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The climate-agriculture nexus. The water footprint of maize production (Northern Bulgaria as a case study)

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Abstract

The water footprint of maize production serves as a comprehensive indicator, encompassing both direct water use for crop yields and indirect water use, including virtual water trade. This indicator provides insight into the total water required throughout the production process, making it essential for understanding water sustainability in agriculture. The main objective of this research is to expand the understanding of how climate variability affects agricultural practices, focusing on promoting sustainable water use in crop production. Specifically, the study emphasizes the assessment and analysis of both green water (rainfall) and blue water (irrigation water) used in maize cultivation in Northern Bulgaria.

The study draws upon several key data sources, including climatic information (such as air temperature, and precipitation) and agricultural and statistical data from local authorities and farmers (covering crop parameters, yields, and irrigation practices). The water footprint for maize cultivation was calculated and assessed using Cropwat software. This analysis determines the irrigation needs across different crop management strategies. The investigated period was 1961-2022, with a specific focus on the water footprints during the extremely dry and wet years. The findings highlight critical areas of water usage and scarcity. Understanding the water footprint and its connection to climate and agriculture can aid in managing water resources and addressing the environmental and economic challenges associated with water scarcity and drought.

Keywords: *water footprint, evapotranspiration, North Bulgaria, dry years, wet years*

Introduction

Agriculture is one of the sectors most vulnerable to climate change and extreme hydrometeorological events. It is affected differently by extreme climatic and weather events depending on regional climatic conditions and the economic development of specific areas. Due to the spatial variability of climate elements, the analysis of the climate-agriculture relationship must be conducted by considering the local characteristics of the particular regions. Climate change can have direct (increased heat stress for farm animals; increased risk of greater damage to certain crops, reduced yields) and indirect (increased pest activity and wider spread of diseases; increased soil erosion, changes in soil fertility) impacts on agriculture (Li et al., 2023; Chaudhry & Sidhu, 2022; Neupane et al., 2022; Hatfield et al., 2020). Maize is among the crops that require significant irrigation. Precipitation and temperatures in Bulgaria during the recent years have risen above the norm (Kazandjiev et al., 2010; Kazandjiev & Georgieva, 2021) but in dry years, irrigation during the growing season is very important for the crops.

According to climate models, an increase in droughts and prolonged dry periods combined with high temperatures is expected in many regions of the world and Europe including Bulgaria (Dai, 2013; Trnka et al., 2011; Trnka et al., 2015). Based on climate model simulations under a pessimistic scenario (of significant warming), it is estimated that climate change could reduce global crop yields by 3–12% by 2050 and 11–25% by 2100 (Wing et al., 2021). Climate change significantly impacts agriculture in Bulgaria, as shifts in temperatures and precipitation levels present new challenges for farmers. Recent studies show that Bulgaria is experiencing an increase in average annual temperatures and uneven precipitation distribution, leading to longer drought periods in the summer and more intense rainfall in the fall and spring (Kazandjiev & Georgieva, 2021). This highlights the need for deeper research on water consumption across various sectors, including agriculture.

In the European Union (EU), the share of water consumed by agriculture has significantly increased over the past 30 years, representing approximately 50% of the EU's total annual water consumption (Zhang et al., 2022). As one of the major global agricultural producers, the EU is highly vulnerable to fluctuations in water availability. Crop production accounts for 99% of the direct water usage in agriculture (Gerveni et al., 2020).

The interconnectedness of the water, energy, and food sectors lies at the heart of the Water–Food–Energy Nexus concept, which aims to explore and assess the synergies and trade-offs among these resources to promote sustainable development (Albrecht et al., 2018). The nexus climate–-agriculture quantitatively analyses the interactions, trade-offs, benefits, and drawbacks that arise in water resource management, food production, and the impact of climate change, while also considering environmental effects, economic factors, and population growth (Golfam et al., 2021). This concept plays an important role in the process of climate adaptation and mitigation of the negative impact on agriculture. As a result, in recent years, the interest in researching the climate-agriculture nexus has been increasing (Chandio et al., 2024; Shahzad et al., 2021).

