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Original Research Article

Changing Water Footprint of Banana Production According to Annual Climate Variability: Implications for Sustainable Management

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ABSTRACT

Water footprint assessments of tropical export crops typically rely on long-term climatic averages, overlooking how interannual climate variability reshapes the balance between green and blue water use and limiting their reliability in regions governed by El Niño and La Niña phases. This study hypothesised that such variability modifies the green- and blue-water components by shifting the balance between rainfall and irrigation. It was tested for banana production in southern Guatemala using 402 farm-year observations across three production zones during 2018–2023, assessing green, blue and grey components across contrasting phases. The total water footprint ranged from 246 to 435 m³/t and differed significantly among zones, while the green contribution increased during wetter phases, and theoretical irrigation requirements increased by 25–30% during drier phases. Water footprint composition is therefore climate-phase dependent rather than stationary, making the integration of climate variability essential for reliable benchmarking.

KEYWORDS

Water footprint, Banana production, Climate variability, El Niño, La Niña, Irrigation management, Rainfall.

INTRODUCTION

Banana production is a major agricultural activity worldwide, with global exports reaching approximately 19.3 million tonnes in 2023 [1]. In the same year, Guatemala consolidated its position as the second-largest banana exporter in Latin America and the Caribbean and the leading supplier to the United States market [1]. Regional analyses have also documented the economic importance of banana exports in Ecuador during 2015–2019 [2]. In Guatemala, the banana industry generated USD 1.99 billion in export revenues [3] and supported approximately 180,000 direct and indirect jobs [4].

For many agricultural systems, effective water resource management has become a key criterion for accessing international markets and obtaining environmental certifications [5], and the water footprint provides an objective, widely used approach for assessing water use and supporting sustainability-oriented decision-making [6]. The global average water footprint of banana cultivation has been estimated at approximately 790 m³/t [7]. More recent global

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modelling covering the period 1990–2019 confirms that this value remains representative of long-term average conditions for tropical fruit crops [8].

Regional studies, however, reveal substantial variability driven by differences in climatic conditions, yield levels, and water management practices. Bulsink *et al.* [9] reported a value of 875 m³/t for Indonesia, associated with high evapotranspiration rates under humid tropical conditions. Pahlow *et al.* [10] estimated 748 m³/t for South Africa, reflecting greater dependence on irrigation under semi-arid conditions. In Latin America, Oliveira *et al.* [11] reported values of up to 1,207 m³/t in the Brazilian semi-arid region, attributable to low yields and high evapotranspiration. Zárate and Kuiper [12] estimated 449 m³/t for small producers in Peru under more favourable rainfall regimes. In Central America, Bolaños [13] estimated 395 m³/t for Honduras under lower-yield conditions. More recently, Gavilánez Luna and Rodríguez Jarama reported a total water footprint of 351 m³/t for banana production in Guayas, Ecuador, based on farm-level data and a nearly balanced green–blue composition under a humid coastal regime [14]. Despite being a major banana exporter, Guatemala currently lacks publicly available farm-level assessments of the water footprint of banana production, limiting comparisons with other producing regions.

Though progress is noted, critical knowledge gaps remain. Most existing studies rely on aggregated or modelled climatic data at national or regional resolution, without incorporating farm-level variability across spatially differentiated production zones. The water footprint framework established by Hoekstra *et al.* [7] provides the methodological basis for such assessments, yet its application using farm-level data across spatially differentiated zones remains limited [6]. Furthermore, the partitioning between green and blue water components depends directly on rainfall, evapotranspiration, and irrigation requirements, all of which are highly sensitive to interannual climate fluctuations. Yet, this dynamic has not been explicitly incorporated into water footprint assessments of banana production. Consistent with this, a recent meta-analysis by Mbewu *et al.* found that increasing rainfall and temperature tend to raise the green water footprint while lowering the blue and grey components across crops, confirming the climate sensitivity of water footprint composition; however, such syntheses have focused on long-term climate change signals rather than on interannual variability [15].

The El Niño-Southern Oscillation (ENSO) is the dominant driver of interannual climate variability in tropical regions, significantly influencing precipitation patterns and water availability [16]. El Niño phases are typically associated with reduced rainfall and increased irrigation demand, as documented by Argueta Mayorga *et al.* [17] for Guatemala's Pacific Slope. La Niña conditions, in contrast, result in above-average precipitation and a greater green water contribution, consistent with Bardales-Espinoza *et al.* [18] description of the regional patterns. Comparable evidence from other Latin American systems reinforces this link, as Novoa *et al.* [19] found that drought episodes driven by interannual climate variability substantially reshaped the agricultural water footprint in northern Mexico, increasing reliance on blue water. These contrasting conditions directly affect the composition of the water footprint by altering the balance between rainfall and irrigation water use. This gap is particularly relevant in Guatemala, where no farm-level assessments have evaluated the water footprint under contrasting ENSO conditions, and where estimates based on long-term averages may systematically misrepresent actual water use, limiting their applicability for water management, benchmarking, and policy development.

Recent scholarship has moved water-footprint assessment towards temporally resolved and spatially explicit analysis. Monthly gridded estimates of blue and green water footprints and climatic-zone benchmarks have demonstrated the importance of resolving seasonal and spatial heterogeneity rather than relying solely on long-term averages [20]. Coupled hydrological and crop models have also been used to quantify annual variations in agricultural water availability and demand under changing climate [21]. Furthermore, spatiotemporal assessments show that crop water-use efficiency reflects interacting climatic, irrigation, and management drivers across space and time [22]. These advances demonstrate the value of dynamic assessment, but

they remain based on gridded, basin, or regional modelling and do not resolve farm-level responses to discrete ENSO phases in a perennial tropical export crop. The present study addresses that methodological gap by combining multiyear farm observations, spatially differentiated production zones, and phase-specific climate analysis.

Recent climatic events further highlight the urgency of incorporating interannual variability into water footprint assessments. The triple-dip La Niña event of 2020–2022, one of the longest on record, brought sustained above-average rainfall across Central America over three consecutive years [16]. It was followed by a strong El Niño in 2023–2024, which reversed these conditions and generated widespread drought and reduced water availability across the region [23]. This sequence of contrasting climatic phases provides a uniquely informative context for evaluating how ENSO variability shapes the composition of the water footprint in banana production systems.

