

RESEARCH ARTICLE

Sustainable Technology for Agriculture at Extreme Altitudes: Design and Evaluation of a Sprinkler Irrigation System in a Peruvian High Andean Community

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Abstract: In high-altitude agroecosystems, erratic rainfall patterns and steep topography severely constrain crop productivity by exposing plants to soil water deficits during critical phenological stages. This study aimed to enhance the productivity of eleven staple and horticultural crops corn (*Zea mays*), tomato (*Solanum lycopersicum*), cucumber (*Cucumis sativus*), eggplant (*Solanum melongena*), lettuce (*Lactuca sativa*), carrot (*Daucus carota*), barley (*Hordeum vulgare*), celery (*Apium graveolens*), bean (*Phaseolus vulgaris*), onion (*Allium cepa*), and pea (*Pisum sativum*) through the design and implementation of a sprinkler irrigation system in the San Carlos district of the Peruvian High Andes. The system was designed to accommodate the region's climatic, edaphic, hydrological, and topographic variability across 20.05 hectares, divided into 14 irrigation sectors with slopes ranging from 2% to 53%. Soil characterization revealed sandy loam as the predominant texture (32.14%), with favorable physical properties real density (2.21–2.77 g cm⁻³), bulk density (1.22–1.35 g cm⁻³), and porosity (40.15–53.60%) that facilitated adequate water infiltration and retention. The total irrigation requirement was 20.80 L s⁻¹ (748.80 m³ day⁻¹), with a 10-day interval and 10-hour daily irrigation periods tailored to crop phenological stages. Implementation of the sprinkler system resulted in statistically significant (*p* < 0.05) yield increases across all crops, ranging from 20% (barley, bean, onion, pea) to 133% (eggplant). Horticultural crops particularly eggplant, cucumber, and lettuce exhibited the strongest responses, reflecting their heightened sensitivity to moisture deficits during flowering and fruit set. Economic analysis confirmed the project's viability, with a social Internal Rate of Return (IRR) of 95% and a Benefit–Cost ratio of 5.07. These findings demonstrate that carefully designed sprinkler

irrigation can substantially improve agricultural productivity in high-altitude, water-limited environments by alleviating phenological-stage water stress. The system offers a replicable model for sustainable intensification in Andean agroecosystems, contributing to food security, economic resilience, and reduced rural out-migration. Strengthening community participation and water governance is essential to ensure long-term sustainability and regional development impact.

Keywords: Crop Water Productivity, Phenological Water Requirements, High-Altitude Agriculture, Sustainable Intensification, Andean Smallholder Farming, Soil-Plant-Water Relations, Irrigation Efficiency

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Introduction

Global food systems are at a critical juncture. With the world population surpassing 8.2 billion in 2025 and projected to approach 9.7 billion by 2050, agricultural production must increase by an estimated 60–70% to meet escalating demand [1]. This challenge is compounded by the fact that agriculture accounts for approximately 70% of global freshwater withdrawals, placing unprecedented stress on finite water resources. Consequently, future food production must pivot toward intensification strategies that maximize yield per unit of water consumed, rather than merely expanding the cultivated area [2].

Water availability is the single most critical abiotic factor limiting crop productivity, particularly during specific phenological windows. Deficit soil moisture during flowering, fruit set, and grain filling triggers stomatal closure, reduces intercellular CO₂ concentration, and impairs photosynthetic assimilation, ultimately leading to reduced biomass accumulation, lower harvest indices, and diminished fruit quality [2, 3]. In rainfed systems, erratic precipitation patterns and prolonged intra-seasonal dry spells expose crops to severe water stress, often resulting in yield penalties ranging from 30 to 80% across diverse agroecosystems [4, 5].