The water footprint is an indicator of freshwater use that looks not only at the direct water use of a consumer, the full chain of a production process, or just a production step of a final product (such as primary agricultural crop yields), but also at the indirect water use and virtual water trade (Hoekstra et al., 2009). The estimated global consumptive water footprint, including both green and blue water, ranges between 5,938 and 8,508 km^3 per year. By 2090, this water footprint is projected to increase by up to 22% due to the impacts of climate change and land use changes (Mekonnen & Gerbens-Leenes, 2020). The concept of water footprint was introduced and developed by Hoekstra and Hung (2002) and Chapagain and Hoekstra (2003), Chenoweth et al. (2014).

The water footprint of agricultural production represents the volume of water used by crops during the growing season (Hoekstra & Chapagain, 2007, 2008). Despite the growing number of publications on the water footprint of crops (Mialyk et al., 2024; Xiao et al., 2022; Wang et al., 2023; Mekonnen & Hoekstra, 2020; Mekonnen & Gerbens-Leenes, 2020; Gobin et al., 2017; Lovarelli et al., 2016) this significant problem has not yet been thoroughly studied for Bulgaria. There are only a few publications that provide information on the water footprint in Bulgaria (Hoekstra & Hung, 2002; Chapagain & Hoekstra, 2003; Hoekstra & Mekonnen, 2012, Schyns & Vanham, 2019). The current study aims to assess the green and blue water footprint of maize production in Northern Bulgaria in the context of air temperature and precipitation variability. Cereal production plays a crucial role in Bulgaria's economy, and analysing the water footprint of this sector can contribute to the advancement of sustainable farming methods.

To achieve the objective of the study, the following key tasks were addressed:

- Analysis of maize grain production in the context of climate change; assessment of the impact of extreme temperatures, precipitation, and droughts.
- Calculation of green and blue evapotranspiration under two scenarios: rainfed and irrigation at critical water depletion, and identification of regional characteristics regarding water use and water scarcity in maize production.

The results of this study can significantly contribute to the overall understanding of the impact of climate change on agriculture. They will provide valuable data that can be used to develop effective strategies for sustainable water resource management in agricultural areas. This includes optimizing irrigation systems, adapting farming practices to changing climate conditions, and planning water supply infrastructures to meet future needs. The results can assist farmers in overcoming the challenges associated with climate change and promoting the sustainable development of the sector.

Study area, data and methods

The study focuses on a specific region in Northern Bulgaria (Fig. 1), where maize production plays a crucial role in the agricultural sector. The region was selected due to its vulnerability to climate variability, particularly in terms of air temperature and precipitation changes. The water footprint of maize production can be influenced by various factors such as climate, soil type, irrigation practices, and crop management techniques.

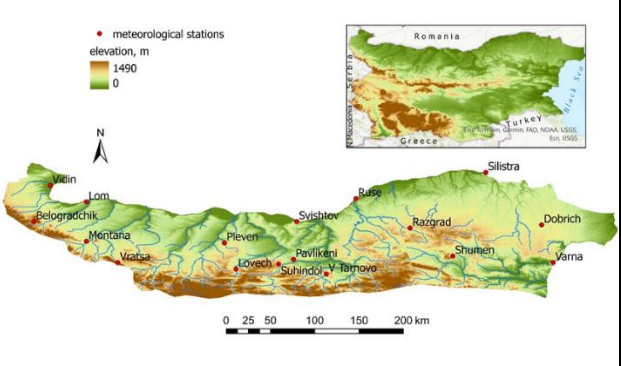

Figure 1: Study area and location of meteorological stations used in the research

The quantity and quality of water resources are critical factors for agricultural production, especially in regions where water availability may limit yields. In the context of increasingly frequent climate extremes, the study focuses on two key components of the water balance in agriculture – green water (rainwater) and blue water (for irrigation), to assess their role and efficiency in maize production in one of Bulgaria's main agricultural regions – the Danube Plain.

For calculating the blue and green evapotranspiration needed to determine the water footprint, monthly data on minimum and maximum air temperatures and precipitation from 17 meteorological stations located in Northern Bulgaria were used (Table 1). The study utilized data from the meteorological yearbooks and bulletins of the National Institute of Meteorology and Hydrology (NIMH), combined with information sourced from Climate-Data.org, based on the European Centre for

Medium-Range Weather Forecasts (ECMWF) data with a resolution of 0.1-0.25 degrees. Additionally, data on maize production of the planning regions in Northern Bulgaria, published by the "Agrostatistics" department of the Ministry of Agriculture and Food for the period 2001–2020, were used to calculate the water footprint.