Accordingly, the scientific problem addressed in this study is whether the composition of the water footprint can be considered stationary when recurring climate phases alter the balance between rainfall and irrigation. We hypothesise that ENSO-driven interannual variability systematically modifies the relative contributions of green and blue water, thereby reducing the reliability of benchmarks based exclusively on long-term climatic averages. This hypothesis was tested using banana production in southern Guatemala as an empirical case, based on 402 farm-year observations from three production zones during 2018–2023. The contribution, therefore, extends beyond establishing local reference values: it provides evidence for a broader class of ENSO-affected tropical cropping systems in which climate phase, spatial heterogeneity, and farm management jointly determine the composition of the water footprint.

METHODS

The analytical design was structured to test whether water footprint composition remains stationary under contrasting interannual climate conditions. It comprised four steps: (i) quantification of green, blue, and grey water footprints at the farm-year level; (ii) classification of reference years according to ENSO phase; (iii) characterisation of green water use and theoretical irrigation requirements under contrasting climatic phases; and (iv) evaluation of spatial, temporal, and farm-level differences in water footprint components. This sequence separates the general analytical procedure from its application to the case study and allows the approach to be replicated in other perennial cropping systems exposed to recurring climate variability.

The water footprint was assessed following the methodology proposed in 2011 by Hoekstra *et al.* [7], which distinguishes three components: green, blue, and grey water footprints. The green water footprint represents the consumption of rainwater stored in the soil and used by the crop. The blue water footprint refers to the consumption of freshwater abstracted from surface and groundwater sources for irrigation. The grey water footprint quantifies the volume of freshwater required to assimilate pollutant loads to concentrations that comply with local environmental water quality standards.

Green Water Footprint

The green water footprint was estimated by considering two components. The first component corresponds to effective rainfall, defined as the fraction of total precipitation that is available for crop uptake [24]. Monthly effective rainfall was calculated for each meteorological station using the empirical method implemented in CROPWAT.

When monthly rainfall was less than or equal to 250 mm, effective rainfall was estimated using eq. (1):

$$Effective\ rain\ = monthly\ rain\ \times \left(\frac{125 - 0.2\ \times\ monthly\ rain}{125}\right) \quad (1)$$

When monthly rainfall exceeded 250 mm, effective rainfall was calculated using eq. (2):

$$Effective\ rain\ = 125 + 0.1\ \times\ monthly\ rain \quad (2)$$

The second component corresponds to banana crop evapotranspiration during the production period. Reference evapotranspiration (ET_0) was calculated using the FAO Penman-Monteith method based on meteorological data from the stations associated with the production zones [25]. Crop evapotranspiration (ET_c) was then estimated by incorporating crop coefficients and phenological stages proposed by Allen *et al.* [25].

For this study, a crop coefficient (K_c) of 1.25 was adopted, following FAO guidelines for banana cultivation [25] and consistent with the approach of Zárate and Kuiper [12], representing typical water demand during the mid-growth stage under tropical conditions. The green water footprint was calculated by selecting the minimum of the monthly values of banana crop evapotranspiration (ET_c) and effective rainfall.

Blue Water Footprint

To estimate the blue water footprint, annual irrigation data for the period 2018–2023 were used. Irrigation requirements were estimated at the farm level using a theoretical soil-water balance approach that accounts for soil texture, rainfall, evapotranspiration, and the banana crop's phenological stage. The irrigation requirement estimated in this study is a theoretical value derived from the water balance approach and does not necessarily reflect the actual irrigation volumes applied in the field. This assumption was adopted to ensure standardised comparisons among farms and production zones.

Grey Water Footprint

The grey water footprint was estimated using the nitrogen (N) pollutant load from fertiliser application. Following the methodology proposed by FAO-GIZ [26] and the Water Footprint Network framework [7], it was assumed that a fixed fraction of the applied nitrogen leaches into water bodies. The nitrogen pollutant load was therefore calculated as a proportion of the total nitrogen applied.

The grey water footprint was calculated using eq. (3):

$$\text{Grey } WF = \frac{\frac{L}{C_{\max} - C_{\text{nat}}}}{Y} = \frac{\frac{\alpha\ \times\ appl}{C_{\max} - C_{\text{nat}}}}{Y} \quad (3)$$

Where: Grey *WF* is the grey water footprint of banana production [m³/t]; L is the nitrogen pollutant load [kg/ha·year]; C_{max} is the maximum allowable nitrogen concentration in water bodies (0.025 kg/m³) according to Guatemalan environmental regulations [27]; C_{nat} is the natural background concentration of nitrogen, assumed to be 0.00 kg/m³; α is the leaching fraction of applied nitrogen, assumed to be 0.1, following the value proposed by Hoekstra *et al.* [7] and consistent with the approach adopted by Zárate and Kuiper [12]; *appl* is the amount of nitrogen applied as fertiliser [kg/ha·year]; Y is the banana yield [t/ha].

Climate analysis

To evaluate the influence of interannual climate variability on the components of the water footprint, six reference years were selected to represent contrasting phases of the El Niño

Southern Oscillation (ENSO). Two years corresponding to El Niño conditions, two to La Niña conditions, and two neutral years were identified based on historical climate records and widely accepted ENSO classifications [16]. The selected reference years, summarised in Table 1, were used to characterise typical rainfall and evapotranspiration patterns for each phase and to support the interpretation of water-footprint variability across different climatic conditions.

Table 1. Reference years analysed by ENSO phase

ENSO phase	Years analysed
Niña	2010, 2020
Neutral	2014, 2017
Niño	2015, 2023

Once the reference years were defined, a subset of meteorological stations was selected to support the climate analysis (Table 2). The selection criteria included: (i) proximity to each banana production zone, (ii) data availability and continuity for the selected reference years, and (iii) representativeness of local climatic conditions along Guatemala's Pacific Slope. One reference station was assigned to each production zone to ensure consistency in the comparison among zones.

For each selected station, monthly rainfall data were compiled and used to estimate effective rainfall. In addition, monthly banana crop evapotranspiration and green evapotranspiration were calculated for each reference year using meteorological data from the selected stations. These variables were used to characterise the climatic conditions associated with each ENSO phase and to support the interpretation of climate-driven variability in the water footprint of banana production.