Among the various irrigation modalities, sprinkler systems offer distinct physiological and agronomic advantages, particularly in topographically complex terrains where surface irrigation is impractical. Unlike flood irrigation, sprinklers provide controlled, uniform water application that can be tailored to the specific phenological requirements of different crops. Furthermore, overhead irrigation can modify the canopy microclimate reducing leaf temperature during heatwaves and mitigating frost damage which directly influences stomatal conductance and net carbon assimilation [6, 7]. For vegetable rotations, sprinklers remain the preferred choice for many smallholder systems due to lower capital costs compared to drip systems and phytosanitary benefits, such as reduced incidence of soil-borne bacterial pathogens [8].

Smallholder farming systems, which underpin the livelihoods of millions in developing regions, are disproportionately vulnerable to climatic variability. In the Andean highlands of South America, these challenges are exacerbated by extreme elevations, steep slopes (often exceeding 50%), and the intensifying impacts of the El Niño Southern Oscillation (ENSO), which induces severe droughts or flooding during critical growth stages [9]. The Peruvian Amazonas region exemplifies these constraints: despite favorable biodiversity and crop diversity, productivity remains constrained by the lack of climate-resilient water management infrastructure [10, 11]. Although various studies have evaluated irrigation efficiency in lowland or semi-arid environments, there is a conspicuous paucity of quantitative research examining the *biological yield response* of diverse horticultural and staple crops such as maize, tomato, cucumber, and quinoa to engineered sprinkler irrigation under the extreme altitudinal and topographic gradients of the High Andes.

Addressing this gap is imperative not only for local food security but also for understanding the physiological thresholds of crop adaptation under managed water supply in montane agroecosystems. Therefore, the present study was designed with three primary objectives:

- (i) To design and hydraulically evaluate a sprinkler irrigation network adapted to the rugged topography of the San Carlos district (Amazonas, Peru)

- (ii) To quantify the productivity gains (biomass yield and harvestable produce) across eleven key crops under the newly implemented system, relative to historical rainfed baselines
- (iii) To assess the economic viability of the intervention to ensure sustained adoption and improved livelihoods for the 20 participating family farming units

Materials and Methods

Study Area and Climatic Context

The study was conducted in the San Carlos Community, located approximately 8 km from the city of Pedro Ruiz in the Bongará Province of the Amazonas Department, Peru. The geographical coordinates of the area are $5^{\circ} 58'$ N latitude and $77^{\circ} 56'$ W longitude, with elevations ranging from 1,650 to 2,500 meters above sea level (m a.s.l.) (Figure 1). The region is characterized by a montane tropical climate with distinct wet and dry seasons [12, 13]. The community comprises approximately 480 inhabitants, who rely primarily on smallholder agriculture for their livelihoods [14]. The predominant crops cultivated in the area include maize (*Zea mays*), tomato (*Solanum lycopersicum*), cucumber (*Cucumis sativus*), eggplant (*Solanum melongena*), lettuce (*Lactuca sativa*), carrot (*Daucus carota*), barley (*Hordeum vulgare*), celery (*Apium graveolens*), bean (*Phaseolus vulgaris*), onion (*Allium cepa*), and pea (*Pisum sativum*).

Climatic data including air temperature, precipitation, relative humidity, wind speed, and pan evaporation (Class A) were obtained from the Jazán Experimental Station of the National Meteorology and Hydrology Service of Peru (SENAMHI-Lambayeque). These data served as inputs for the reference evapotranspiration (ET₀) calculations.

Soil Sampling and Physical Characterization

To characterize the edaphic conditions, soil samples were collected from each of the 14 designated irrigation sectors. Sampling was performed at two depths (0–30 cm and 30–60 cm) using a stainless-steel auger, resulting in 28 composite samples. The sectors were selected to represent the topographic heterogeneity of the study area, with slopes ranging from 2 to 53%.