Table 1: Meteorological stations used for calculating the water footprint

Meteorological station	Latitude (N)	Longitude (E)	Altitude (m)
Vidin	43° 59'	22° 51'	31
Belogradchik	43° 37'	22° 41'	544
Lom	43° 49'	23° 13'	32
Montana	43° 25'	23° 13'	270
Vratsa	43° 12'	23° 32'	309
Pleven	43° 24'	24° 37'	160
Svishtov	43° 37'	25° 21'	24
Lovech	43° 08'	24° 44'	220
Pavlikeni	43° 14'	25° 19'	126
Suhindol	43° 11'	25° 10'	233
Veliko Tarnovo	43° 05'	25° 39'	195
Russe	43° 51'	25° 57'	37
Silistra	44° 07'	27° 16'	15
Razgrad	43° 33'	26° 30'	346
Shumen	43° 16'	26° 56'	218
Dobrich	43° 35'	27° 50'	212
Varna	43° 14'	28° 01'	11

For the current analysis, the blue and green water footprints were calculated using two options from the CROPWAT model: crop water requirements (CWR) and an irrigation schedule (Fig. 2). The CWR option assesses the total water needs of the crop based on climatic conditions and the biological requirements of the plants. This approach determines the necessary amounts of blue water (from surface and groundwater sources) and green water (from precipitation) required for the normal growth of the crop and increased yields.

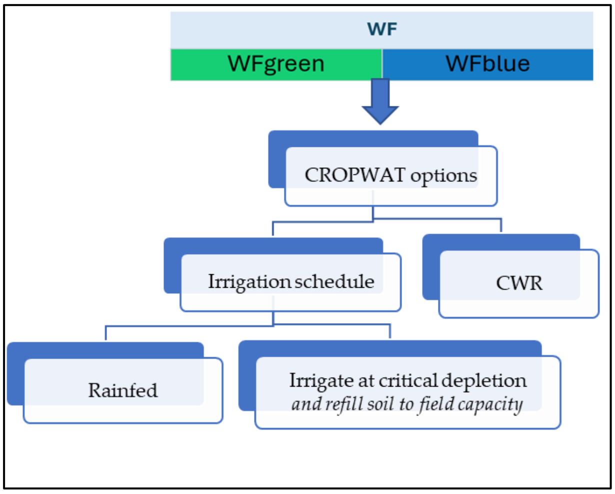

Figure 2: Diagram of the Model Used for Calculating the Water Footprint

The "irrigation schedule" option includes two specific scenarios for managing water resources. The first scenario, “rainfed”, assesses the water footprint when the crop primarily relies on natural precipitation. In this case, green water consumption is the main source of water for maize, minimizing the use of blue water, but it may lead to lower yields in dry years. The second scenario, “irrigation at critical depletion”, involves supplementary irrigation when soil moisture reaches critically low levels. Irrigation at critical depletion means that the readily available water (RAW) or the water that a crop can extract from the root zone without suffering from water stress is completely exhausted.

The "irrigate at critical depletion" option and "refill soil to field capacity" suggest optimal irrigation, where irrigation intervals are maximized while avoiding any stress for the crops (Hoekstra & Mekonnen, 2012). This approach optimizes the water balance and maintains high yield levels while increasing reliance on blue water. Employing this scenario results in a higher blue water footprint but ensures yield stability even in years with insufficient precipitation.

In this study, green and blue water were calculated according to Hoekstra et al. (2011) and expressed as m^3/ton, which is equivalent to l/kg. The total water footprint of the cultivation process for a given agricultural crop, in this case, maize (WF_proc), is calculated as the sum of the green (WF_proc, green), blue (WF_proc, blue), and grey (WF_proc, grey) components.

$$WFproc = WFproc,gren + WFproc,blue + WFproc,grey\ [volume/mass]$$

The green component of the water footprint for the technological water used in crop cultivation (*WFproc, green*, m^3/ton) is calculated by dividing the green component of Crop Water Use (CWU) for the crops (CWU_green, m^3/ha) by the crop yield (*Y*, t/ha). Likewise, the blue component (*WFproc, blue*, m^3/ton) is determined using the same approach.