Table 2. Meteorological stations selected for ENSO-based climate analysis

Production zone	Weather station	Geographic coordinate	
		Longitude	Latitude
A	Alamo	92° 8' 15.97" W	14° 37' 41.58" N
B	Irlanda	91° 25' 36.36" W	14° 8' 45.46" N
C	San Antonio El Valle	91° 12' 0.75" W	13° 59' 43.70" N

Statistical Analysis

Statistical differences among production years and production zones were evaluated using analysis of variance (ANOVA) for total, blue, green, and grey water footprints at the 0.05 significance level. In the extended green water footprint model, the farm was treated as nested within a production zone to quantify within-zone heterogeneity. ENSO-phase comparisons were interpreted descriptively because only two reference years represented each phase; therefore, no formal inferential tests were applied to differences among climatic phases.

CASE STUDY AREA AND DATA

Southern Guatemala was selected as the empirical case because its banana production systems are exposed to recurrent ENSO-driven rainfall variability and combine rainwater and irrigation water use, providing suitable conditions for testing the proposed hypothesis.

The study area was divided into three banana production zones located along Guatemala's Pacific Slope (Figure 1). Production Zone A includes farms located near the border with Mexico; Production Zone B comprises farms located near the municipality of Tiquisate, Escuintla; and Production Zone C includes farms located near the municipality of La Gomera, Escuintla.

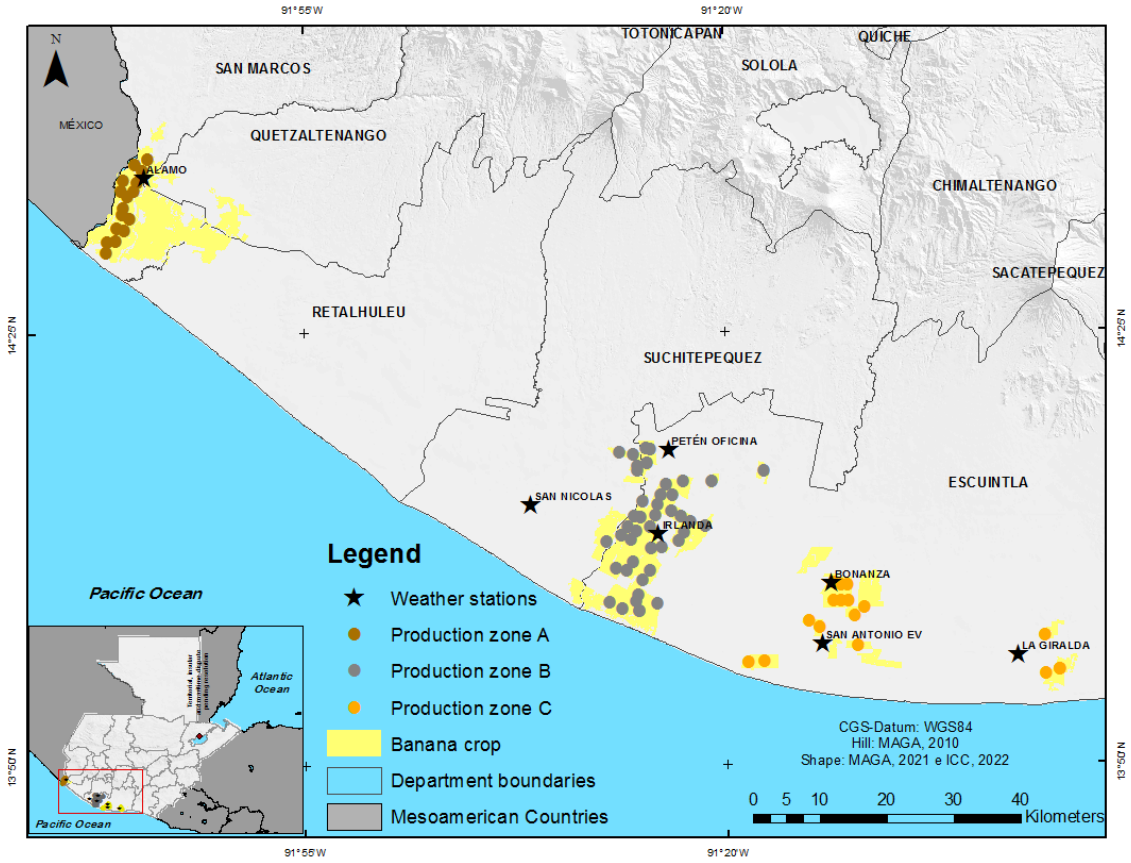

Figure 1. Location of banana farms and production zones assessed for the water footprint analysis along Guatemala's Pacific Slope

Data on monthly yield [t/ha], monthly irrigation [m³], and annual nitrogen application [kg/ha] were collected for the period 2018–2023 across three banana production zones. The final analytical dataset comprised 402 banana farm-year observations. The spatial distribution of these zones and their corresponding cultivated areas is summarised in **Table 3**. The number of farm-year observations included per zone and year varied over time (**Table 4**), and the total cultivated area analysed ranged between 11,084 and 20,986 ha, depending on the year (**Table 5**).

Table 3. Location reference and cultivated area of the banana production zones assessed in southern Guatemala

Production zone	Location reference	Cultivated area [ha]
Zone A	Near the Mexico-Guatemala border	4,521
Zone B	Near Tiquisate, Escuintla	12,143
Zone C	Near La Gomera, Escuintla	4,794

Table 4. Number of banana farm-year observations included in the analysis by production zone and year

Year	Zone A	Zone B	Zone C
2018	16	19	4
2019	16	35	12
2020	16	39	15
2021	16	44	19
2022	16	40	18
2023	18	39	20

Table 5. Total cultivated banana area analysed per year (2018–2023)

Year	Total cultivated area analysed [ha]
2018	11,084
2019	17,300
2020	18,748
2021	20,986
2022	19,543
2023	19,997

To estimate monthly accumulated evapotranspiration, meteorological data from eight stations located near banana production zones were used (**Figure 1**). Production Zone A was represented by the Alamo station; Production Zone B by the Irlanda, Petén Oficina, Puyumate, San Antonio El Valle, and San Nicolás stations; and Production Zone C by the Bonanza, La Giralda, and San Antonio El Valle stations. All meteorological stations are operated by the Private Institute for Climate Change Research (ICC) **[28]**. Monthly rainfall data were obtained directly from rain gauges installed at each farm.

