Influence of Seasonal Snow Conditions on Winter Wheat Irrigation Requirement in a Semi-Arid Region

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Abstract: Seasonal snow can influence agricultural water demand in semi-arid environments by modifying the timing and temporary storage of cold-season precipitation. However, the contribution of observed snow conditions to winter wheat irrigation requirement has remained largely unresolved at station scale in Türkiye. This study investigated the relationship between seasonal snow conditions and winter wheat irrigation requirement in Niğde for the 1972–2025 period. Winter wheat irrigation requirement was estimated using seasonally aligned CROPWAT simulations, while seasonal snow indicators were derived from station-based observations. The analysis focused on actual irrigation requirements, effective rainfall, seasonal snow water input, and seasonal snow water equivalent (SWE). After the effect of effective rainfall had been removed statistically, seasonal snow water input retained a significant negative relationship with rainfall-adjusted residual irrigation requirement ($r = -0.341$, $p = 0.011$), and seasonal SWE showed a similarly significant but slightly weaker relationship ($r = -0.312$, $p = 0.021$). The results indicate that snow in Niğde provides hydroclimatic information beyond rainfall alone. Years with weaker snow conditions were associated with higher irrigation pressure than would be expected from effective rainfall alone. These results suggest that seasonal snow metrics should be considered in irrigation-risk assessment for semi-arid, snow-affected wheat environments in Central Anatolia.

Keywords: CROPWAT, hydroclimate**,** Niğde, precipitation, snow water equivalent

Mevsimsel Kar Koşullarının Yarı Kurak Bir Bölgede Kışlık Buğdayın Sulama Gereksinimine Etkisi

Öz: *Mevsimsel kar, yarı kurak ortamlarda soğuk mevsim yağışlarının zamanlamasını ve geçici depolanmasını değiştirerek tarımsal su talebini etkileyebilir. Bununla birlikte, gözlenen kar koşullarının kışlık buğdayın sulama gereksinimine katkısı Türkiye'de istasyon ölçeğinde büyük ölçüde netlik kazanmamıştır. Bu çalışmada, 1972–2025 dönemi için Niğde ilinde mevsimsel kar koşulları ile kışlık buğdayın sulama gereksinimi arasındaki ilişki incelenmiştir. Kışlık buğdayın sulama gereksinimi, mevsimsel olarak hizalanmış CROPWAT simülasyonları kullanılarak tahmin edilmiş; mevsimsel kar göstergeleri ise istasyon tabanlı gözlemlerden türetilmiştir. Analiz; gerçek sulama gereksinimi, etkili yağış, mevsimsel kar su girdisi ve mevsimsel kar su eşdeğeri (SWE) üzerine odaklanmıştır. Etkili yağışın etkisi istatistiksel olarak giderildikten sonra, mevsimsel kar su girdisinin yağıştan arındırılmış artık sulama gereksinimi ile anlamlı ve negatif bir ilişkiyi sürdürdüğü belirlenmiştir ($r = -0.341$, $p = 0.011$). Benzer şekilde, mevsimsel SWE de anlamlı ancak biraz daha zayıf bir ilişki göstermiştir ($r = -0.312$, $p = 0.021$). Bulgular, Niğde koşullarında karın yalnızca yağışın ötesinde hidroklimatik bilgi sağladığını ortaya koymaktadır. Daha zayıf kar koşullarının gözlendiği yıllar, yalnızca etkili yağışa dayalı beklentinin ötesinde daha yüksek sulama baskısı ile ilişkilendirilmiştir. Bu sonuçlar, Orta Anadolu'daki yarı kurak ve kar etkisindeki buğday üretim sistemlerinde sulama riski değerlendirmelerinde mevsimsel kar metriklerinin dikkate alınması gerektiğini göstermektedir.*

Anahtar kelimeler: *CROPWAT, hidroklima, Niğde, yağış, kar su eşdeğeri*

INTRODUCTION

Supplemental irrigation is increasingly important for winter wheat production in semi-arid environments, where in-season precipitation often remains insufficient to satisfy crop water demand and stabilize yield (Ali et al., 2019). This issue is especially relevant in Central Anatolia, one of major wheat producing regions of Türkiye, where winter wheat production is constrained by limited water availability and recurrent drought stress (Tari, 2016; Kale and Madenoğlu, 2018). At the national scale, climate change assessments further suggest that Turkish wheat systems, including the winter wheat zone, are becoming more exposed to combined heat and drought stress, increasing the importance of understanding the climatic controls of irrigation requirement (Kaya, 2021).