$$WFproc, green = \frac{CWUgreen}{Y}\ [\mathrm{m^3/ton}]$$

$$WFproc, blue = \frac{CWUblue}{Y}\ [\mathrm{m^3/ton}]$$

The green component (*ET green*) refers to the rainwater absorbed by the soil, which is then either evaporated or transpired by the plants. This includes the water that plants extract directly from the soil and is a result of natural precipitation. Green evapotranspiration is crucial for assessing the efficiency of using natural water resources. The blue component (*ET blue*) includes the water used from irrigation systems, which is artificially added to the fields through irrigation. This water comes from rivers, lakes, reservoirs, or groundwater. Blue evapotranspiration is important for assessing dependence on external water sources and for managing water resources for agricultural needs.

The green and blue components of water use for crops (*CWU*, m^3/ha) are calculated by summing daily evapotranspiration (*ET*, mm/day) over the entire growing period of the crop.

$$CWUgreen = 10 * \sum_{d=1}^{lgp} ETgreen$$

$$CWUgreen = 10 * \sum_{d=1}^{lgp} ETgreen$$

Results and Discussion

Climate peculiarities and drouth impact on maize yields

The analysis of climate data from the selected stations in the study area for the period 1961–2020 reveals significant changes in climate indicators. The data clearly show an increase in temperature levels during the period 1991–2020 compared to 1961–1990.

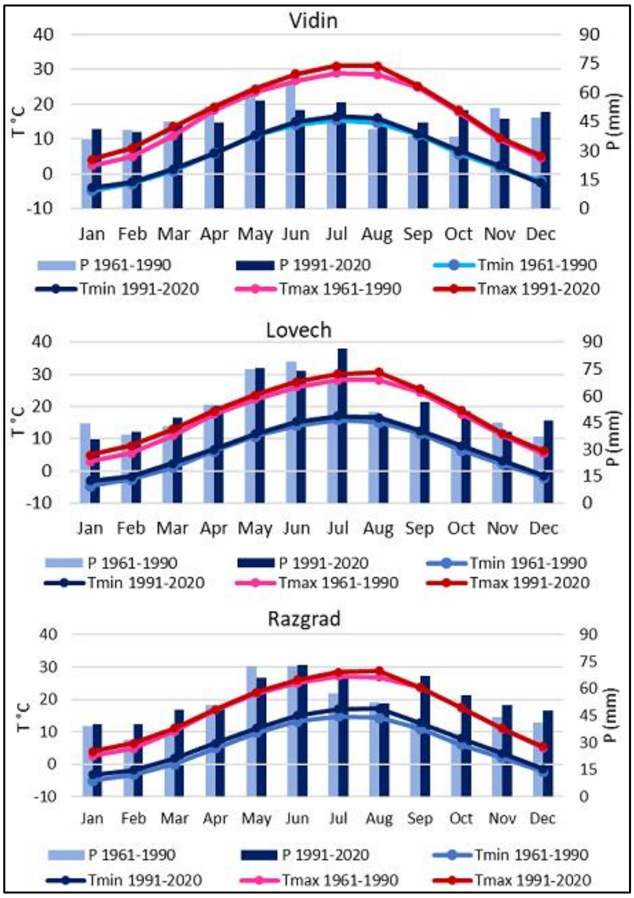

Figure 3: Climate charts of the selected stations from Northern Bulgaria

The most significant rise was observed in maximum temperatures during the summer months, indicating stronger warming during the warmer periods of the year. Additionally, there was an increase in precipitation during the autumn months (Fig. 3), which may lead to changes in seasonal patterns of water supply and soil moisture. Higher temperatures could increase evaporation, while changes in precipitation may result in uneven distribution of water resources throughout the year.

The increased temperatures and altered precipitation patterns could affect agricultural practices, necessitating crop and irrigation method adaptation. The shifts in climate conditions highlight the need for updates to climate and water policies to address new challenges and minimize negative impacts on the environment and society.