RESULTS AND DISCUSSION

This section presents the water footprint results for banana production, discusses their implications, and notes the study's limitations arising from its specific scope and methodological considerations.

Water Footprint Components Across Production Zones and Years

During the 2018–2023 study period, banana production in southern Guatemala ranged from 61 to 84 t/ha. Annual irrigation requirements ranged from 1,001 to 1,672 mm, while annual rainfall ranged from 931 to 2,202 mm. Annual potential crop evapotranspiration ranged between 1,478 and 1,985 mm, and nitrogen application rates varied from 291 to 575 kg/ha (**Table 6**). Overall, these values indicate substantial variability across production zones and years, attributable to differences in climatic conditions and farm management practices.

On average, the blue water footprint ranged from 135 to 268 m^3/t, the green water footprint from 85 to 148 m^3/t, and the grey water footprint from 15 to 37 m^3/t. As a result, the total water footprint of banana production ranged from 246 to 435 m^3/t, with noticeable differences across production zones and years (**Table 7**).

The analysis of the water footprint across production zones reveals contrasting patterns in the green and blue water components. Periods characterised by La Niña conditions show a greater contribution of the green water footprint than El Niño years, reflecting the greater role of rainfall under wetter climatic conditions. In contrast, during El Niño phases, green water availability decreases, accompanied by an increase in theoretical irrigation requirements.

Table 6. Average yield, irrigation, rainfall, evapotranspiration, and nitrogen application by production zone and year

Year	Production Zone	Yield **[t/ha]**	Irrigation **[mm]**	Rain **[mm]**	Evapo-transpiration **[mm]**	Nitrogen **[kg/ha]**
2018	A	74	1,001	1,286	1,582	428
	B	72	1,481	1,298	1,534	518
	C	61	1,672	1,213	1,478	575
2019	A	82	1,263	1,165	1,578	446
	B	71	1,398	1,470	1,562	500
	C	67	1,571	1,776	1,541	483

Year	Production Zone	Yield [t/ha]	Irrigation [mm]	Rain [mm]	Evapo-transpiration [mm]	Nitrogen [kg/ha]
2020	A	84	1,543	1,403	1,517	439
	B	68	1,343	1,328	1,521	438
	C	66	1,583	1,430	1,542	427
2021	A	83	1,111	1,194	1,534	329
	B	73	1,375	1,233	1,751	427
	C	75	1,508	1,410	1,588	378
2022	A	79	1,128	1,180	1,484	425
	B	69	1,248	1,642	1,509	323
	C	70	1,296	2,202	1,556	291
2023	A	79	1,189	1,072	1,985	297
	B	69	1,316	1,212	1,597	313
	C	67	1,429	931	1,482	312

Table 7. Blue, green, grey, and total water footprints [m^3/t] of banana production by production zone and year; *SD* – Standard Deviation, *WF* – Water Footprint

Year	Product-ion Zone	Blue *WF*		Green *WF*		Grey *WF*		Total *WF*
		Average/ *SD*	Range	Average/ *SD*	Range	Avera ge/ *SD*	Range	Average
2018	A	137/40	88–204	105/13	89–133	23/2	20–25	266
	B	207/54	128–320	116/9	102–132	29/6	8–37	352
	C	268/19	244–291	131/23	102–158	37/5	31–43	435
2019	A	154/28	121–202	93/9	77–107	22/1	19–24	268
	B	202/58	105–328	119/23	80–191	29/7	12–50	350
	C	236/39	171–295	123/15	104–157	29/6	19–37	388
2020	A	186/75	104–359	98/8	83–110	21/2	16–23	305
	B	205/54	86–339	127/22	88–188	26/6	18–45	358
	C	247/63	141–355	128/22	85–167	26/5	17–38	402
2021	A	135/31	97–209	95/14	79–121	16/3	12–23	246
	B	210/78	75–494	126/45	73–264	25/7	16-44	335
	C	201/55	147–371	113/17	87–138	20/6	7–28	334
2022	A	144/24	112–198	95/11	80–112	22/4	17–34	260
	B	192/63	76–329	135/21	94–186	19/4	9–27	346
	C	190/45	121–294	148/20	115–178	17/4	12–24	355
2023	A	151/24	120–203	85/6	77–98	15/2	12–20	251
	B	197/59	83–292	115/26	67–193	19/5	2–28	331
	C	213/59	128–326	94/12	78–120	19/4	13–26	326

However, contrary to expectations, the blue water footprint did not increase during the El Niño year (2023) compared to the La Niña year (2020), with slightly higher average values observed in 2020. This result suggests that factors beyond climatic variability, particularly farm-level management practices associated with banana production, as well as methodological assumptions used in estimating irrigation requirements, may have influenced the observed water-use patterns. Therefore, the theoretical irrigation requirement presented in **Table 8** should be interpreted as an estimate based on climatic and soil parameters rather than on measured irrigation volumes. This distinction is essential, as the calculated irrigation demand represents potential water requirements under standardised management conditions and not the actual quantities applied.

Table 8. Relationship between ENSO phases, green water use, and theoretical irrigation requirement across banana production zones

Variable	ENSO phase	Production Zone			Average
		A	B	C	
Green water use [mm]	Niña	847.0	706.9	813.8	789.2
	Neutral	819.2	794.9	759.7	791.3
	Niño	666.6	745.4	582.8	664.9
	Average	777.6	749.1	718.8	748.5
Theoretical irrigation requirement [mm]	Niña	809.7	965.8	927.1	900.8
	Neutral	891.1	796.9	1,010.4	899.4
	Niño	1,200.3	950.5	1,303.7	1,151.5
	Average	967.0	904.4	1,080.4	983.9

The results partially support the hypothesis: green water use and theoretical irrigation requirements shifted consistently with ENSO-related rainfall conditions, whereas the observed blue water footprint was also influenced by farm-level management and methodological assumptions. The contribution, therefore, extends beyond a local water footprint inventory by demonstrating that the climate phase must be explicitly considered when interpreting the composition of water footprints and potential irrigation demand in ENSO-affected tropical cropping systems. The following subsections discuss the mechanisms, spatial heterogeneity, and transferability of these findings.

Overall Water Footprint and Main Driving Factors

The total water footprint of banana production in southern Guatemala (**Figure 2**) is primarily driven by yield, followed by annual rainfall and irrigation, while the contribution of nitrogen fertiliser is comparatively smaller.