In snow affected environments, agricultural water availability is not governed by rainfall alone. Seasonal snow stores part of cold season precipitation and releases it later through melt, thereby redistributing water in time and functioning as a natural reservoir (Qin et al., 2020; Aragon and Hill, 2024). This reservoir function matters for agriculture because irrigation demand usually peaks after the main cold season accumulation period.

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The agricultural relevance of snow is not limited to runoff generation. Snow conditions can influence subsequent soil moisture, soil temperature, and the protection of overwintering crops against frost damage. Large scale studies have shown that winter snow cover can exert lagged effects on growing season vegetation productivity, mainly through its controls on soil thermal and moisture conditions (Liu et al., 2023). Recent evidence also indicates that winter wheat systems across the Northern Hemisphere are becoming increasingly sensitive to snow drought, and that snow drought frequency has risen in major wheat growing areas in recent decades (Chen et al., 2026). At the local scale, urban warming around meteorological stations may also influence snow retention and melt timing (Hinkel and Nelson, 2007; Mori and Sato, 2015). Taken together, these studies suggest that snow metrics deserve closer attention in agricultural water demand studies, especially for winter crops whose development spans the cold season and the subsequent spring period.

This issue is particularly important in the Konya Closed Basin and its surrounding semi-arid agricultural environments, including Niğde. Konya Closed Basin receives less precipitation than the national average (Yetik et al., 2024) while groundwater consumption exceeds the national average, underlining strong pressure on groundwater dependent agriculture. Regional drought analyses also show that Niğde is among the stations with a high number of dry years within the Konya Closed Basin, reinforcing the vulnerability of region to prolonged hydroclimatic stress (Sarış and Gedik, 2021).

Previous studies have evaluated winter wheat irrigation strategies under semi-arid conditions (Tari, 2016), tested crop model performance for winter wheat under different irrigation regimes in Türkiye (Kale and Madenoğlu, 2018), assessed the vulnerability of Turkish winter wheat to climate change (Kaya, 2021), and documented changes in snow contribution to runoff across Türkiye (Cevahir and Duygu, 2023). However, despite this growing literature, the explicit role of observed station scale snow conditions in relation to crop model derived winter wheat irrigation requirement remains largely unresolved. In particular, no study has been identified that directly links long-term snow observations from Niğde with irrigation water requirement estimates to evaluate whether cold season snow metrics help explain subsequent irrigation demand in a semi-arid winter wheat system.

Accordingly, this study investigates the relationship between seasonal snow conditions and winter wheat irrigation requirement in Niğde during 1972–2025. Using CROPWAT-derived irrigation requirement estimates together with station-based meteorological observations, the analysis examines whether years with greater cold season snow input are associated with lower irrigation demand after accounting for effective rainfall.

MATERIAL and METHODS

Study area

The study was carried out for Niğde (37°58′ N, 34°41′ E), located in the semi-arid Central Anatolian region of Türkiye. The analysis focused on winter wheat and on the role of cold-season snow conditions in shaping subsequent irrigation requirement. All calculations were performed at station scale using a single, seasonally aligned time series. Accordingly, the study represents a station-scale temporal assessment rather than a spatial analysis, and no interpolation or inter-station comparison was performed.

Meteorological and snow data

Daily meteorological observations for Niğde were compiled from official station records and harmonized into a single dataset for irrigation modelling and snow analysis. The variables used to prepare the climate inputs were minimum and maximum air temperature (°C), relative humidity (%), wind speed (m s^{-1}), sunshine duration (hours), and precipitation (mm). Daily snow information included snow water amount and snow water equivalent (SWE). Seasonal snow water input was defined as the cumulative total of observed daily snow-water amount over the October-June wheat season, representing snowfall-derived water input rather than snowmelt or day-to-day SWE change. Seasonal SWE was calculated as the cumulative sum of daily SWE values over the same period and used as an integrated indicator of snow storage (mm day^{-1}), following Aragon and Hill (2024). Because winter wheat spans two calendar years, the analysis was organized using a harvest-year framework. For each harvest year, the wheat season was defined from 5 October of the previous year to 30 June of the harvest year. Based on this definition, the final analytical dataset covered 54 harvest years (1972–2025).

