



ÇOMÜ

ZİRAAT FAKÜLTESİ DERGİSİ

COMU Journal of Agriculture Faculty

ISSN : 2147 - 8384

e-ISSN : 2564 - 6826

Volume : 14

Issue : 1

Year : 2026

RESEARCH ARTICLE

Assessment of Agricultural Water Footprint Dynamics of Niğde Province Using Innovative Trend Analysis

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Abstract

Climate change and rising food demand are increasing pressure on limited water resources in semi-arid agricultural regions. This study combined water footprint assessment and Innovative Trend Analysis to examine long-term changes in crop production and agricultural water use in Niğde Province, Turkey, between 2005 and 2024. Green, blue, and grey water footprint components were estimated for the dominant crops and then upscaled to the regional level using annual yield and harvested area data. Results revealed a critical hydrological paradox between efficiency and scale. Despite increasing atmospheric water demand, the unit water footprint showed a decreasing trend, driven by modern irrigation technologies and high-yielding varieties. However, this technical efficiency did not translate into absolute water savings on the regional scale. On the contrary, the regional water footprint volume exhibited an increasing trend. This hydrological expansion points to a clear rebound effect driven by population growth and rising economic demand. Analyses indicate that water savings from efficiency gains were utilized to alter the crop pattern rather than to conserve groundwater. During the study period, the share of wheat declined from 55% to 38%, while blue water intensive crops such as potato and dry bean expanded rapidly, reaching 18% and 7.2%, respectively. Results highlight that technological modernization alone is insufficient; policies must be supported by quantitative allocation caps and strategic planning to alleviate pressure on groundwater.

Keywords: Blue water, green water, irrigation rebound effect, Jevons Paradox, semi-arid region

Niğde İli Tarımsal Su Ayak İzi Dinamiklerinin Yenilikçi Trend Analizi Kullanılarak Değerlendirilmesi

Öz

İklim değişikliği ve artan gıda talebi, yarı kurak tarım bölgelerinde sınırlı su kaynakları üzerindeki baskıyı artırmaktadır. Bu çalışma, 2005-2024 döneminde Niğde İlindeki bitkisel üretim ve tarımsal su kullanımındaki uzun dönemli değişimleri incelemek amacıyla su ayak izi değerlendirmesini Yenilikçi Trend Analizi ile birlikte kullanmıştır. Baskın ürünler için yeşil, mavi ve gri su ayak izi bileşenleri hesaplanmış, ardından bu değerler yıllık verim ve hasat edilen alan verileri kullanılarak bölgesel ölçüğe taşınmıştır. Bulgular, verimlilik ile ölçek arasında kritik bir hidrolojik paradoks olduğunu ortaya koymuştur. Atmosferik su talebi artmasına rağmen, modern sulama teknolojileri ve yüksek verimli çeşitlerin etkisiyle birim su ayak izi bir azalma eğilimi göstermiştir. Ancak bu teknik verimlilik, bölgesel ölçekte mutlak su tasarrufuna dönüşmemiştir. Aksine, bölgesel su ayak izi hacmi artış eğilimi göstermiştir. Bu hidrolojik genişleme, nüfus artışı ve yükselen ekonomik talebin tetiklediği belirgin bir geri tepme etkisine işaret etmektedir. Analizler, verimlilik artışlarından sağlanan su tasarrufunun yeraltı suyunu korumaktan çok ürün desenini değiştirmek için kullanıldığını göstermektedir. Çalışma döneminde buğdayın payı %55'ten %38'e gerilerken, katma değeri yüksek ancak mavi su yoğunluğu fazla olan patates ve kuru fasulye gibi ürünler sırasıyla %18 ve %7.2 düzeyine ulaşarak hızla genişlemiştir. Sonuçlar, teknolojik modernizasyonun tek başına yeterli olmadığını; yeraltı suyu üzerindeki baskının azaltılabilmesi için politikaların nicel su tahsis sınırları ve stratejik ürün planlaması ile desteklenmesi gerektiğini ortaya koymaktadır.

Anahtar Kelimeler: Mavi su, yeşil su, sulama geri tepme etkisi, Jevons Paradoksu, yarı kurak bölge

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Received: 11.02.2026

Accepted: 13.06.2026

Citation: Yetik, A. K., & Candoğan, B. N. (2026). Assessment of agricultural water footprint dynamics of Niğde province using innovative trend analysis. *COMU Journal of Agriculture Faculty*, 14(1): 91-103.

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Introduction

The complex nexus between global climate change, rapid population growth, and agricultural production exerts unprecedented pressure on freshwater resources. As the agricultural sector is the single largest consumer of the available water supplies in the world (Wang et al., 2025), it stands as the primary driver of water scarcity and plays a pivotal role in sustainable resource management (Ricart et al., 2021; Biswas et al., 2025). The imperative to ensure food security for a growing population necessitates the expansion of agricultural output; however, shifting precipitation regimes and rising temperatures are increasingly constraining the available water budget. This stress is particularly acute in semi-arid and arid regions, where the competition for limited water resources is most intense. Consequently, quantifying the pressure of agriculture on these resources is no longer merely an environmental concern but a necessity for global stability. In this context, the Water Footprint (WF) assessment emerges as a comprehensive framework, providing a multi-dimensional indicator that evaluates water consumption and pollution in crop production (Hoekstra et al., 2009; Yin et al., 2022).