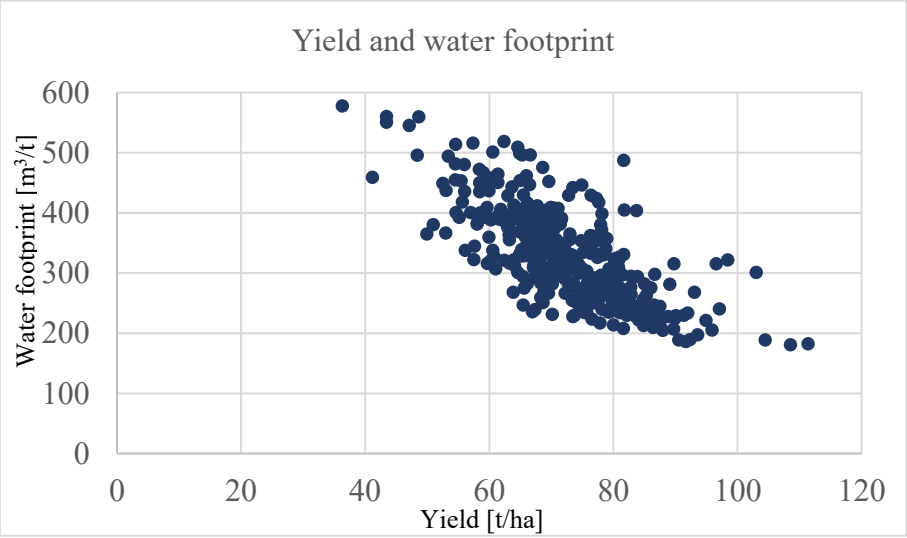

Figure 2. Relationship between banana yield and total water footprint in southern Guatemala

Higher productivity dilutes water consumption per unit of output: as yield increases, the same volume of water is distributed across a greater amount of production, reducing the water footprint per tonne. This dilution effect is a primary determinant of water footprint variability in the study area and provides the conceptual basis for interpreting differences across zones, years, and production systems.

The weighted mean total water footprint is 329 m³/t, approximately 58% lower than the global average of 790 m³/t reported by Hoekstra and Hung [6], Hoekstra *et al.* [7], and confirmed by more recent global assessments [8]. Rainfall variability can increase or decrease the water footprint, but this relationship is not strictly linear, even in years with higher precipitation. Substantial irrigation volumes were required, highlighting the influence of farm-level management decisions, irrigation infrastructure, and soil characteristics on actual water use, as illustrated in Figure 2.

Spatial Variability Across Production Zones

The water footprint varies significantly among production zones (95% confidence level), with Zone A exhibiting the lowest value (266 m³/t) and the highest average yield (80 t/ha), while Zone C presents the highest footprint (373 m³/t) and the lowest yield (68 t/ha). This inverse relationship between yield and water footprint, illustrated in Figure 2, is consistent with the dilution mechanism described in Section 4.2 and reinforces the importance of productivity gains as a primary lever for improving water-use efficiency in tropical export agriculture. Differences in solar radiation, rainfall distribution, and agronomic management across zones explain the observed yield gradients and, consequently, the spatial pattern of water footprints.

In comparative terms, Bolaños [13] reported 395 m³/t in Honduras under average yields of 29 t/ha, and Oliveira *et al.* [11] reported values of up to 1,207 m³/t in the Brazilian semi-arid region under low yields and high evapotranspiration. These contrasts further support yield as the primary driver of international variability in banana water footprints, independent of methodological differences across studies.

The interannual variability of the total water footprint across production zones is illustrated in Figure 3. Regarding the blue water footprint, significant differences were detected among zones (95% confidence level), with Zone A showing the lowest average (151 m³/t), followed by Zones B (200 m³/t) and C (226 m³/t), as shown in Figure 4.

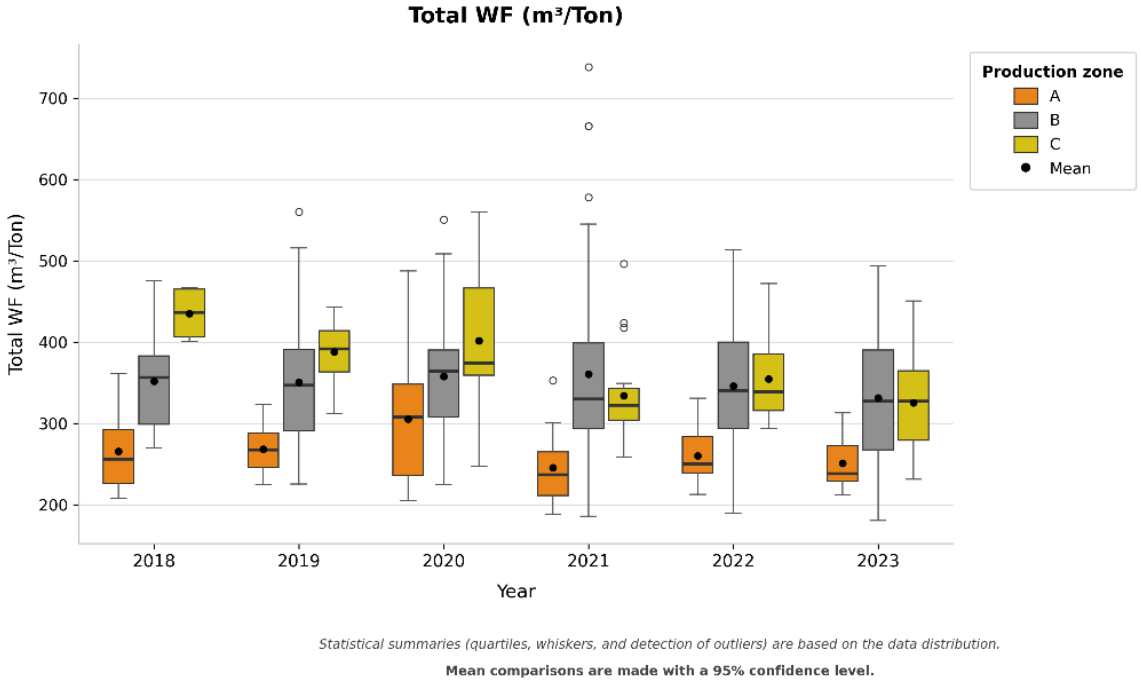

Figure 3. Average total water footprint across production zones and evaluated years