CROPWAT model and parameterization

Winter wheat irrigation requirement was estimated using CROPWAT 8.0, the FAO decision support model for crop water requirement, irrigation requirement, and irrigation scheduling (FAO, 2009). CROPWAT is based on the FAO-56 framework, in which reference evapotranspiration (ETo) is calculated with the FAO Penman-Monteith method and crop evapotranspiration is determined using crop coefficients and crop stage information (Allen et al., 1998; FAO, 2011). It should be noted that CROPWAT does not explicitly simulate snow accumulation and melt processes; therefore, snow was not modelled as a process-based water-storage component within the crop-water balance.

For each harvest year, seasonally aligned monthly climate and rainfall files were generated so that October-December conditions were taken from the previous calendar year and January-June conditions from the harvest year. This step was necessary because a standard calendar year file structure does not represent the full winter wheat season correctly. The crop was parameterized as winter wheat with a fixed sowing date of 5 October and a seasonal endpoint of 30 June, corresponding to a total season length of 270 days. The crop development stages were set to 30 days for the initial stage, 170 days for the development stage, 40 days for the mid-season stage, and 30 days for the late-season stage. The determined Kc values of winter wheat cultivated in Niğde are 0.53 for the initial stage, 1.16 for the mid-season, and 0.27 for the late season according to the national crop water use guide prepared under the coordination of the General Directorate of Agricultural Research and Policies of Türkiye (TAGEM, 2016). Soil conditions were represented with a Niğde specific soil file prepared from Harmonized World Soil Database based soil water information (FAO, 2012). In this file, total available soil moisture was set to 170 mm m^{-1}, maximum rain infiltration rate to 35 mm day^{-1}, maximum rooting depth to 0.90 m, and initial soil moisture depletion to 50%. These crop and soil settings were held constant for all annual simulations so that interannual differences in irrigation requirement reflected climatic variation rather than changing parameter choices.

Statistical Analysis

The statistical analysis was designed to test whether snow conditions explained part of the interannual variability in irrigation requirement beyond the contribution of effective rainfall. First, descriptive statistics were calculated for AIR, effective rainfall, seasonal snow water input, and seasonal SWE. Second, a rainfall only baseline model was fitted by regressing actual irrigation requirement against effective rainfall (Equation 1):

$$AIR_y = \alpha + \beta ER_y + \varepsilon_y \quad (1)$$

where AIR_y is actual irrigation requirement in harvest year (y) and ER_y is effective rainfall in the same season. This model was used as a statistical baseline to remove the dominant rainfall effect from irrigation requirement rather than as a closed physical water balance model. From this model, a rainfall adjusted residual irrigation requirement was calculated for each year as:

$$RIR_y = AIR_y - \widehat{AIR_y} \quad (2)$$

where RIR_y is residual irrigation requirement and $\widehat{AIR_y}$ is the value predicted solely from effective rainfall. Positive residuals therefore indicate seasons in which irrigation requirement was higher than expected based on rainfall alone, while negative residuals indicate seasons in which irrigation requirement was lower than expected.

Third, the relationship between snow conditions and irrigation pressure was evaluated using two complementary approaches. Pearson correlation and simple linear regression were applied to relate rainfall-adjusted residual irrigation requirement to seasonal snow indicators, including total snow water input and seasonal SWE. In addition, harvest years were classified into low, normal, and high snow groups based on the lower and upper tertiles of seasonal snow water input. The resulting thresholds were ≤45.6 mm for low-snow years, 45.6–112.7 mm for normal-snow years, and >112.7 mm for high-snow years.