The average maize yields in Northern Bulgaria for the period 2001-2021 show significant fluctuations related to climatic conditions. During the dry years of 2001, 2003, 2007, 2012, and 2020 yields dropped sharply, while in the wet years of 2010, 2014, and 2018, significantly higher yields were observed (Fig. 4). The years 2012 and 2007 were the driest in Bulgaria. Because of that, we present more detailed information about these years. An analysis of seasonal precipitation found that in both dry years (2007 and 2012), there were three seasons with negative precipitation anomalies (Matev et al., 2023).

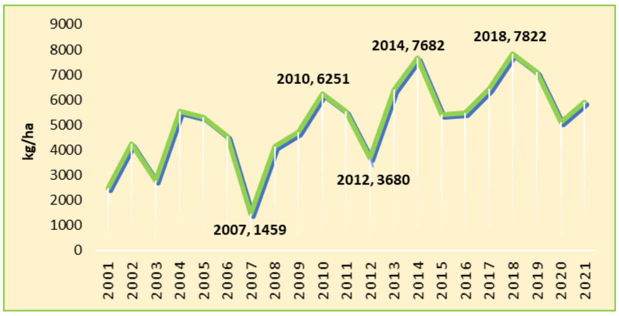

Figure 4: Average maize yields in Bulgaria

In 2007, precipitation during spring and summer was slightly below the climatic average, while in 2012, summer rainfall amounted to only 53% of the norm. Rainfall in March, April, June, and July was below the long-term average. In April 2007, monthly precipitation dropped to just 8% of the norm. Although May registered increased rainfall in both years (2007 and 2012), it was not enough to ensure favourable agricultural outcomes as a consequence of the drier conditions from March and April in March and April, followed by even drier periods in June and July. Temperature patterns also had an impact, with 2012 experiencing one of the hottest summers on record in Bulgaria, while June and July 2007 were marked by extreme heat and prolonged heatwaves (Matev et al., 2023).

In years with higher average yields (e.g., 2010 and 2014), precipitation during spring and summer was above the norm. In March, April, and July of 2014, the monthly normal were exceeded by two to three times. In 2014, the annual air temperature for areas at altitudes up to 800 m was, on average, 1.2°C above the normal, but no prolonged extremely hot periods were observed (Matev et al., 2023). Under wet conditions, temperatures do not have as significant an impact as they do during dry years. The climate in Northern Bulgaria, characterized by hot summers and variable precipitation, strongly influences the water footprint of maize. In dry years, the demand for irrigation increases, leading to greater use of blue water and, consequently, a higher water footprint. This not only raises irrigation costs but also places additional strain on the region's water resources.

Evapotranspiration determined through the Crop Water Requirement (CWR) option

The results of calculating *ETgreen* and *ETblue* for average 30-year periods show no significant difference between the values for 1961–1990 and 1991–2020 (Table 2). However, higher values of green evapotranspiration are noted for the Lovech station. This is mainly due to the higher monthly and annual precipitation levels observed at this location, which are influenced by the geographical position of the station at the northern foothills of the Pre-Balkan Mountain which determines the orographic lifting of moist air masses. The results indicate that local geographical factors, such as those in the Lovech area, can significantly impact the dynamics of the green component of the water footprint. This underscores the importance of accounting for regional geographical differences when assessing water resource management and land use planning.

Table 2: Green (ETgreen) and blue (ETblue) evapotranspiration for 1961–1990 и 1991–2020 г. (mm/dec)

Meteorological station	**1961-1990**		**1991-2020**		1961-1990	1991-2020
	ETgreen	**ETblue**	**ETgreen**	**ETblue**	**Total (ETgreen+ETblue)**	
Vidin	212.5	392.4	215	425.7	604.9	640.7
Lovech	252.7	337.9	264.5	356.1	590.6	620.6
Razgrad	241.9	330.9	253.8	337.9	572.8	591.7
Varna	165.3	335.4	188.1	336.2	500.7	524.3