The WF, introduced by Hoekstra (2003), provides a comprehensive framework that transcends traditional water withdrawal statistics by distinguishing between the different sources of water consumed and the pollution generated. This multi-dimensional indicator is composed of three distinct components: the green water footprint (WF_{green}), referring to the consumption of rainwater stored in the soil profile; the blue water footprint (WF_{blue}), representing the volume of surface and groundwater consumed via irrigation; and the grey water footprint (WF_{grey}), which quantifies the volume of freshwater required to assimilate the pollutant load to meet specific water quality standards (Hoekstra et al., 2011). In semi-arid regions where precipitation is insufficient to meet crop evapotranspiration demands, the WF_{blue} becomes the critical determinant of agricultural water stress, directly reflecting the intensity of irrigation practices (Wada et al., 2011). Unlike classical efficiency indicators that focus solely on the volume of water applied, the WF approach offers a holistic assessment by integrating effective precipitation, irrigation requirements, and the environmental impact of agrochemicals, thereby revealing the true hydrological cost of crop production.

In recent years, the temporal evolution of WF has been investigated in various studies conducted at global or national scales (Yang and Cui, 2014; Ercin and Hoekstra, 2016; Ma et al., 2020; Adetoro et al., 2021; Wang et al., 2023). While these macro-scale assessments provide valuable insights into general trends and structural changes in water consumption over the past two decades, they often mask the heterogeneity of local hydrological realities. Most existing long-term research tends to rely on aggregated data or static parameters, which may fail to capture the specific inter-annual variations in crop yield, local management practices, and micro-climatic conditions at the regional scale. Therefore, there is a distinct divergence between broad-scale trend analyses and the need for high-resolution, region-specific evaluations. To bridge this gap, longitudinal studies that focus on specific production centers are essential to reveal how local cropping patterns and irrigation requirements respond to climate change over time, offering a more granular basis for regional policymaking.

Turkey, located in the climate change-sensitive Mediterranean Basin, is characterized by pronounced spatial and seasonal variability in precipitation and temperature, which strongly controls surface water availability and agricultural water demand (Aktaş, 2014). Increasing irrigation requirements, together with rising evapotranspiration under changing climatic conditions, have led to growing dependence on groundwater resources for agriculture in many basins, raising concerns over long-term hydrological sustainability (Ertürk et al., 2014). The province of Niğde, located in the Central Anatolia Region, constitutes a representative example of agricultural water use dynamics in a semi-arid environment. As a major production center for high-value and water-demanding crops such as potatoes, the region has experienced a marked expansion of irrigated agriculture, resulting in increasing anthropogenic pressure on local groundwater resources (Lermi and Ertan, 2019; Kocalar, 2022). Consequently, Niğde serves not only as a local study area but also as a representative case illustrating broader challenges of groundwater sustainability in semi-arid agricultural systems.

While the WF concept has attracted increasing attention in the national literature, existing studies in Turkey have predominantly focused on national-scale assessments (Turan, 2017; Boyacıoğlu, 2018; Pilevneli et al., 2023), industrial sectors (Ocak et al., 2013; Güney and Demirel, 2021; İlhan et al., 2023; Karaçil Ermumcu et al., 2024), or single-crop analyses (Muratoglu, 2020; Bulut, 2023). However, despite the valuable contributions of these studies, comprehensive long-term, region-specific assessments that simultaneously consider WF components across entire crop patterns remain relatively

scarce at the provincial scale. Specifically, for the Niğde province, despite its strategic importance in national food security, no production-based evaluation has yet been conducted that simultaneously analyzes the green, blue, and grey water footprints of the entire crop pattern.

To bridge this critical gap, the present study aims to conduct a comprehensive long-term analysis of the WF of major crops in Niğde covering a 20-year period (2005-2024). By utilizing dynamic yield data and actual harvested areas rather than static averages, this research seeks to reveal the structural evolution of the water budget of region and provide evidence-based insights for sustainable irrigation planning.

Materials and Methods

Study Area

The study was conducted in Niğde province, located in the Central Anatolia Region of Turkey (37°58' N, 34°40' E). The region is characterized by a semi-arid continental climate, exhibiting a distinct hydrological deficit where annual precipitation is typically insufficient to meet agricultural water demands (Korkanç et al., 2017). Due to the limited availability of surface water resources, agricultural production in the region relies heavily on groundwater extraction. Long-term average meteorological data covering the study period (2005-2024), including average temperature, precipitation, and relative humidity, are summarized in Table 1 (TSMS, 2025).

Table 1. Long-term meteorological characteristics of the study area (2005-2024)

Month	Max. Air Temperature (°C)	Min. Air Temperature (°C)	Relative Humidity (%)	Solar Radiation (MJ m ⁻² day ⁻¹)	Wind Speed (m s ⁻¹)	Total Precipitation (mm)
January	5.97	-3.64	72.32	2.78	2.51	39.39
February	8.23	-2.23	67.80	3.74	2.56	29.60
March	12.49	1.29	60.06	4.93	2.90	42.14
April	17.91	5.43	53.18	6.15	2.76	35.68
May	22.55	9.34	53.46	7.10	2.39	39.21
June	27.21	13.35	48.31	7.95	2.46	31.79
July	30.67	16.11	40.59	8.05	2.79	6.09
August	31.13	16.06	40.69	7.28	2.55	7.88
September	26.62	11.72	45.37	6.14	2.30	14.96
October	20.42	6.85	55.54	4.39	2.16	26.17
November	13.52	1.55	65.26	3.00	2.21	34.47
December	8.26	-1.72	72.36	2.39	2.27	39.05