RESULTS AND DISCUSSION

The results show that interannual variability in winter wheat irrigation requirement in Niğde cannot be interpreted only through rainfall totals. Instead, the hydroclimatic setting of the wheat season varied substantially in terms of both atmospheric water supply and snow related storage conditions, and this variability was reflected in the seasonal irrigation signal. The hydroclimatic context of the study period is summarized in Table 1 and illustrated in Figure 1.

Table 1. Descriptive statistics of the main irrigation and snow variables for Niğde winter wheat seasons during 1972–2025

Variable	Mean	SD[a]	Min	Max
AIR[b] (mm)	323.1	79.2	128	493.6
Effective rainfall (mm)	302.5	63.8	159.8	461.1
Seasonal snow water input (mm)	111.2	120	0	700.2
Seasonal SWE[c] (mm day^{-1})	11.1	10.1	0	57.1

[a]SD: Standard deviation, [b]AIR: Actual irrigation requirement, [c]SWE: Snow water equivalent.

Table 1 indicates that the Niğde winter wheat system was characterized by a broad hydroclimatic range rather than by stable seasonal conditions. In particular, the snow variables were markedly more dispersed than the rainfall related variables, suggesting that the cold season storage component of the system changed more sharply among years than the direct rainfall supply component. This contrast is important because it implies that interannual irrigation pressure in Niğde emerged under strongly shifting winter backgrounds, from nearly snow free seasons to seasons with substantial snow derived input and storage.

From an agronomic perspective, the descriptive statistics suggest two points. First, irrigation demand remained consistently relevant throughout the record, supporting the broader understanding that winter wheat production in semi-arid Central Anatolia operates under recurrent water limitation (Tari, 2016; Kale and Madenoğlu, 2018).

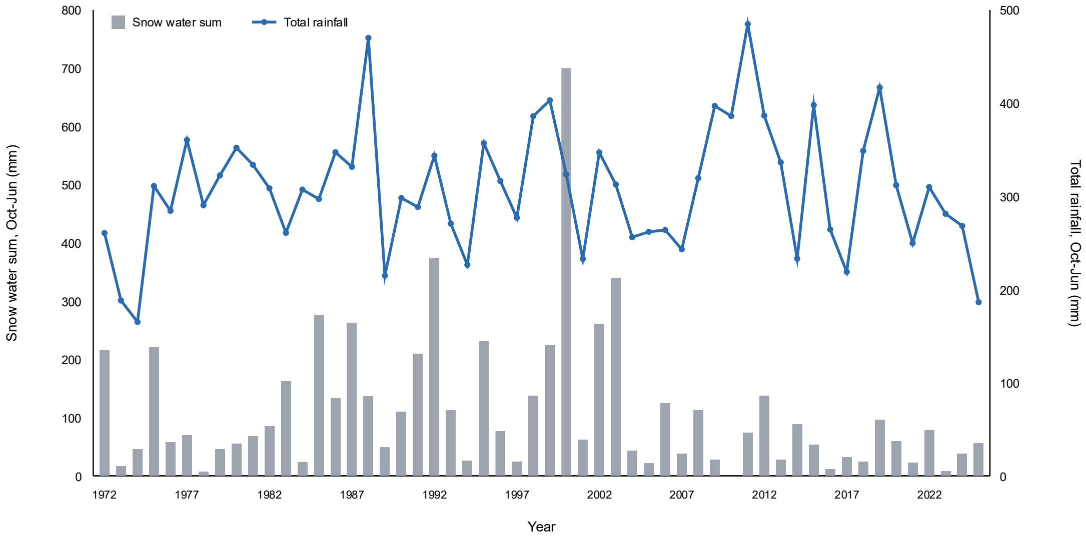

Figure 1. Combined interannual variation in seasonal snow water input and total rainfall for Niğde winter wheat seasons during 1972–2025

Second, the snow related spread was large enough to justify examining snow separately from rainfall, because the seasonal water environment was shaped not only by how much precipitation occurred, but also by the form in which a considerable part of that precipitation was seasonally stored. Figure 1 shows that total seasonal rainfall and seasonal snow water input did not evolve synchronously across the record. Some seasons combined relatively limited snow input with moderate or even substantial rainfall, whereas others showed pronounced snow input without correspondingly high total rainfall. This distinction matters because it indicates that snow was not simply a constant fraction of total seasonal precipitation. Instead, the form in which cold season precipitation occurred varied strongly among years. This behavior is consistent with the broader literature showing that warming climates alter snowfall fraction, snow retention, and melt timing (Qin et al., 2020; Räisänen, 2023). It is also compatible with national scale evidence from Türkiye showing that the contribution of snowfall to runoff has changed spatially and temporally in snow influenced regions of the country (Cevahir and Duygu, 2023).