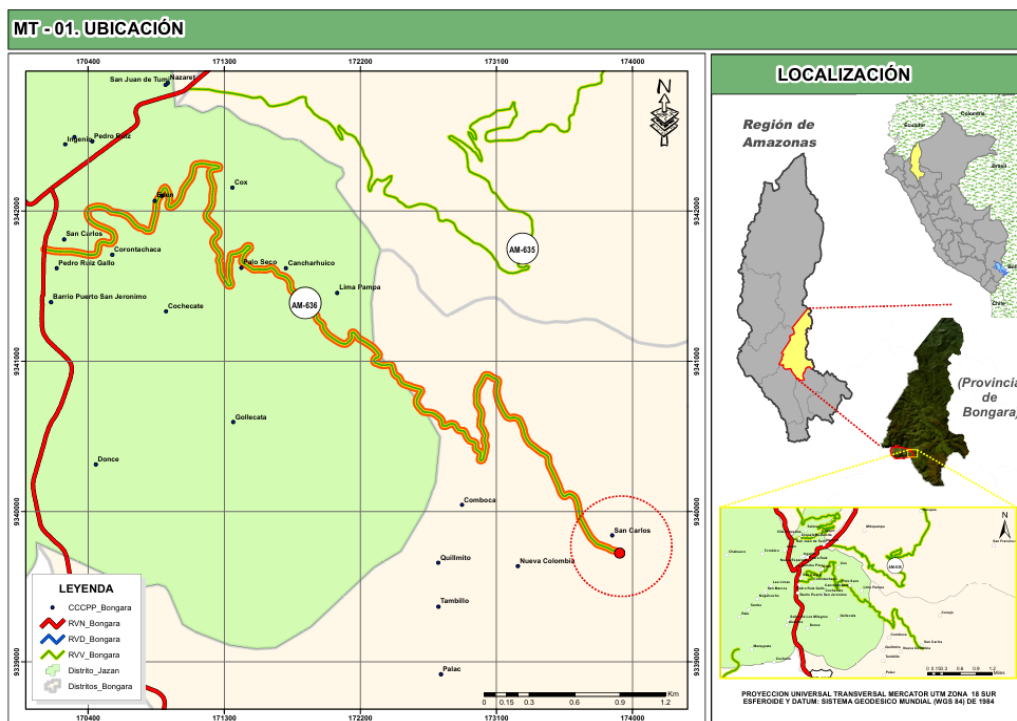


Fig. 1: Geographical location of the study area. (a) Map of Peru highlighting the Amazonas Department (shaded in dark gray). (b) Detailed view of the Bongará Province showing the San Carlos community (red marker) and the primary water sources (Kaká and Calché streams). Elevations within the study area range from 1,650 to 2,500 m above sea level

Granulometric (particle size) analysis was conducted using the wet sieving method for the coarse fractions (>0.05 mm), while the fine fractions (silt and clay) were quantified using the combined pipette and hydrometer sedimentation methods, following standard protocols [15, 16]. Soil texture was determined using the USDA textural triangle. Additionally, the following physical properties were evaluated for each sample: real particle density (using pycnometry), bulk density (via the core method), total porosity (calculated from density data), basic infiltration rate (using double-ring infiltrometer measurements), and field capacity and permanent wilting point (determined using pressure plate apparatus) [17]. All soil analyses were performed at the Water Resources Laboratory of the Faculty of Agricultural Engineering, National University Pedro Ruiz Gallo.

Water Source Assessment and Flow Measurement

The Kaká and Calché streams were identified as the primary surface water sources for the irrigation system. Flow rate measurements were conducted during both the dry season (low-flow period) and the wet season (peak-flow period) using the velocity-area sectioning method [18]. To ensure environmental sustainability, the ecological flow required to maintain downstream aquatic habitats and riparian buffers was calculated and preserved in accordance with the Peruvian Water Resources Law No. 29338 [19-21]. Furthermore, to protect the watershed headwaters, reforestation activities using native alder (*Alnus glutinosa*) were promoted in collaboration with the community [22].

Sprinkler Irrigation System Design and Hydraulic Infrastructure

The hydraulic design was developed based on the hydrological balance of the catchment, following the standard FAO methodologies for irrigation system planning [23]. The irrigation network was structured into three main components:

- (i) A conveyance system (from the intake points in the streams to the pressure chambers and main reservoir)
- (ii) An adduction pipeline
- (iii) A distribution network comprising 14 independent lateral lines servicing the 14 sectors

The selected emitter was the NAAN 5022 sprinkler, equipped with dual nozzles (3.5×2.5 mm diameter). Each sprinkler operated at a discharge rate of 0.26 L s^{-1} , a working pressure range of 2–4 atmospheres (atm), and achieved a wetted diameter of 22 m. Sprinklers were mounted at a height of 0.80 m on metallic tripods to minimize crop interference and ensure adequate overlap, as specified in the Peruvian Technical Standard NTP 399.002:2015 [24].