In addition to its semi-arid climatic constraints, Niğde has a water resource structure that increases the importance of irrigation planning at the provincial scale. According to the Türkiye's General Directorate of State Hydraulic Works (SHW) 4th Regional Directorate, the province has an annual surface-water potential of 764 million m³ and a groundwater potential of 394 million m³, corresponding to a total water potential of 1.158 billion m³ year⁻¹ (SHW, 2025). Official provincial reports also show that agricultural production in Niğde is divided between irrigated and dry farming systems. In 2021, the total agricultural area was reported as 269 027 ha, of which 125 898 ha were irrigated, and 143 129 ha were under dry farming; this corresponds to 46.8% irrigated land and 53.2% dry farming land. The same report showed that irrigated land was distributed among flood irrigation (22 500 ha), drip irrigation (29 798 ha), and sprinkler irrigation (73 600 ha), and it explicitly stated that the water source used in flood-irrigated land was 100% groundwater supplied by wells. A comparison with earlier and later official records indicates that irrigated land increased from 120 231 ha in 2018 to 125 898 ha in 2021, while a 2023 provincial statement reported 126 638 ha of irrigated land, confirming the persistence of a strongly irrigation-dependent agricultural structure in the province (Niğde Governorship, 2022; TURKSTAT, 2025).

Data Sources and Study Period

The study spans a 20-year period (2005-2024), utilizing high-resolution agricultural statistics obtained from the Turkish Statistical Institute (TURKSTAT, 2025). To ensure regional representativeness, a rigorous filtering criterion was applied based on cumulative harvested area statistics; crops constituting 95% of the total harvested area in Niğde were selected, while minor crops

with negligible cultivation footprints were excluded to minimize statistical noise (Perry et al., 2003). A critical methodological distinction of this study is the integration of year-specific yield data (ton ha^{-1}) and actual harvested areas (ha) for each growing season, allowing for the precise capture of inter-annual production variability compared to static approaches.

Regarding the climatological and crop-specific parameters, meteorological variables required for the Penman-Monteith equation (Allen et al., 1998), including monthly maximum and minimum temperatures ($^{\circ}\text{C}$), relative humidity (%), wind speed (m s^{-1}), and sunshine duration (hours), were sourced from the Turkish State Meteorological Service (TSMS, 2025). Furthermore, instead of using generic global averages, crop coefficients (K_c) and regional based growth stage durations were derived specifically from the national technical guide published by TAGEM (2016), to reflect local phenological characteristics accurately.

Crop Pattern

To characterize the regional WF accurately, the study analyzes a diverse crop portfolio that reflects the agricultural structure of Niğde. Based on the cumulative harvested areas over the study period, the selected crops are categorized into three primary agronomic groups: (i) cereals (wheat, barley, rye, oat), which occupy the largest portion of the cultivated land spatially; (ii) tubers and legumes (potato, dry bean, chickpea), which are economically significant cash crops characterized by relatively high irrigation water requirements during critical growth stages; and (iii) fodder crops (alfalfa, silage maize), which support the intensive livestock sector. The average percentage distribution of harvested areas for these crops over the study period is illustrated in Figure 1.

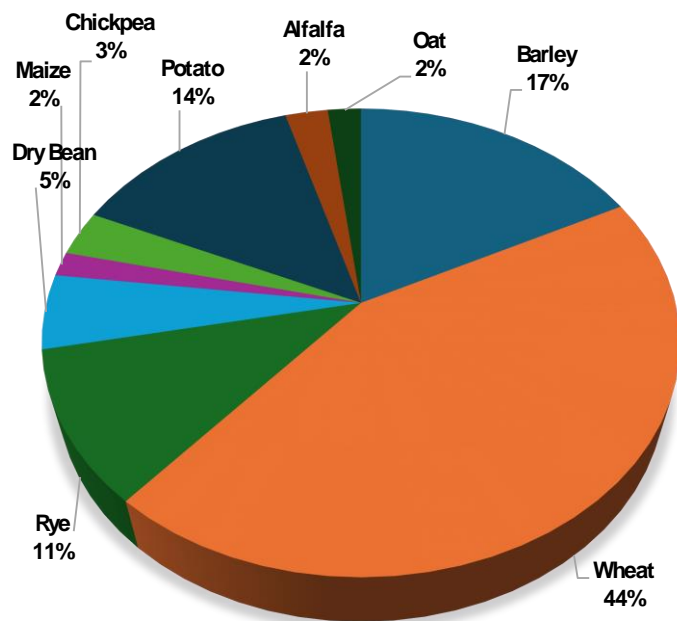


Figure 1. Percentage distribution of harvested areas for the selected crops (2005-2024)

Water Footprint Assessment

The WF assessment was conducted following the global standard established by the Water Footprint Network (Hoekstra et al., 2011). The process utilized the CROPWAT 8.0 model to simulate crop water requirements (Smith, 1992), followed by the calculation of specific and regional WF.

The crop evapotranspiration (ET_c) and irrigation water requirements were determined based on the FAO-56 Penman-Monteith approach. Instead of a dynamic irrigation schedule simulation, the calculation assumed optimal hydrological conditions where water is not a limiting factor for crop development, thereby estimating the potential crop evapotranspiration demand. The effective precipitation (P_{eff}) was determined using the USDA Soil Conservation Service method (Muratoglu et al., 2023). Regarding soil characteristics, data derived from the Harmonized World Soil Database (Nachtergaele et al., 2010) indicate that the region is predominantly characterized by medium-textured soils. Accordingly, a uniform soil profile with a Total Available Soil Moisture of 170 mm m^{-1} and a

Maximum Rain Infiltration Rate of 35 mm day⁻¹ was defined to represent the regional pedological context and to ensure methodological consistency for the effective precipitation calculations across all crops.

