in response to global environmental change: A review of emerging concepts. Ambio 44(5): 376–390. Available at: https://doi.org/10.1007/s13280-014-0582-z

IPCC (Intergovernmental Panel on Climate Change) (2023) Climate change 2023: Synthesis report (H. Lee & J. Romero, Eds.). Available at: https://doi.org/10.59327/IPCC/AR6-9789291691647

Jamin J.-Y, Bouarfa S., Poussin J.-C., Garin P. (2011) Les agricultures irriguées face à de nouveaux défis [Irrigated agriculture facing new challenges]. Cahiers Agricultures 20(1–2): 10–15. Available at: https://doi.org/10.1684/agr.2011.0477 (*in French*).

Jiang Y. (2009) China's water scarcity. Journal of Environmental Management 90(11): 3185–3196. Available at: https://doi.org/10.1016/j.jenvman.2009.04.016

Jolliffe I. T. and Cadima J. (2016) Principal component analysis: A review of recent developments. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 374(2065): 20150202. Available at: https://doi.org/10.1098/rsta.2015.0202

Laoubi K. and Yamao M. (2009) Management of irrigation schemes in Algeria: An assessment of water policy impact and perspectives on development. WIT Transactions on Ecology and the Environment 125: 503–514. Available at: https://doi.org/10.2495/WRM090451

Lever J., Krzywinski M., Altman N. (2017) Points of significance: Principal component analysis. Nature Methods 14(7): 641–642. Available at: https://doi.org/10.1038/nmeth.4346

MedECC (Mediterranean Experts on Climate and Environmental Change) (2020) Climate and environmental change in the Mediterranean Basin – Current situation and risks for the future: First Mediterranean assessment report. Zenodo. Available at: https://doi.org/10.5281/zenodo.4768833

Mvongo V. D., Defo C., Tchoffo M. (2022) Developing a novel tool for assessing water service sustainability in rural sub-Saharan Africa. Journal of Water, Sanitation and Hygiene for Development 12(3): 278–285. Available at: https://doi.org/10.2166/washdev.2022.203

Naseer M. A. u. R., Ashfaq M., Hassan S., Abbas A., Razzaq A., Mehdi M., Ariyawardana A., Anwar M. (2019) Critical issues at the upstream level in sustainable supply chain management of agri-food industries: Evidence from Pakistan's citrus industry. Sustainability 11(5): 1326. Available at: https://doi.org/10.3390/su11051326

Nini F. (2021) From the dam to the irrigated plot: Study on water and valorisation of large irrigated perimeters in north-eastern Algeria (Doctoral dissertation, Université Constantine 1).

Noto L. V., Cipolla G., Francipane A., Pumo D. (2023) Climate change in the Mediterranean Basin (Part I): Induced alterations on climate forcing and hydrological processes. Water Resources Management 37(6): 2287–2305. Available at: https://doi.org/10.1007/s11269-022-03400-0

OECD (Organisation for Economic Co-operation and Development) (2014) Water governance in the MENA region: Progress and challenges. OECD Publishing. Available at: https://doi.org/10.1787/9789264202405-en

Parinet B., Lhote A. Legube B. (2004) Principal component analysis: An appropriate tool for water quality evaluation and management-Application to a tropical lake system. Ecological Modelling 178(3–4): 295–311. Available at: https://doi.org/10.1016/j.ecolmodel.2004.03.007

Saleth R. M. (2014) Water governance: Institutional response as an adaptation to water scarcity. In Water for the Americas (pp. 45–67). Routledge.

Tabachnick B. G. and Fidell L. S. (2019) Using multivariate statistics (7th ed.). Pearson.

Toumi A. and Remini B. (2020) A dam that is silting up Zardezas (Algeria). Larhyss Journal 41: 7–22.

Walker G. (2014) Water scarcity in England and Wales as a failure of (meta) governance. Water Alternatives 7(2): 350–371.

Wold S., Esbensen K., Geladi P. (1987) Principal component analysis. Chemometrics and Intelligent Laboratory Systems 2(1–3): 37–52. Available at: https://doi.org/10.1016/0169-7439(87)80084-9