Each hydrant supplied two mobile polyethylene laterals (25–32 mm diameter), except in Sectors 1 and 5, which utilized a single 38 mm diameter line to accommodate higher flow demands. Pipeline diameters, pressure-breaking chambers, and valve locations were sized to maintain operating pressures and minimize friction losses, ensuring a distribution uniformity coefficient exceeding 85%.

Agronomic Practices and Yield Assessment (Critical Addition)

To quantify the biological productivity gains, the same crop varieties and agronomic management practices (planting density, fertilization schedule, and pest control) were maintained during the intervention as were used in the preceding rainfed seasons [25].

Crops were sown at the onset of the rainy season, and the sprinkler system was activated to supplement rainfall deficits according to the calculated irrigation schedule (see Section 2.6). At physiological maturity, total biomass and marketable yields (Mg ha^{-1}) were determined for each crop across all 14 sectors. Standard harvest protocols were followed: for cereals and pulses, yields were measured from 1 m^2 quadrats randomly placed within each sector; for vegetables, total harvestable fruit or root weight was recorded per plant and extrapolated to area-based metrics. These post-intervention yields were systematically compared against the historical five-year baseline averages (2018–2022) for the same land parcels under rainfed conditions, as documented in the local agricultural extension records (AGRO RURAL, Amazonas). This before-after comparison framework allowed the isolation of the irrigation effect from other agronomic variables.

Irrigation Scheduling and Water Application

The irrigation interval was established at 10 days, comprising 9 days of active irrigation followed by 1 day of system maintenance and rest. The total design flow rate of the system was calculated as 20.8 L s^{-1} (equivalent to $74.88 \text{ m}^3 \text{ h}^{-1}$), which was distributed across the 14 sectors. This flow rate supplied water to an average of 80 sprinkler positions per day, with each position receiving an irrigation duration of 10 hours. Consequently, the total daily water application volume was 748.8 m^3 .

day⁻¹. The irrigation requirements were adjusted according to the specific phenological stage (vegetative, flowering, or fruit-filling) of each crop to optimize water use efficiency and prevent physiological stress.

Statistical Analysis

All yield data were expressed as mean $\pm$ Standard Deviation (SD) for each crop across the 14 sectors. Normality of the yield distributions was assessed using the Shapiro Wilk test. To determine the statistical significance of the yield changes between the irrigated intervention and the historical rainfed baselines, paired Student's *t*-tests were applied for each crop, given the paired nature of the data (same plots, sequential seasons). Statistical significance was set at $p < 0.05$. All statistical analyses were performed using R software (version 4.3.1; R Core Team, 2023). Economic indicators, including Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit Cost (B/C) ratio, were calculated at both private and social prices using standard project evaluation methodologies.