From an agricultural perspective, this pattern means that two seasons with broadly similar total precipitation could still differ in their irrigation implications if one season stored a larger share of its cold season water in snow form. In other words, total rainfall alone does not fully describe the hydroclimatic setting of winter wheat in Niğde. The distinction between rainfall input and snow derived input therefore provides the necessary climatic context for interpreting seasonal irrigation requirement. This is particularly relevant in the Konya Closed Basin, where prolonged drought propagation and water renewal vulnerability have already been documented and where Niğde stands out among the stations with frequent dry conditions (Sarış and Gedik, 2021).

Against this hydroclimatic background, Figure 2 shows that irrigation requirement and snow water input varied strongly through time, but not independently of each other. Periods characterized by relatively weak snow input frequently coincided with elevated irrigation requirement, whereas years with stronger snow input often occurred under lower seasonal irrigation demand. This inverse co-variation was not perfectly uniform, which is expected in a semi-arid wheat environment where the seasonal water balance is affected by multiple controls, including rainfall amount, atmospheric demand, and the timing of cold season precipitation. Even so, the visual pattern indicates that snow should not be treated merely as a winter background condition; rather, it appears to be part of the seasonal hydroclimatic structure that shapes irrigation requirement in Niğde.

The year-to-year variability also shows that irrigation pressure did not simply track one monotonic trajectory over the study period. Instead, the series was characterized by alternating low and high demand years. This pattern supports the decision to focus on interannual hydroclimatic relationships rather than on a pure long term trend framework. For a winter wheat system in a semi-arid environment, such interannual contrasts are agronomically meaningful because irrigation planning is carried out season by season.

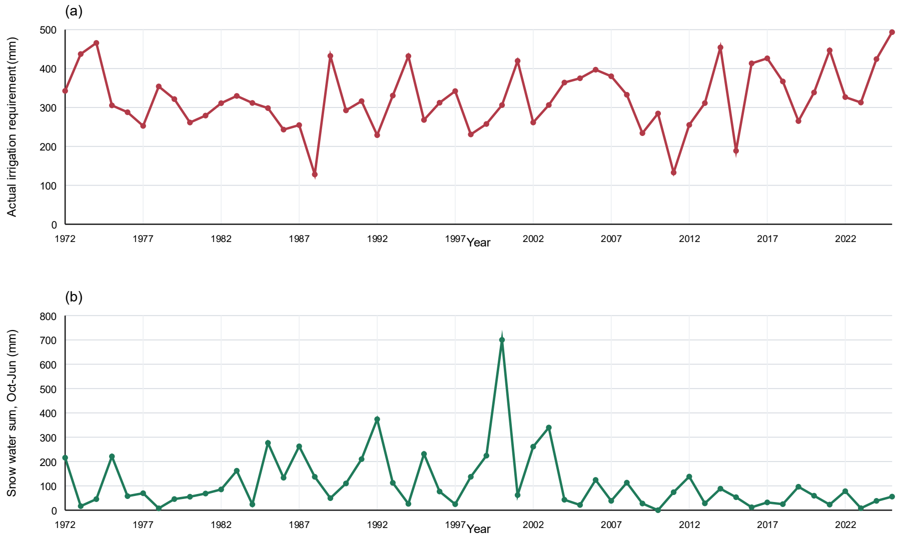

Figure 2. Interannual variability in (a) actual irrigation requirement and (b) seasonal snow water input for Niğde winter wheat harvest years during 1972–2025