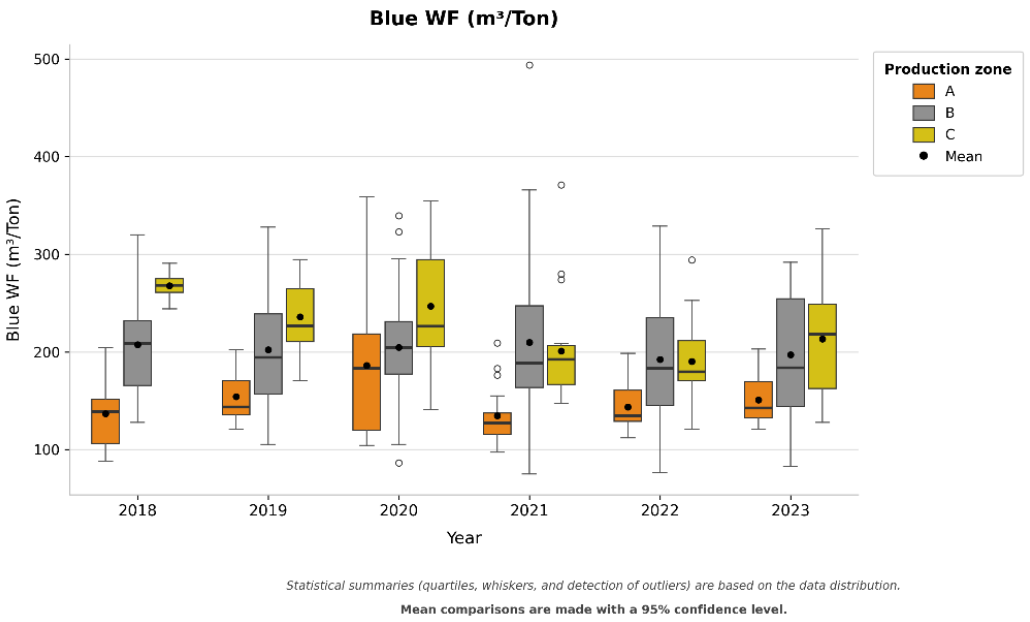

Figure 4. Average blue water footprint across production zones and evaluated years

Bolaños [13] reported 160 m³/t in Honduras, and Zárate and Kuiper [12] estimated 169 m³/t in Peru and Ecuador; these values fall within a comparable range, reflecting similar rainfall regimes. In contrast, Pahlow *et al.* [10] estimated 431 m³/t in South Africa while Shtull-Trauring *et al.* [29] reported values up to 863 m³/t in Israel, primarily attributable to greater irrigation requirements under lower annual rainfall and higher evapotranspiration.

The green water footprint also varies significantly among zones (95% confidence level), with Zone A showing the lowest average (95 m³/t) and Zones B and C presenting similar values of 121 and 123 m³/t, respectively (**Figure 5**). Oliveira *et al.* [11] reported 110 m³/t in Brazil and Palacios [30] estimated 133 m³/t in Panama; both values are consistent with the range observed in this study. Higher values reported by Bolaños [13] in Honduras and by Bulsink *et al.* [9] in Indonesia reflect greater accumulated rainfall and lower yields, consistent with the positive relationship between annual rainfall and green water contribution, similar to that observed by Novoa *et al.* [31] in cereal crops in Chile.

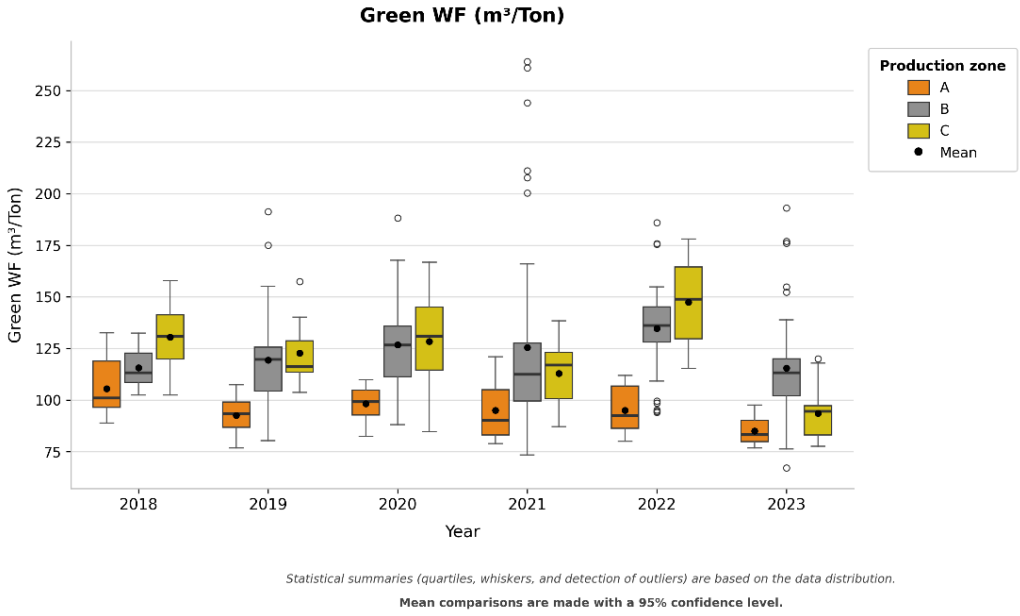

Figure 5. Average green water footprint across production zones and evaluated years

The ANOVA results confirm that the production zone is a significant source of variation in all water footprint indicators. Zone effects were highly significant for total *WF* ($F_{2,394} = 59.13$; $p < 0.001$), blue *WF* ($F_{2,394} = 40.89$; $p < 0.001$), green *WF* ($F_{2,394} = 57.52$; $p < 0.001$), and grey *WF* ($F_{2,394} = 25.18$; $p < 0.001$), indicating that agro-climatic, edaphic, and infrastructural conditions structurally influence water-use efficiency at the production-zone level [7]. In the extended green water footprint model (**Table 9**), farm nested within the production zone was also highly significant ($F_{130,264} = 4.57$; $p < 0.001$), demonstrating substantial farm-level heterogeneity within production zones. Across the total, blue, and green water footprint indicators, coefficients of variation ranged from approximately 22% to 31%.