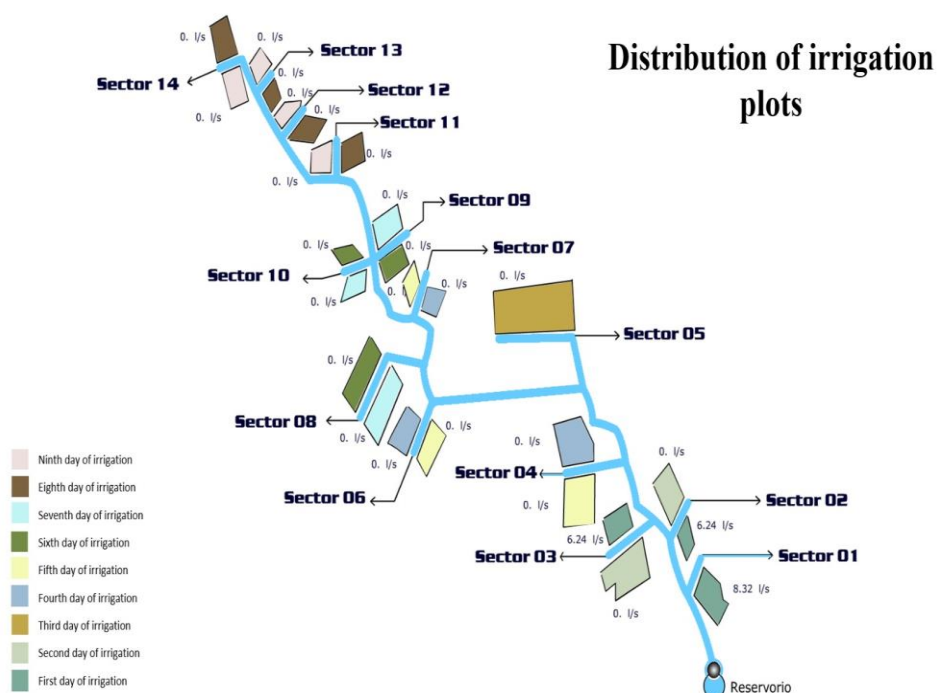


Fig. 2: Operational irrigation schedule across the 9-day cycle. Each panel (a–i) represents a single irrigation day, displaying the flow rate ($L s^{-1}$) allocated to each active lateral line (L1–L14). Flow rates range from 4.16 to 20.80 $L s^{-1}$ depending on the sector area and crop water requirements. This variable flow scheduling ensures that all 14 sectors receive their full irrigation requirement within the 9-day cycle, followed by one maintenance day

Results

Water Balance and Evapotranspiration

The reference evapotranspiration (E_{To}) for the study area, calculated using the Hargreaves and Samani method, was 1,357.99 $mm year^{-1}$. The actual evapotranspiration (E_{Tr}) of the crop was 1,023.04 $mm year^{-1}$, resulting in a water deficit of 806.67 $mm year^{-1}$ and a surplus of 0 $mm year^{-1}$ (Table 1). The E_{Tr} value observed in this study substantially exceeds those reported for shallow-rooted vegetables (166–174 $mm year^{-1}$) and deep-rooted vegetables (92–112 $mm year^{-1}$) in other montane systems, reflecting the higher evaporative demand and extended growing seasons at the study altitude [26, 27].

Soil Physical Properties

Granulometric analysis of soil samples collected from the 14 irrigation sectors revealed a heterogeneous textural distribution. Sandy loam was the dominant texture, accounting for 32.14% ($n = 9$) of the samples, followed by clay loam (25.00%, $n = 7$), clay (21.43%, $n = 6$), sandy clay loam (17.86%, $n = 5$), and sandy clay (3.57%, $n = 1$).

The physical properties of the soils are summarized in Table 2. Real particle density ranged from 2.21 to 2.77 g cm⁻³, consistent with the mineralogical composition of Andean montane soils. Bulk density ranged from 1.22 to 1.35 g cm⁻³, with lower values observed in clay loam soils and higher values in sandy loam soils. Total porosity ranged from 40.15% to 53.60%, indicating adequate aeration and water-holding capacity for the cultivated crops.

Field Capacity (FC) ranged from 36.7% to 58.96%, while the Permanent Wilting Point (PWP) ranged from 18.32% to 29.48%. The available water capacity (AWC = FC – PWP) was consequently between 18.38% and 29.48%, providing a favorable moisture buffer for crop production during dry periods.