The total WF of a crop is the sum of green, blue, and grey components. WF_{green} represents the volume of rainwater consumed by the crop. It is calculated by accumulating the daily evapotranspiration derived from effective precipitation (ET_{green}) over the growing period. WF_{blue} refers to the volume of surface and groundwater consumed (evaporated) to meet the irrigation requirement (ET_{blue}). These components were calculated using Equations 1 and 2 (Hoekstra et al., 2011; Muratoglu et al., 2023).

$$WF_{green} = 10 \times \frac{ET_{green}}{Y} \quad (1)$$

$$WF_{blue} = 10 \times \frac{ET_{blue}}{Y} \quad (2)$$

Where, ET_{green} and ET_{blue} are the green and blue crop evapotranspiration components (mm), respectively, and Y is the crop yield (ton ha⁻¹). The factor 10 converts water depth (mm) into volume per area (m³ ha⁻¹). The partitioning of crop evapotranspiration into ET_{green} and ET_{blue} components was performed internally within the CROPWAT Model, based on effective precipitation and irrigation water requirement.

Due to the lack of long-term, site-specific data on nitrogen application rates, leaching rates, and pollutant concentrations, the grey water footprint was estimated using standard crop-specific grey water footprint coefficients rather than direct pollutant-load calculations. Following Gültaş (2024) and Gültaş et al. (2025), the crop-specific grey water footprint coefficients ($C_{grey,i}^{M\&H}$, m³ ton⁻¹) were adopted from Mekonnen and Hoekstra (2011). These coefficients represent the average freshwater volume required to assimilate pollutant loads per ton of crop production under country-specific production conditions. Therefore, the unit grey water footprint of each crop was defined as Equation 3:

$$WF_{grey,i} = C_{grey,i}^{M\&H} \quad (3)$$

where $WF_{grey,i}$ is the grey water footprint of crop i (m³ ton⁻¹), $C_{grey,i}^{M\&H}$ is the crop-specific grey water footprint coefficient obtained from Mekonnen and Hoekstra (2011) (m³ ton⁻¹). The resulting $WF_{grey,i}$ values were then used together with the green and blue water footprint components in the subsequent regional water footprint calculations.

Following the calculation of individual components, the total WF per unit of mass (m³ ton⁻¹) for each crop was obtained by summing the green, blue, and grey water footprints, as shown in Equation 4:

$$WF = WF_{blue} + WF_{green} + WF_{grey} \quad (4)$$

Subsequently, to evaluate the aggregate hydrological pressure on the Niğde region, these unit values were upscaled to the regional level using the dynamic agricultural statistics. The Total Regional Water Footprint (WF_{regional}, m³ year⁻¹) was calculated by multiplying the specific total WF of each crop by its annual yield (ton ha⁻¹) and harvested area (ha), as formulated in Equation 5:

$$WF_{regional} = WF \times Y \times A \quad (5)$$

Where, WF is the sum of green, blue, and grey water footprints (m³ ton⁻¹), Y is the crop yield (ton ha⁻¹), and A is the harvested area (ha) for the respective year. This calculation was performed for each year of the study period (2005-2024) to reveal the temporal evolution of water consumption in the region.

Statistical Analyses

The datasets were analyzed using descriptive statistics specifically arithmetic mean, standard deviation (SD), and coefficient of variation (CV), to determine the central tendency and inter-annual variability of the WF components over the 2005-2024 period.

To identify temporal changes and trends in these components, the Innovative Trend Analysis (ITA) method proposed by Şen (2012) was adopted. This method was preferred over traditional non-parametric tests as it is free from restrictive assumptions such as serial independence and normal distribution, providing a visual evaluation of trends across low, medium, and high data clusters. In the ITA procedure, both sub-series are sorted in ascending order and plotted on a Cartesian coordinate system, with the first half on the horizontal axis (x_i) and the second half on the vertical axis (x_j). The trend interpretation relies on the position of data points relative to the 1:1 (45°) no-trend line; data points accumulating above the line ($x_j > x_i$) signify an increasing trend, whereas points falling below the line ($x_j < x_i$) indicate a decreasing trend. The magnitude of this trend, denoted as the slope (S), is calculated based on the arithmetic averages of the first (\bar{x}_1) and second (\bar{x}_2) sub-series using Equation 6:

$$S = \frac{2(\bar{x}_2 - \bar{x}_1)}{n} \quad (6)$$

Where, \bar{x}_1 and \bar{x}_2 are the arithmetic averages of the first and second sub-series, respectively, and n is the total number of data points ($n=20$). In addition to Innovative Trend Analysis, the Mann-Kendall trend test was applied as a complementary non-parametric method to evaluate the presence and direction of monotonic trends in the annual series. To support the interpretation of trend magnitude, Sen's slope estimator was also calculated for the same variables. These analyses were performed for the annual irrigation requirement and the green, blue, grey, total and regional water footprint series. The Mann-Kendall and Sen's slope results were used as supporting evidence for the trends identified by Innovative Trend Analysis. All statistical analyses and graphical representations were performed using the R programming language (version 4.3.2) within the RStudio environment.