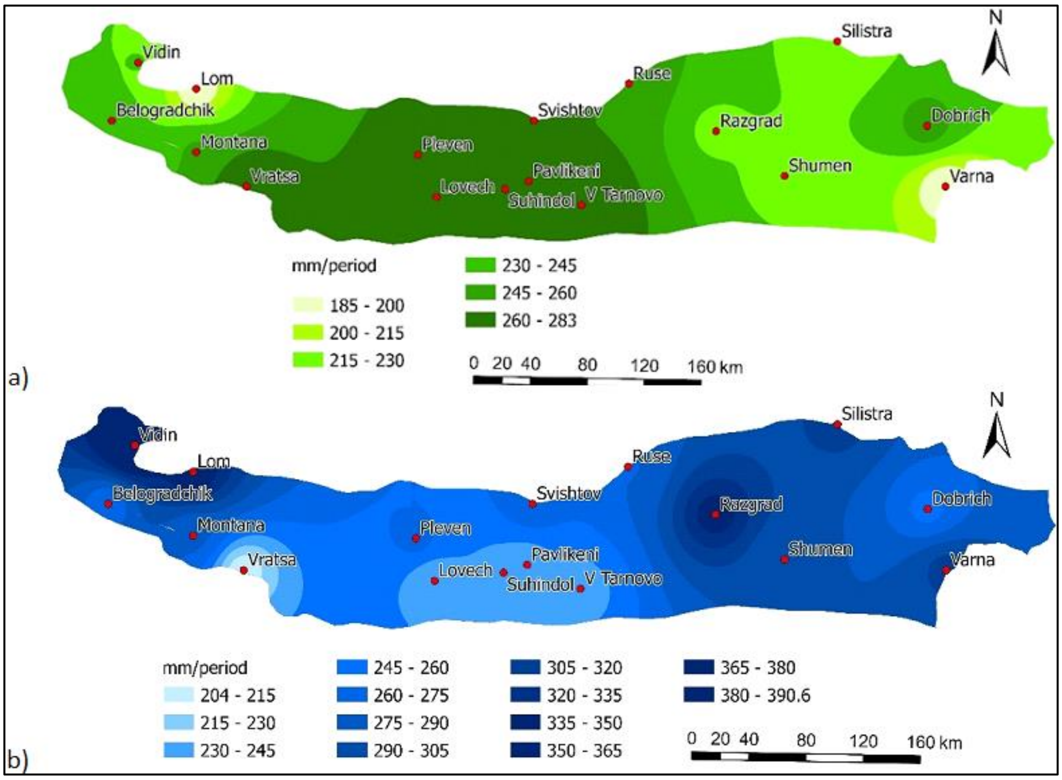

Figure 5: Average annual values of green evapotranspiration (a) and blue evapotranspiration (b) for the period 1961-2021

The ratio between green and blue evapotranspiration over the two 30-year periods remains nearly unchanged, with a larger share of blue evapotranspiration. This indicates that the contribution of water sources such as surface and groundwater (blue evapotranspiration) to the total evapotranspiration is significantly higher than that of rainfall (green evapotranspiration) during both periods.

The analysis of the spatial distribution of green evapotranspiration for 1961–2021 reveals significant regional differences. The highest values are recorded in the central parts of the Danube Plain and the Fore-Balkan, where green evapotranspiration reaches 260–280 mm annually on average (Fig. 5a). These regions are characterized by more favourable conditions for soil moisture availability, resulting from higher rainfall. The lowest values are observed in the eastern parts of the studied area, particularly along the Black Sea coast, as well as in the northwestern region around Vidin and Lom. These areas experience the lowest rainfall totals during the studied period.