Table 1: Water Balance for the Study Area (Hargreaves and Samani Method)

	Months												Total
	E	F	M	A	M	J	J	A	S	O	N	D	
Parameter Effective	46.74	79.43	82.94	68.51	22.8	24.29	24.74	24.11	22.9	48.46	43.28	63.14	551.34
Precipitation 75% (mm month ⁻¹)	145.19	111.33	114.85	93.13	85.91	81.62	90.71	110.69	119.31	128.89	139.51	136.85	1357.99
Eto (mm month ⁻¹)	98.35	96.64	131.53	0	44.34	73.19	100.95	95.16	22.27	87.31	118.58	156.72	1025.04
Etr (mm month ⁻¹)	98.44	31.9	31.92	24.62	63.11	57.33	65.97	86.58	96.42	80.43	96.23	73.71	806.66
Déficit	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Source: Meteorological Data "CO" Station, Jazan; Monthly Averages (1997–2006)

Table 2: Physical Soil Analysis of the 14 Sprinkler Irrigation Sectors

POINT	SECTOR	Depth (cm)	Real Density (gr/cm ³)	Bulk Density (gr/cm ³)	Porosity (%)	Field Capacity (%)	Witing Point (%)	Texture
01	14	0-30	2.77	1.35	51.21	43.55	21.77	FrArAo
01	14	30-60	2.43	1.3	46.56	39.83	19.92	FrArAo
02	13	0-30	2.77	1.29	53.6	37.01	18.5	FrAo
02	13	30-60	2.37	1.31	44.63	38.89	19.44	FrAo
03	12	0-30	2.7	1.32	51.19	37.93	18.97	FrAo
03	12	30-60	2.21	1.27	42.83	40	20	FrAo
04	11	0-30	2.22	1.28	42.29	47.73	21.36	FrAr
04	11	30-60	2.27	1.25	44.7	38.2	19.1	FrAr
05	10	0-30	2.56	1.28	50.08	49.13	24.57	Ar
05	10	30-60	2.27	1.28	43.57	45.27	22.64	Ar
06	09	0-30	2.56	1.22	52.27	58.96	29.48	FrAr
06	09	30-60	2.27	1.28	43.42	53.74	26.87	FrAr
07	08	0-30	2.43	1.23	49.13	40.82	20.41	FrAr
07	08	30-60	2.22	1.26	43.17	45.32	22.66	FrAr
08	07	0-30	2.43	1.23	49.13	40.54	20.27	FrArAo
08	07	30-60	2.22	1.28	42.29	45.65	22.83	FrArAo
09	06	0-30	2.37	1.27	46.63	42.14	21.07	ArAo
09	06	30-60	2.26	1.35	40.31	46.83	23.41	Ar
10	05	0-30	2.43	1.34	44.69	40.19	20.09	Ar
10	05	30-60	2.43	1.33	45.06	37.25	18.63	Ar
11	04	0-30	2.43	1.34	44.69	40.19	20.09	FrAo
11	04	30-60	2.43	1.33	45.06	39.73	19.86	FrAo
12	03	0-30	2.22	1.31	40.78	38.89	19.44	FrAo
12	03	30-60	2.37	1.32	44.36	37.78	18.89	FrAo

13	02	0-30	2.4	1.32	45.24	41.9	20.95	FrAo
13	02	30-60	2.37	1.34	43.61	37.78	18.89	FrAr
14	01	0-30	2.22	1.33	40.15	36.7	18.35	FrArAo
14	01	30-60	2.37	1.32	44.5	38.64	19.32	Ar

Source: Water Resources Laboratory, Faculty of Agricultural Engineering, [28]

Water Availability and Flow Characteristics

Flow measurements conducted during the dry season (low-flow period) recorded discharges of 9.85 L s^{-1} in the Calché Creek and 16.80 L s^{-1} in the Kaká Creek. During the peak-flow (wet) season, discharges increased substantially to 700.40 L s^{-1} and 904 L s^{-1} , respectively (Tables 3 and 4). The combined dry-season flow of 26.65 L s^{-1} exceeded the total system design requirement of 20.80 L s^{-1} (equivalent to $74.88 \text{ m}^3 \text{ h}^{-1}$), confirming the hydrological capacity of the catchment to sustain the irrigation scheme without compromising ecological flow requirements.