In that context, understanding whether snow rich and snow poor winters are associated with systematically different irrigation requirements becomes more informative than asking whether a single linear trend dominates the entire record. To isolate the snow signal from the dominant contribution of rainfall, a rainfall only baseline relationship was first established between effective rainfall and AIR. The fitted equation was (Equation 3):

$$AIR = 670.10 - 1.147 \times Effective\ Rainfall \quad (3)$$

The baseline relationship was statistically strong (R^2=0.853, p<0.001, n = 54), indicating that effective rainfall explained a substantial share of the interannual variability in AIR. It was not interpreted as a physical closure of the seasonal water balance; rather, it provided a practical means of removing the primary rainfall signal from seasonal irrigation requirement and thereby testing whether snow still explained part of the remaining interannual variability. The first direct test of snow effects beyond rainfall is shown in Figure 3.

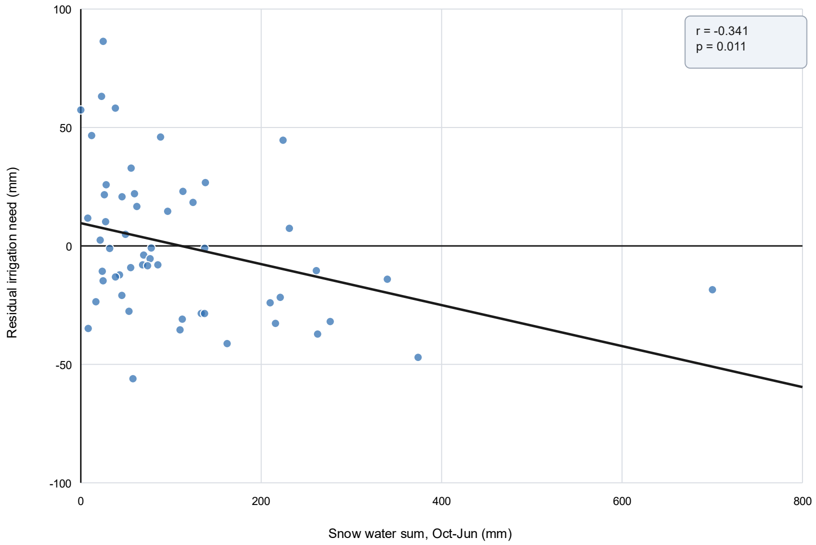

Figure 3. Relationship between rainfall adjusted residual irrigation requirement and seasonal snow water input for Niğde winter wheat seasons during 1972–2025

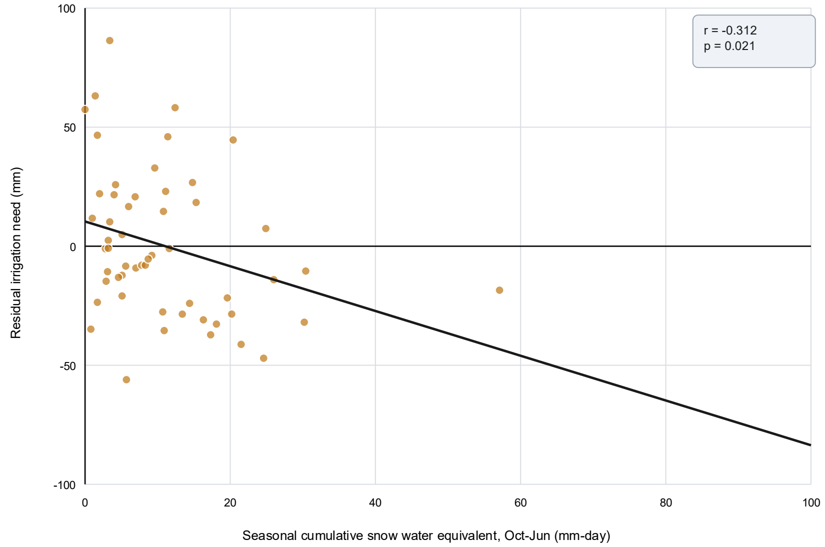

Figure 4. Relationship between rainfall adjusted residual irrigation requirement and seasonal snow water equivalent for Niğde winter wheat seasons during 1972–2025

After rainfall adjustment, seasonal snow water input still showed a significant negative relationship with residual irrigation requirement (r=-0.341, p=0.011). This result indicates that years with higher cold season snow input generally requires less irrigation than would be expected on the basis of effective rainfall alone. In other words, once the direct rainfall effect had been statistically removed, snow still retained explanatory value. This finding is central to the study because it suggests that snow was not simply duplicating the precipitation information already embedded in CROPWAT through rainfall. Instead, it carried an additional hydroclimatic signal relevant to seasonal irrigation pressure.