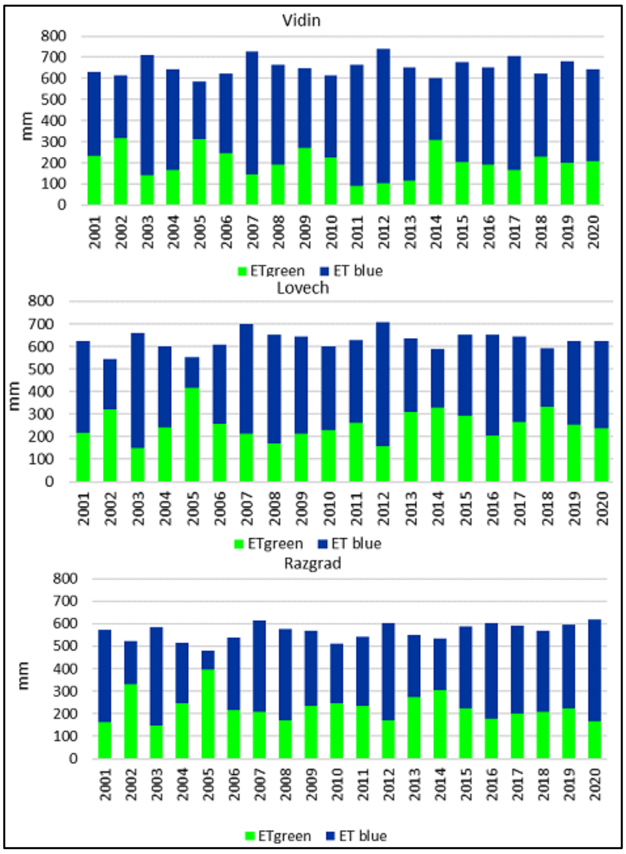

Figure 6: Temporal distribution of green (ETgreen) and blue (ETblue) evapotranspiration

Overall, the distribution of blue evapotranspiration shows an inverse trend compared to green evapotranspiration. The highest values of blue evapotranspiration are recorded in areas with the lowest values of green evapotranspiration, such as Vidin and the eastern part of the Danube Plain, where the annual averages for the period 1961–2021 reach 380–390 mm. At the same time, in the central parts of the Danube Plain, where green evapotranspiration is higher, blue evapotranspiration is significantly lower, with values ranging between 200 and 245 mm annually (Fig. 5b).

The temporal distribution of evapotranspiration shows an established pattern—higher values of blue evapotranspiration during dry years (2003, 2007, 2012, 2016), as illustrated in Figure 6. The years are also characterized by increased overall evapotranspiration levels.

On the other hand, green evapotranspiration registered the lowest values. In addition to precipitation, temperature levels also contribute to changes in evapotranspiration. Generally, dry years are characterized by some of the highest air temperatures, further amplifying the negative effects of drought, increasing evapotranspiration, and raising the need for additional irrigation.

Evapotranspiration and water footprint determined through the "irrigation schedule" option – rain-fed scenario

In the rain-fed scenario, *ETgreen* is equal to total evaporation, while *ETblue* is 0 (Hoekstra et al., 2011), reflecting the actual water consumption by the crop. The analysis of the results for the two 30-year periods shows that *ETgreen* typically ranges between 413 and 529 mm/decade. The values for the period 1991–2020 are slightly higher in comparison to those for 1961–1990, except for the Vidin station located in the northwestern part of the study area (Fig. 7). When comparing the dry year of 2012 with the rainy year of 2014, a clear difference emerges: the values of green evapotranspiration are significantly higher during the rainy year. Conversely, the water footprint in the dry year is greater due to the reduced crop yields (Fig. 8).

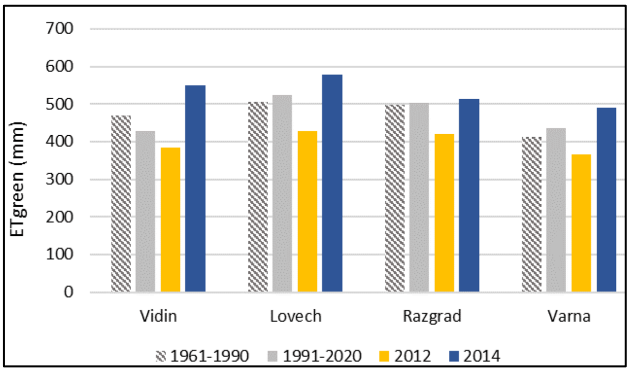

Figure 7: Green evapotranspiration (ETgreen) calculated based on the rain-fed irrigation scenario

Regional differences are prominently observed during the dry year, highlighting the significant impact of local climatic conditions on evapotranspiration. This includes higher temperatures and lower rainfall, which increase the need for additional irrigation and elevate the water footprint of agricultural production.