Production year was significant for total *WF* ($F_{5,394} = 3.89$; $p = 0.002$), blue *WF* ($F_{5,394} = 2.63$; $p = 0.023$), green *WF* ($F_{5,394} = 13.87$; $p < 0.001$), and grey *WF* ($F_{5,394} = 36.71$; $p < 0.001$). The particularly strong temporal response of green *WF* is consistent with its direct dependence on effective rainfall and interannual climatic variability, according to Argueta Mayorga *et al.* [17]. The simultaneous significance of spatial, temporal, and farm-level effects is consistent with recent spatiotemporal water-footprint research showing that climatic conditions, irrigation infrastructure, and management drivers interact rather than operate independently [22].

Table 9. Multifactor analysis of variance (degrees of freedom, sum of squares, etc.) for green water footprint across production years, production zones, and farms nested within production zones; significance level: *** $p < 0.001$

Source of variation	df	SS	MS	F	p-value	Sig.
Year	5	30,644.70	6,128.94	30.188	< 0.0001	***
Zone	2	50,848.93	25,424.46	125.226	< 0.0001	***
Farm (Zone)	130	120,549.24	927.30	4.567	< 0.0001	***
Residual	264	53,599.40	203.03	-	-	
Total	401	255,642.26	-	-	-	

Dynamics of Green and Blue Water Footprints Under ENSO Variability

ENSO-driven climatic variability generates a compensatory dynamic between the green- and blue-water components of the water footprint. During La Niña phases, above-average precipitation enhances effective rainfall, increasing the green water contribution, with an average of approximately 789 mm across production zones, while simultaneously reducing theoretical irrigation requirements. Conversely, during El Niño phases, reduced rainfall decreased green evapotranspiration to approximately 665 mm, representing a 15.8% reduction relative to La Niña conditions, while theoretical irrigation requirement increased by approximately 25–30% across production zones. This inverse relationship is illustrated in **Figure 6**, where theoretical irrigation represents potential water demand estimated from a soil water balance, not measured irrigation volumes. Argueta Mayorga *et al.* [17] documented that ENSO phases drive marked shifts in precipitation regionalisation across Guatemala's Pacific Slope. Bardales-Espinoza *et al.* [18] confirmed that El Niño conditions are associated with drought in the region, whereas La Niña is associated with above-average rainfall. The World Meteorological Organization [16] has reported that these contrasting phases generate widespread and persistent effects on water availability across Central America; these findings are directly consistent with the green-blue compensatory dynamic observed in this study.

The observed green-blue compensation is also consistent with recent temporally explicit assessments. Monthly gridded analyses have shown that blue and green water consumption and their benchmarks vary across seasons and climatic zones [20]. Coupled climate-crop modelling has also demonstrated annual changes in water availability and agricultural demand [21].

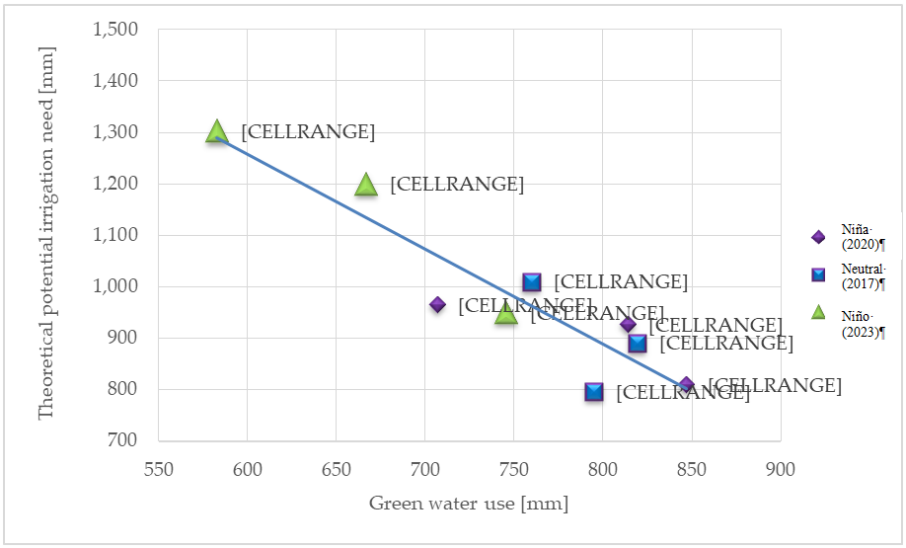

Figure 6. Relationship between theoretical irrigation requirement and green water use for banana cultivation in southern Guatemala; points representing production zones are coloured according to ENSO phase: 2017 (neutral), 2020 (La Niña), and 2023 (El Niño)

Unlike those regional modelling approaches, the present design evaluates a single perennial crop using farm-level observations across contrasting ENSO phases; this isolates the climate-phase signal while retaining management variability among farms. The implication is that the composition of the water footprint is not static but shifts systematically with climate phase, challenging the use of fixed benchmarks for sustainability assessments and certification. Strategies that assume stationary climatic conditions may systematically underestimate irrigation demand during El Niño years and overestimate it during La Niña phases, leading to inefficient resource allocation. Incorporating ENSO phase forecasts into farm-level water management planning could substantially improve the accuracy of irrigation scheduling and the reliability of water footprint benchmarks for the Guatemalan banana sector.

It is important to note that the blue water footprint did not increase during the El Niño year (2023) relative to the La Niña year (2020), with slightly higher average values observed in 2020. This observation suggests that farm-level management practices and the methodological assumptions inherent in estimating theoretical irrigation requirements may modulate actual water use independently of rainfall conditions. The irrigation demand in **Table 8**, therefore, represents potential water requirements under standardised conditions and should not be interpreted as measured irrigation volumes. These findings highlight the need to integrate climate variability into water footprint assessment frameworks, particularly in tropical export-oriented agricultural systems, where ENSO-driven fluctuations in rainfall and irrigation demand can substantially alter the composition of water use from year to year.