The magnitude of the correlation was moderate rather than strong, which is reasonable given the complexity of seasonal crop water interactions in semi-arid systems (Snyder and Tartowski, 2006). Irrigation requirement is not determined by snow alone, and the remaining unexplained variance likely reflects other interannual controls, such as within season temperature anomalies, evaporative demand, and the exact timing of water availability relative to crop development stages. Because CROPWAT does not explicitly simulate snow accumulation and melt processes, the observed relationship should be interpreted as a hydroclimatic association rather than as direct evidence of modelled snowmelt contribution to crop water supply. In Niğde, snow rich years may also coincide with cooler conditions, lower atmospheric demand, different cloudiness regimes, and more favorable seasonal moisture conditions, all of which can contribute to lower modelled irrigation requirement. This interpretation is agronomically plausible for Central Anatolia and is consistent with the stage specific water sensitivity of winter wheat reported by Tari (2016). The complementary storage based test is presented in Figure 4.

A comparable result was obtained for seasonal SWE, which also showed a significant negative relationship with residual irrigation requirement (r = -0.312, p = 0.021). This indicates that not only the cumulative amount of snow derived input, but also the integrated seasonal storage behavior of snow, was relevant to irrigation pressure. Because SWE combines the magnitude and duration of snow storage, its significance supports the interpretation that the reservoir like role of snow matters in this system. At the same time, the slightly stronger performance of cumulative snow water input suggests that, under Niğde conditions, the amount of seasonal snow derived water entering the system may be a somewhat clearer hydroclimatic indicator than snow persistence alone.

This difference between snow water input and SWE is informative. Seasonal snow water input describes the total snow derived contribution during the wheat season, whereas SWE represents how long that water remains stored in snow form.

The fact that both variables were significant suggests that the Niğde signal is not purely a matter of precipitation amount. Rather, it also reflects seasonal storage dynamics, even if that storage effect is somewhat weaker than the cumulative input signal. In that respect, the results support the logic of Aragon and Hill (2024), who argued that integrated snow storage metrics capture information that is missed by single point snow indicators. The practical agronomic expression of this signal is illustrated in Figure 5.

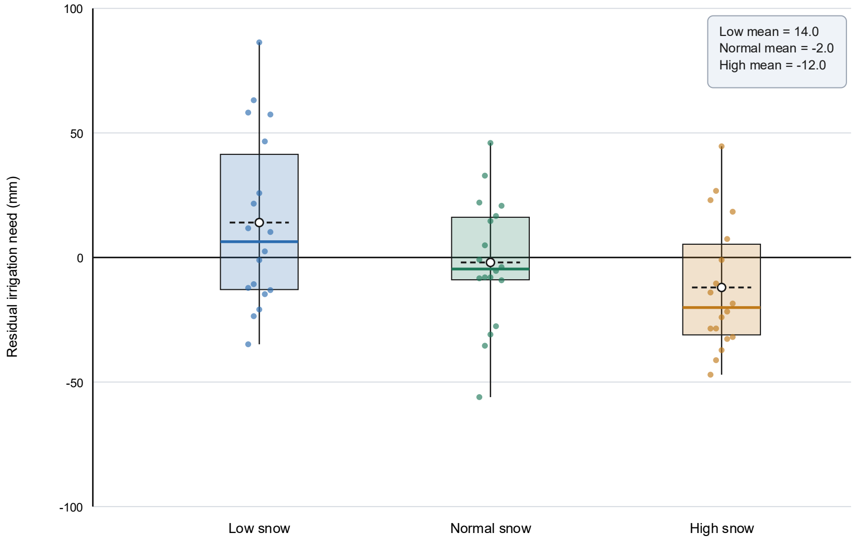

Figure 5. Distribution of rainfall adjusted residual irrigation requirement across low-snow, normal-snow, and high-snow years