Results and Discussion

General Evaluation of Water Footprint Components

The breakdown of the average WF ($\text{m}^3 \text{ton}^{-1}$) for the major crops cultivated in Niğde over the study period is presented in Figure 2. The results reveal a striking disparity in water use efficiency among crop groups, driven primarily by the physiological yield potential rather than evapotranspiration rates alone.

As illustrated in the Figure 2, legumes exhibited the highest total WF per unit of mass. Chickpea recorded the highest average total WF ($6681 \text{ m}^3 \text{ton}^{-1}$), followed by dry bean ($2708 \text{ m}^3 \text{ton}^{-1}$). This magnitude is largely attributed to the relatively low yield levels of legumes compared to other crop groups. This finding is consistent with the meta-analysis by Wang et al. (2025), which identifies crop yield as a primary factor negatively correlated with the Water Footprint. Furthermore, as observed by Mwadzingeni et al. (2022) in smallholder irrigation schemes, local WF estimates often exceed global averages when yield gaps exist due to management or climatic constraints. The inverse relationship between yield and WF dictates that even moderate water consumption results in a high specific footprint when biomass production is limited. In contrast, tuber and fodder crops demonstrated the lowest WF. silage maize and potato were calculated to have total WFs of approximately $117 \text{ m}^3 \text{ton}^{-1}$ and $250 \text{ m}^3 \text{ton}^{-1}$, respectively.

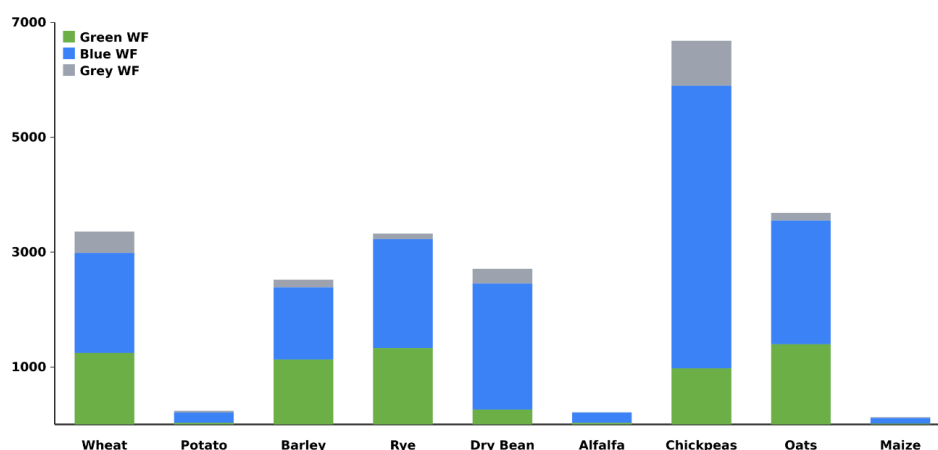


Figure 2. Average unit water footprint composition of cultivated crops in Niğde over the study period (2005-2024)

However, the composition of these footprints reveals a critical hydrological trade-off. While cereals such as wheat ($3370 \text{ m}^3 \text{ ton}^{-1}$) and barley ($2520 \text{ m}^3 \text{ ton}^{-1}$) have a substantial green water (rainwater) component, the production of high-value crops like potato relies heavily on Blue Water resources. This pattern aligns with the national spatial analysis by Muratoglu and Avanoz (2021), who reported that while cereals constitute the largest share of total WF of Türkiye (57%), the pressure on blue water resources is increasingly driven by the shift towards irrigated cash crops. Notably, although alfalfa and maize appear to be the most water-efficient crops per ton, this metric requires cautious interpretation. Their low unit WF is a mathematical outcome of high vegetative yields (multiple cuttings per season for alfalfa) and does not imply low absolute water consumption. On the contrary, these crops maintain high evapotranspiration rates throughout the arid summer season, exerting the most significant absolute pressure on the groundwater reserves of region per hectare of cultivated land. Detailed descriptive statistics, including the inter-annual variability (CV) for all footprint components, are summarized in Table 2.

Table 2. Descriptive statistics of water footprint (WF) components for cultivated crops in Niğde (2005-2024)

Group	Crop	Green WF ($\text{m}^3 \text{ ton}^{-1}$)	Blue WF ($\text{m}^3 \text{ ton}^{-1}$)	Grey WF ($\text{m}^3 \text{ ton}^{-1}$)	Total WF ($\text{m}^3 \text{ ton}^{-1}$)	CV (%)
Cereals	Barley	1131 ± 338	1256 ± 457	134 ± 34	2522 ± 727	28.8
	Oats	1396 ± 461	2153 ± 1295	135 ± 53	3684 ± 1736	47.1
	Rye	1330 ± 389	1897 ± 771	96 ± 30	3322 ± 1101	33.2
	Wheat	1247 ± 414	1739 ± 628	372 ± 113	3358 ± 1055	31.4
Legumes	Chickpeas	977 ± 199	4920 ± 956	784 ± 112	6681 ± 1043	15.6
	Dry Bean	257 ± 88	2197 ± 479	257 ± 55	2711 ± 570	21
Tubers & Fodder	Alfalfa	27 ± 7	180 ± 20	5 ± 0	213 ± 20	9.5
	Maize	13 ± 2	100 ± 11	15 ± 1	128 ± 13	10.3
	Potato	28 ± 8	181 ± 17	29 ± 2	238 ± 20	8.5

It is important to note that the statistics presented in Table 2 were calculated based solely on years with active production to ensure that zero-yield years do not skew the stability analysis. CV values offer critical insights into the production reliability of these crop groups. A distinct stability difference was observed between rainfed and irrigated crops. Cereals, particularly oats (CV=47.1%) and rye (CV=33.2%), exhibited high inter-annual variability, reflecting their vulnerability to fluctuating precipitation regimes (Green Water dependency). In contrast, intensively irrigated crops such as potato (CV=8.5%) and alfalfa (CV=9.5%) demonstrated remarkable stability across their active cultivation years. This low variability indicates that irrigation effectively acts as a buffer against climate anomalies, stabilizing the specific WF but simultaneously increasing the dependency on groundwater resources. Similar hydrological pressures were highlighted by Çakmak and Torun (2023) in the neighboring Konya Closed Basin, emphasizing that meeting the rising blue water requirement from groundwater reserves poses a severe threat to regional food security.