Contribution of the Grey Water Footprint

The grey water footprint accounted for 5%–9% of the total, with an average of 6.82%, reflecting moderate nitrogen application rates and the assimilative capacity of local water bodies, as defined by Guatemalan environmental regulations [27]. Bolaños [13] reported a comparable grey contribution in Honduras, and Oliveira *et al.* [11] observed similar proportions in Brazil, both attributable to nitrogen fertiliser application as the primary determinant of the grey component. The relatively low contribution of the grey water footprint indicates that water quantity, expressed through the green and blue components rather than diffuse nitrogen pollution, currently dominates the water footprint profile of banana production in southern Guatemala. This situation has direct implications for intervention prioritisation: measures focused on irrigation efficiency and rainfall utilisation will have a substantially greater impact on the total water footprint than reductions in nitrogen application alone.

Uncertainty and Methodological Limitations

This study is subject to specific scope and methodological considerations that should be noted when interpreting the results: (1) the evaluated farms are located exclusively in southern Guatemala, consistent with the defined study area, and banana production areas in the Caribbean region were not included; (2) farm-level water footprint data cover the period 2018–2023, while the ENSO-based climate analysis draws on meteorological records from 2010 onwards to include representative reference years for each climatic phase. Water footprint values may therefore differ under more extreme or prolonged climatic conditions not captured within either period; (3) in some production zones, a single meteorological station was used, applying the same evapotranspiration data across areas with contrasting altitudes; (4) reference evapotranspiration was estimated using the FAO-56 Penman-Monteith method, which represents a standardised approximation rather than direct field measurement, a limitation inherent to studies of this nature and consistent with the methodology adopted in comparable regional assessments; (5) the leaching fraction applied for grey water footprint calculation corresponds to the value proposed by Hoekstra *et al.* in the Water Footprint Assessment Manual [7], as locally measured leaching data were not available; (6) the grey water footprint calculation considered only nitrogen inputs derived from fertiliser application, excluding nitrogen loads deposited through precipitation, which may result in an underestimation of the grey component under conditions of high atmospheric nitrogen deposition; (7) only two reference years were used per ENSO event type, which precludes the calculation of associated error measures and the application of formal statistical tests to compare water footprint components across climatic phases; consequently, the observed differences between phases should be interpreted as indicative reference values rather than statistically inferred estimates; (8) information regarding whether farms employed standardised methods to estimate applied irrigation depth was not available, introducing uncertainty in the quantification of the blue water component; and (9) water use associated with packing facilities was not considered in the present assessment, and reported values therefore correspond exclusively to the field crop production stage.

CONCLUSIONS

This study tested whether ENSO-driven interannual climate variability alters the balance between green- and blue-water use in an irrigated tropical export crop. The results partially support the hypothesis: green water contribution increased under wetter La Niña conditions, and theoretical irrigation requirements increased under drier El Niño conditions. However, the observed blue water footprint was also shaped by farm-level management and methodological assumptions. The scientific contribution is therefore not limited to a local water footprint inventory; it demonstrates that water footprint composition and the reliability of associated benchmarks depend on climate phase in ENSO-affected tropical cropping systems.

The weighted mean total water footprint was 329 m^3/t, approximately 58% lower than the global average of 790 m^3/t. This result was primarily explained by the relatively high banana yields achieved in the region, which ranged from 61 to 84 t/ha, and by the diluted water consumption per unit of output. The yield-driven dilution effect is the central mechanism that distinguishes southern Guatemala from other banana-producing regions, where higher water footprints have been reported.

The blue water footprint accounted for 58.18% of the total, the green water footprint for 34.99%, and the grey water footprint for 6.82%. These proportions were not fixed; they varied among production zones and across years in response to differences in rainfall distribution, irrigation management, and nitrogen application rates. The dominance of the blue component underscores the critical role of irrigation management in determining the system's overall water footprint.

Significant differences were detected among production zones for all three water footprint components ($p < 0.001$). Zone A exhibits the lowest total water footprint (266 m³/t) and the highest average yield (80 t/ha), while Zone C presents the highest footprint (373 m³/t) and the lowest yield (68 t/ha). These differences are structurally determined by agro-climatic, edaphic, and infrastructural conditions inherent to each zone, as confirmed by the ANOVA results. Farm nested within the production zone was also a significant source of variation in the green water footprint ($F_{130,264} = 4.57$; $p < 0.001$), while coefficients of variation of approximately 22–31% indicate that zone-level averages do not fully capture farm-level heterogeneity.

ENSO-driven climatic variability generates a compensatory dynamic between the green- and blue-water components. During La Niña conditions, higher rainfall increased the green water contribution to approximately 789 mm and reduced theoretical irrigation requirements. During El Niño conditions, mean green evapotranspiration was 15.8% lower than during La Niña conditions, while theoretical irrigation requirement was 25–30% higher. This ENSO-driven shift in water footprint composition demonstrates that fixed water footprint benchmarks based on long-term climatic averages may systematically misrepresent actual water use under contrasting climatic phases, limiting their reliability for sustainability assessments, environmental certification, and water management planning.

The relatively low contribution of the grey water footprint (5–9%) indicates that water quantity expressed through the green and blue components, rather than diffuse nitrogen pollution, currently dominates the water footprint profile of banana production in southern Guatemala. Intervention strategies focused on irrigation efficiency and rainfall utilisation will therefore have a substantially greater impact on the total water footprint than reductions in nitrogen application alone.

Future research should incorporate measured irrigation volumes, a larger number of reference years per ENSO phase, watershed-scale sustainability indicators, and projected climate scenarios. Applying the phase-explicit design to additional perennial crops and ENSO-affected regions would enable formal comparisons among climatic phases and determine whether the observed non-stationarity persists across production systems. For management and certification, the results indicate that water footprint benchmarks should be stratified by climatic phase and local production conditions rather than represented by a single fixed value.

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DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available within the article.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

NOMENCLATURE

Symbols

$appl$	Amount of nitrogen applied as fertiliser	[kg/ha·year];
C_{max}	Maximum acceptable concentration of pollutant	[kg/m³]
C_{nat}	Natural concentration of pollutant in the water body	[kg/m³]
ET_0	Reference evapotranspiration	[mm/month]
ET_c	Crop evapotranspiration	[mm/month]
K_c	Crop coefficient	[-]
L	Nitrogen pollutant load	[kg/ha·year]
WF	Water footprint	[m³/t]

Greek letters

α	Leaching fraction of nitrogen	[-]

Abbreviations

ANOVA	Analysis of Variance
APIB	Association of Independent Banana Producers
CROPWAT	Computer Program for Irrigation Planning and Management
ENSO	El Niño – Southern Oscillation
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
ICC	Private Institute for Climate Change Research

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