The class based analysis confirms the regression based interpretation. Harvest years were grouped into low-snow, normal-snow, and high-snow classes using the lower and upper tertiles of seasonal snow water input, with thresholds of ≤45.6 mm, 45.6–112.7 mm, and >112.7 mm, respectively. Mean AIR was 371.3 mm in low-snow years, 316.7 mm in normal-snow years, and 281.3 mm in high-snow years. Thus, the difference between low-snow and high-snow seasons approached 90 mm of seasonal irrigation requirement. This is not a trivial contrast for a winter wheat system in a semi-arid environment; rather, it indicates a substantial shift in seasonal water demand across snow classes. The same ordering was preserved after rainfall adjustment. Mean residual irrigation requirement was +14.0 mm in low-snow years, -2.0 mm in normal-snow years, and -12.0 mm in high-snow years (Figure 5). Therefore, low-snow years tended to require more irrigation than expected from rainfall alone, while high-snow years tended to require less. This result is particularly useful because it translates the regression signal into a more intuitive agronomic pattern. It shows that the snow effect was not confined to a statistical slope in scatter space; it was also visible when the record was separated into distinct hydroclimatic classes.

Taken together, Figures 3–5 indicate that seasonal snow was negatively associated with irrigation pressure in the Niğde winter wheat system, such that years with weaker snow conditions tended to experience higher irrigation pressure than would be expected from rainfall alone. In the present case, the snow signal appears to reflect not only the amount of cold season water input, but also the broader winter hydroclimatic environment within which irrigation demand develops. This interpretation is consistent with the broader concern that winter wheat systems are increasingly exposed to compound hydroclimatic stress under warming conditions (Kaya, 2021; Chen et al., 2026).

This interpretation also fits the regional context of Central Anatolia. Previous work has shown that supplementary irrigation is essential for winter wheat under semi-arid Turkish conditions and that model based assessments of wheat water use are highly sensitive to the climatic inputs used to characterize seasonal conditions (Kale and Madenoğlu, 2018). At basin scale, Niğde is located within a drought-prone sector of the Konya Closed Basin, where recurrent dry periods and ongoing climatic variability increase the importance of seasonal hydroclimatic controls (Sarış and Gedik, 2021; Koycegız and Büyükyıldız, 2020). Within this framework, the present findings suggest that snow should be viewed not merely as a winter climatic descriptor, but as a relevant indicator of the hydroclimatic setting under which winter wheat irrigation demand develops.

Nevertheless, the present station-scale design does not allow the observed snow variability to be attributed specifically to regional climate change or local Urban Heat Island effects. Such attribution would require homogenized station metadata, information on changes in the surrounding land cover, urban-rural station comparisons, and/or remotely sensed snow-cover observations. Therefore, climate warming and urbanization should be considered plausible contextual influences rather than directly tested causal mechanisms in the present study.

CONCLUSION

This study demonstrated that seasonal snow conditions were significantly associated with winter wheat irrigation requirement in Niğde. After the effect of effective rainfall had been removed statistically, both seasonal snow water input and seasonal snow water equivalent retained explanatory value, indicating that snow contributed hydroclimatic information beyond rainfall alone. The contrast between low-snow and high-snow years supported the interpretation of snow as a relevant hydroclimatic indicator within the Niğde winter wheat system. In practical terms, snow observations should not be treated only as background winter climate indicators in semi-arid wheat environments. They may provide useful additional information for irrigation-risk assessment, particularly in drought-prone and groundwater-stressed parts of Central Anatolia. At the same time, the present analysis should be interpreted as a station scale hydroclimatic assessment rather than as a full catchment scale water-balance analysis, because CROPWAT does not explicitly simulate snow accumulation and melt processes. Future research may strengthen this framework by incorporating streamflow, soil moisture, groundwater, or yield records in order to clarify more explicitly how the snow signal propagates through the broader agro-hydrological system. Future studies should also combine station metadata, urban–rural reference observations, and spatial snow products to distinguish the effects of regional climate change from potential local urbanization influences.

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