The total daily water volume required for the 10-hour irrigation period was $748.80 \text{ m}^3 \text{ day}^{-1}$. Basic infiltration rates across the 14 sectors ranged from 0.43 to 2.5 cm h^{-1} (Table 5), with the mean infiltration rate of 1.5 cm h^{-1} exceeding the sprinkler precipitation rate of 0.36 cm h^{-1} , thereby minimizing surface runoff risk.

Table 3: Amount of Water for Agricultural Irrigation During the Dry Season

Parameters	Results	Unit	Cross Sectional Area (m^2)	Velocity (m/s)	Width (m)	Water Depth (m)	Time (sec)
Calche Ravine	9.85	L/s^{-1}	0.0372	0.2648	0.31	0.12	11.33
Kaka Ravine	16.8	L/s^{-1}	0.056	0.3	0.4	0.14	10

Source: Own elaboration, based on field data

Table 4: Amount of water for agricultural irrigation during the maximum flow period

Parameters	Results	Unit	Cross Sectional Area (m^2)	Hydraulic Radius (m)	Width (m)	Water Depth (m)	Slope (%)
Calche Ravine	700.4	L/s^{-1}	0.262	0.206	1.31	0.3	0.001
Kaka Ravine	904	L/s^{-1}	0.334	0.237	1.39	0.36	0.001

Source: Own elaboration, based on field data

Table 5: Infiltration Capacity of Soils

Test	Accumulated runoff (l) cm	Instantaneous infiltration rate (li) cm/hr	Cumulative infiltration rate (La) cm/hr	Minimum infiltration time (min) $T = 600n$	Basic Infiltration rate (cm/h)	Infiltration velocity basic (mm/hr)
1	$1.056^{+0.343}$	$21.796^{+0.677}$	$63.492^{+0.677}$	394.2	0.43	4.3
2	$0.960^{+0.544}$	$31.348^{+0.456}$	$57.634^{+0.456}$	273.6	2.4	24
3	$0.854^{+0.591}$	$28.948^{+0.41}$	$55.256^{+0.41}$	261.1	2.5	25

Source: Own elaboration, based on field data

Sprinkler System Hydraulic Performance

The irrigation network comprised 14 independent lateral lines, each servicing a designated sector (Sectors 1–14). The total system capacity was 20.94 L s^{-1} , with 80 sprinkler positions operating simultaneously per day across a 9-day irrigation cycle (followed by one maintenance day). Each sprinkler (NAAN 5022, dual nozzle: $3.5 \times 2.5 \text{ mm}$) operated at a discharge of 0.26 L s^{-1} , a pressure range of 2–4 atm, and achieved a wetted diameter of 22 m. Sprinklers were mounted at 0.8 m height on metallic tripods.

Key design parameters for the representative crop (lettuce) included a root depth of 0.39 m, a gross irrigation requirement of $11.97 \text{ mm day}^{-1}$, an irrigation efficiency of 64.8%, and a sprinkler precipitation rate of 3.6 mm h^{-1} . The irrigation period per

position was 10 hours, with a 10-day rotation interval (Tables 6 and 7). This schedule ensured that the water application rate (0.36 cm h^{-1}) did not exceed the basic infiltration rate, preventing surface ponding and optimizing water use efficiency.

Table 6: Summary of the Hydraulic Design for Sprinkler Irrigation

Technical specifications			NAAN 5022	UND
of the sprinkler to be selected NAAN 5022 with 1/2" diameter connection				
Sprinkler spacing	e asp	=	16	m
Sprinkler flow rate	Q asp	=	0.94	m ³ /h
Sprinkler flow rate	Q asp	=	0.26	Lt/s
Nozzle Diameter	diám B	=	3.5	mm
Minimum sprinkler pressure	P	=	2	atm
Precipitation	Prec	=	3.67	mm/h
Wetted Diameter	diám M	=	22	m
elevator height H elev (m)			0.8	m
distance between spacers = 0.65 (M diameter)			14.3	m
permitted distance between sprinklers(D asp)=0,65(diam M+4*H elev)			16.38	m
rounded permissible distance between sprinklers d asp Dist PER asp rda			16	m
distance between hydrants = 2(d asp)			32.00	m
calculated sprinkler precipitation rate = $Q_{asp} \cdot 1000 / (D_{asp} \cdot D_{asp})$			3.50	mm/h