Trend Analysis of Water Footprint Components

The temporal evolution of hydrological parameters and WF components was analyzed using the ITA method to evaluate the long-term sustainability and efficiency of agricultural production in Niğde. The results, visualizing the scatter points of the first period (2005-2014) against the second period (2015-2024), are presented in Figure 3. A critical examination of the Irrigation Water Requirement (IWR) reveals a significant increasing trend ($S=79.82$), with data points predominantly clustering above the 1:1 no-trend line. This trajectory indicates that the atmospheric demand for water has intensified over the last two decades. This finding is strongly supported by recent climate projections in similar semi-arid regions of Turkey. For instance, Deveci and Konukcu (2024) reported that reference evapotranspiration is projected to increase by up to 21% in the long term due to rising temperatures, leading to severe water deficits for summer crops like sunflowers. Similarly, Yetik et al. (2024) identified statistically significant decreases in precipitation during critical summer months (July) in the Central Anatolia Region, confirming that the atmospheric thirst of the basin is intensifying due to climate change.

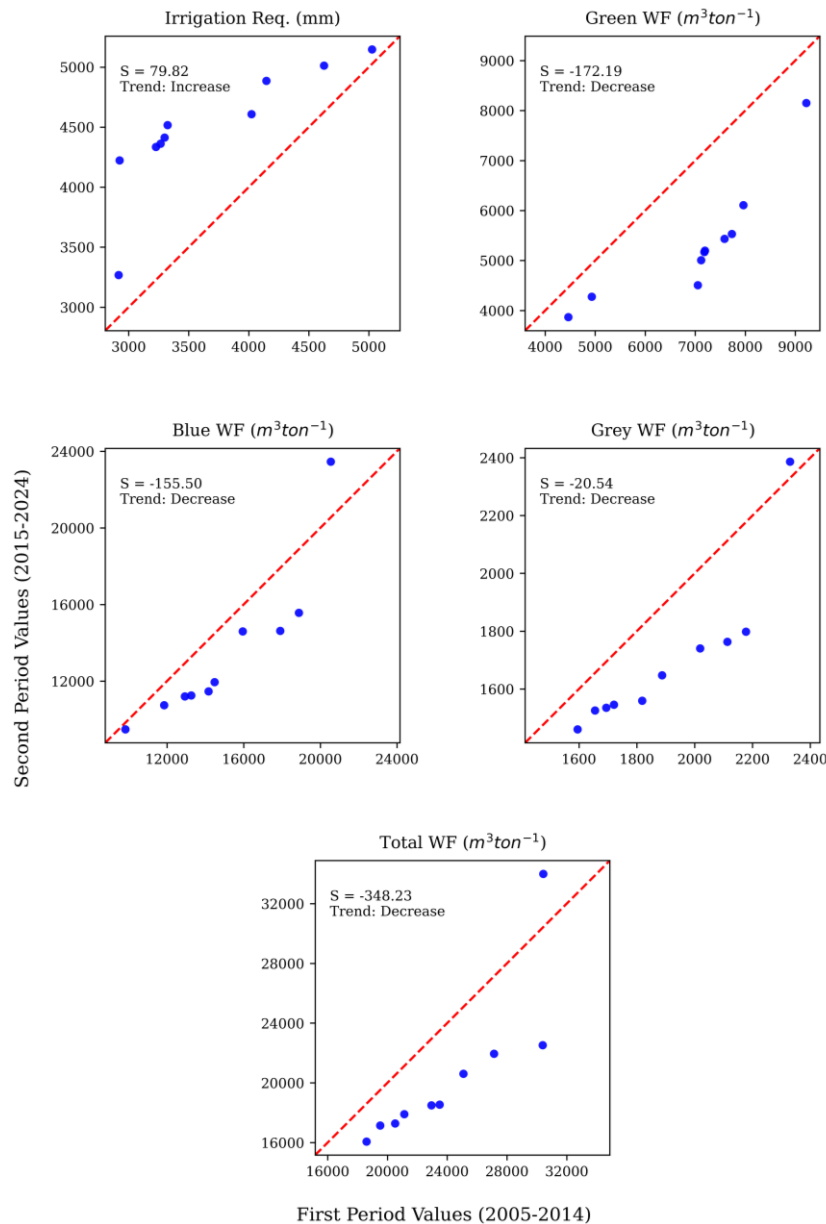


Figure 3. Innovative Trend Analysis results for Irrigation Water Requirement and unit water footprint components including Green, Blue, Grey, and Total Water Footprint (2005-2024)

However, contrary to the rising hydrological pressure, the WF components exhibited a distinct downward trend, revealing a compelling inverse relationship between climatic stress and production efficiency. The sharpest decline was observed in the WF_{green} ($S=-172.19$), which reflects the diminishing contribution of effective rainfall to crop growth, inevitably forcing the agricultural system to rely more heavily on irrigation resources (Figure 3). Despite this forced shift towards irrigation, the specific WF_{blue} also demonstrated a strong decreasing trend ($S=-155.50$). This implies that although the total volume of water applied to the fields may have increased to compensate for the rain deficit, the crop yield (ton ha^{-1}) achieved during this period significantly outpaced the increase in water consumption. Consequently, the Total WF showed the most substantial decreasing trend ($S=-348.23$), while the WF_{grey} followed a similar, albeit moderate, downward path ($S=-20.54$), suggesting a relative reduction in the pollution load per unit of yield.