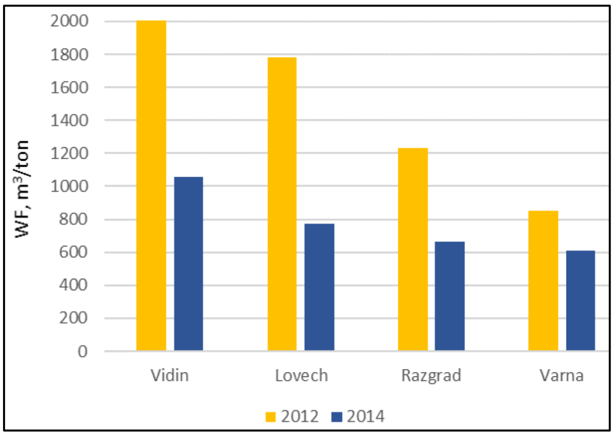

Figure 8: Water footprint (WF) calculated using the irrigation schedule scenario: rain-fed

Evapotranspiration and water footprint determined through the irrigation schedule option – irrigating at critical depletion and refilling the soil to field capacity

Table 3 provides information on the water footprints (*WF*) for the dry year (2012) and the wet year (2014), calculated using two different options: "crop water requirement" (*CWR*) and "irrigation schedule" – irrigating at critical depletion and refilling the soil to field capacity. The blue water footprint) (*WFblue*) shows significantly high values for the dry year, 2012, especially for the CWR option. This is attributed to the increased need for irrigation to compensate for the lack of natural rainfall. Since, with irrigation, the water either infiltrates into groundwater or drains through surface runoff, the actual volume of irrigation applied during the maize growing season exceeds the blue water evaporation.

Table 3: Evapotranspiration (ET) and water footprint (WF) calculated under different scenarios of the CROPWAT model

	CROPWAT option	ETgreen	ETblue	Y	WFgreen	WFblue	WFgreen+ blue
		mm / growing period		ton/ha	m³/ton		
2012							
Vidin	CWR	105	636	1.9	555	3345	3899.5
Lovech		159	551	2.4	662	2295	2956.3
Razgrad		172	431	3.4	506	1268	1773.8
Vidin	Irrigation schedule	309	430	1.9	1627	2263	3889.5
Lovech		195	513	2.4	813	2136	2948.3
Razgrad		278	323	3.4	818	951	1769.4
2014							
Vidin	CWR	310	290	5.5	564	527	1090.7
Lovech		330	261	7.5	439	348	786.9
Razgrad		304	230	7.7	394	298	692.5
Vidin	Irrigation schedule	436	162	5.2	839	312	1150.8
Lovech		424	165	7.5	566	219	785.3
Razgrad		370	163	7.7	480	211	690.9

The overall water footprint for both models (CWR and the "Irrigation Schedule" options) is nearly identical. However, for the dry year, the water footprint is slightly lower in the "Irrigation Schedule" option. This suggests that optimizing irrigation can lead to more efficient use of water resources, even in drought conditions. The findings of this analysis highlight the importance of effective water resource management through appropriate irrigation schedules, particularly in years with varying climatic conditions.

Conclusions

Maize cultivation involves a significant water footprint, encompassing both green and blue water usage. In Bulgaria, where maize is predominantly rainfed, green water accounts for the majority of water consumption in maize cultivation. However, irrigation practices, particularly in regions experiencing water stress, contribute to blue water usage and associated challenges.

The variability in the WF of growing crops is mainly due to variability in crop yield while crop water use has a lower impact. During the dry years, irrigation is very important to provide optimal conditions for crops.

Tillage, crop rotation, and efficient irrigation techniques can optimize water usage while improving soil health and resilience. Moreover, leveraging precision agriculture technologies, including soil moisture sensors and remote sensing, enables farmers to make informed decisions and minimize water waste.

Efficient irrigation systems, such as drip irrigation, along with the implementation of water-saving technologies, can optimize water use and reduce the water footprint of corn compared to traditional surface irrigation methods, thereby helping to decrease overall water consumption. Agricultural management practices and crop cultivation techniques, such as no-till farming and optimizing planting dates, can also impact the water footprint by improving soil moisture retention and reducing evaporation losses. Integrating these practices with effective water management can contribute to lowering the total water footprint of maize production in Northern Bulgaria. Employing various water resource management strategies is essential for understanding the influence of climatic conditions on the water footprint of corn and for making informed decisions regarding sustainable agriculture.

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Author contribution

Conceptualization, N.N. and N.H.; methodology, N.N.; formal analysis, N.N. and N.H.; investigation, N.N.; writing—original draft preparation, N.N.; writing—review and editing, N.N., N.H. and S.M. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

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