The divergence between rising irrigation requirements and falling unit WF can be attributed to the structural modernization of agricultural practices in the region. The transition from traditional surface irrigation to pressurized irrigation systems (drip and sprinkler) has drastically improved water application efficiency, minimizing conveyance and evaporation losses. As highlighted by Askaraliev et al. (2024), modern irrigation technologies, particularly drip irrigation and automated systems, can

reduce water consumption by up to 50% compared to traditional methods while simultaneously increasing yields, thereby significantly lowering the WF. Furthermore, Chukalla et al. (2015) demonstrated that shifting from furrow to drip or subsurface drip irrigation reduces the consumptive blue water footprint by 8-10%, and when combined with deficit irrigation strategies, the reduction is even more pronounced. Our ITA results confirm that agricultural activities in Niğde have effectively successfully leveraged these technological advancements (pressurized systems and high-yielding varieties) to achieve a qualitative intensification, masking the hydrological stress imposed by climate change in unit-based indicators.

To support the visual interpretation provided by Innovative Trend Analysis, the same annual series were also evaluated using the Mann-Kendall test and Sen's slope estimator. The Mann-Kendall results confirmed the direction of the ITA patterns for all variables examined. A statistically significant increasing trend was detected for irrigation water requirement ($p < 0.01$), while a significant decreasing trend was identified for the grey water footprint ($p < 0.05$). For green, blue, and total water footprint components, Mann-Kendall analysis supported the decreasing direction indicated by ITA, although these trends were not statistically significant at the 5% level. Similarly, the regional water footprint volume showed an increasing tendency consistent with ITA, but this increase was not statistically significant according to the Mann-Kendall test.

Regional Evaluation: The Paradox of Efficiency and Scale

The central finding of this study emerges from the comparison between unit-based efficiency and regional-scale consumption. While the previous section demonstrated a clear reduction in the WF, the ITA applied to the $WF_{regional}$ (million m^3) reveals a contradictory and concerning trajectory. As illustrated in Figure 4, the total water consumption of the region exhibits a distinct increasing trend ($S=3.43$), with data points consistently clustering in the increase zone. This creates a critical dichotomy known as the Jevons Paradox or the Rebound Effect (Alcott, 2005). This phenomenon occurs when the expected water savings from efficiency improvements are offset by additional water demand arising from increased agricultural output (Song et al., 2017).

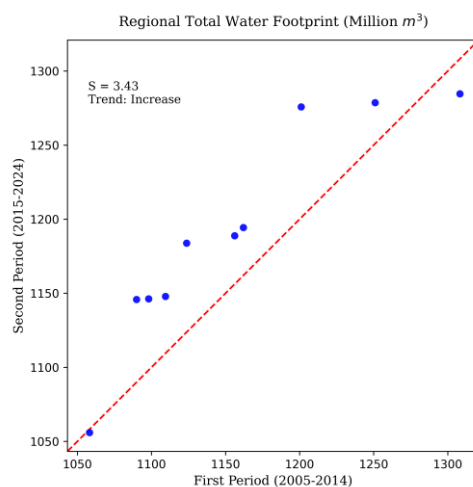


Figure 4. Innovative Trend Analysis results for the Regional Total Water Footprint volume (2005-2024)

This hydrological expansion is driven by the synergistic effect of population growth, rising agricultural demand, and the intensification of production capabilities. The transition to pressurized irrigation systems, while technically efficient, has enabled farmers to cultivate previously marginal lands and to intensify production schedules. This behavior aligns with the findings of Ward and Pulido-Velazquez (2008), who demonstrated that subsidies for water-conserving technologies often lead to increased water depletion because farmers use the saved water to expand irrigated acreage. Similarly, Pfeiffer and Lin (2014) provided empirical evidence that efficient irrigation technology can lead to increased groundwater extraction rather than conservation. Consequently, the water saving per unit has been effectively reinvested to support a larger scale of production. The increasing trend in Figure 4 confirms that the agricultural output of Niğde (Total Production in tons) has grown at a rate that outpaces the gains in WF, resulting in a net increase in pressure on the finite freshwater reserves of Niğde.

To understand the structural dynamics behind this total increase, the temporal evolution of the crop pattern was analyzed (Figure 5). The breakdown of the WF regional indicates a shift from a cereal-dominated rainfed system to a diversified, irrigation-dependent model. wheat, despite remaining the primary crop, saw its share in the total water budget decline from approximately 55% to 38%. However, this reduction was offset by the aggressive expansion of high-value, water-intensive crops. Notably, the share of potato expanded to 18%, and dry bean reached 7.2% of the total volume. This shift characterizes the intensification mechanism described by Berbel et al. (2018). Their microeconomic analysis suggests that as irrigation efficiency improves, water demand functions become more rigid (inelastic), rendering water pricing policies less effective. In Niğde, the anticipated water savings identified by Berbel et al. (2015) have been utilized to switch to higher-value crops like potatoes, cementing the paradox observed in the trend analysis.

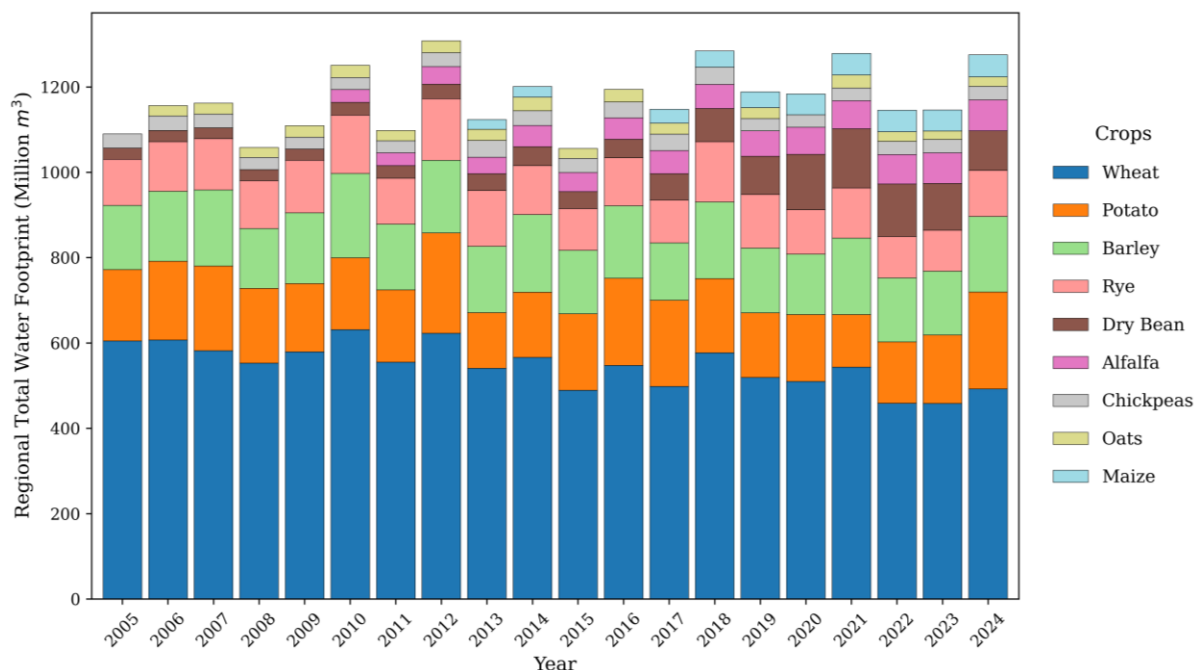


Figure 5. Temporal evolution and breakdown of the Regional Total Water Footprint by crop pattern (2005-2024)

However, it is essential to interpret these regional findings within the context of certain methodological constraints. First, the calculation of the WF_{grey} relied on global standard leaching fractions and ambient water quality standards, as region-specific nutrient leaching data were unavailable. Although this is a standard approach in data-scarce regions, it may introduce uncertainty regarding the precise magnitude of the pollution load. Second, the study estimated the ET_c based on optimal climatic conditions, assuming that water is not a limiting factor for crop development. In agricultural practice, semi-arid farmers often resort to deficit irrigation due to water scarcity or economic constraints; consequently, our WF_{blue} results represent the theoretical upper bound of water demand. Despite these assumptions, the identified trends and the structural paradox remain robust indicators for the long-term hydrological trajectory of Niğde Province.

Conclusion

This study examined long-term changes in agricultural water use in Niğde by integrating the Water Footprint (WF) methodology with Innovative Trend Analysis (ITA). The findings revealed a complex dichotomy between farm-level efficiency and region-scale sustainability, characterized by the Jevons Paradox. The trend analysis of unit-based indicators demonstrated that the agricultural system has achieved significant modernization. Despite the increasing atmospheric demand for water (Irrigation Requirement, $S=79.82$) driven by climate change, the water footprint per ton of crop (Total WF, $S=-348.23$) showed a decreasing trend. This direction was also supported by the Mann-Kendall test, although the trend was not statistically significant at the 5% level.

However, the regional-scale evaluation exposed that these efficiency gains did not translate into absolute water savings. On the contrary, the Regional Total Water Footprint Volume (million m³) exhibited an increasing trend (S=3.43). This direction was consistent with the Mann-Kendall results, although the increase was not statistically significant at the 5% level. This hydrological expansion was primarily driven by a structural shift in the crop pattern: the relative contraction of cereal production (wheat share declined from 55% to 38%) was counterbalanced by the aggressive expansion of high-value, water-intensive crops such as potato (reaching 18%) and dry bean (reaching 7.2%).

Consequently, the saved water from efficiency improvements was reallocated to intensify production and expand the irrigated area, rather than being conserved in the aquifer. This rebound effect suggests that technological improvements alone are insufficient to ensure the hydrological sustainability of the region. To halt the depletion of groundwater reserves, policy interventions must move beyond mere efficiency targets and implement quantitative caps on water allocation, coupled with strategic crop pattern planning that aligns economic incentives with the finite water availability of the region.

Authors' Contributions

Authors declare that they have contributed equally to the article.

Conflicts of Interest Statement

The authors declare that there is no conflict of interest.

Ethical Statement

This research did not contain any studies involving animal or human participants, nor did it take place in any private or protected areas.

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