Source: Own elaboration, based on field data

Table 7: Irrigation Period and Water Module of the Sprinkler Irrigation Design for the Locality of San Carlos

Crops	Irrigation Period (Months)	Irrigation Module (M ³ /ha/day)	Area (ha)	Volume Daily (m ³ /day)
Corn	5	206	2.195	453
Tomato	5	208	2.155	448
Cucumber	5	180	2.29	412
Eggplant	5	137	2.165	297
Lettuce	5	185	2.165	400
Carrot	5	223	2.26	504
Cebada	5	192	2.26	434
Tomato	5	208	2.28	474
Celery	5	173	2.28	394

Source: Own elaboration, based on field data

Crop Yield Response to Sprinkler Irrigation

The implementation of the sprinkler irrigation system resulted in substantial and statistically significant yield increases across all 11 evaluated crops, compared to the historical five-year rainfed baseline (2018–2022). The yield responses were crop-specific, with the highest relative increases observed in eggplant (133.33%), cucumber (100%), and lettuce (71.43%), while cereals such as barley showed more modest but still significant gains (20%).

All yield increases were statistically significant at $p < 0.05$ (paired Student's t^* -test). The marked improvement in horticultural crops likely reflects their higher sensitivity to soil moisture deficits during critical phenological stages, particularly flowering and fruit set, which were effectively mitigated by the supplemental irrigation.

Economic Viability

The economic analysis confirmed the financial and social profitability of the sprinkler irrigation investment (Table 9). At private prices, the Net Present Value (NPV) was S/. 813,604.52, with an Internal Rate of Return (IRR) of 74% and a Benefit–Cost (B/C) ratio of 3.97. When indirect effects, positive externalities, and collective welfare benefits were incorporated at social

prices, the indicators improved substantially: NPV increased to S/. 877,689.11, IRR rose to 95%, and the B/C ratio reached 5.07. These results demonstrate that the irrigation system is not only economically viable but also generates significant social returns through improved livelihoods, food security, and sustainable resource management.

Table 8: Economic Indicators of the Sprinkler Irrigation Design for the Locality of San Carlos

Indicators	Private Prices	Social Prices
Net Present Value NPV (S/.)	813,604.52	877,689.11
Internal Rate of Return IRR (%)	74%	95%
Benefit - Cost Ratio	3.97	5.07

Source: Own elaboration, based on field data

Table 9: Detailed technical characteristics of the irrigation sectors

Sector	Main Line Sections (Station Range)	PVC Type/Class/ Diameter	Gate Value	Hydrants (Star Station and Quantity)	Modile Line Lenght (m)	Mobile Line Diameter (mm)	Additional Notes
1	0+000 - 0+036/0+036-0+069	c-5Ø2.5"/c-7.5 Ø 2.5"	2.5"	0+036 (H1 -H2)-2	123	32 (first line 38 mm)	2 Quick Coupling Values per hydrant (Ø 0.75", 1", 1.25")
2	0+000 - 0+133/0+033-0+066	c-5 Ø 2"/c-7.5 Ø 2"	2"	0+033 (H1- H2)-2	91	32	2 Quick Coupling Values per hydrant
3	0+000 - 0+063/0+063-0+185	c-7.5 Ø 3"/c-7.5 Ø 2"	3"	0+063 (H1- H5)-5	59/91	32	Right lines: 59 m; left lines: 91 m; last two lines: 59 m
4	0+000 - 0+132/0+132-0+197	c-5 Ø 2.5"/c-7.5 Ø 2"	2.5"	0+132 (H1- H3)-3	107/91	32/25	Lines from H3: 91 m
5	0+000 - 0+175/0+175-0+271/0+271-0+367	c-5 Ø 4"/c-7.5 Ø 3"/c-7.5 Ø 1.5"	4"	0+0143 (H1- H8)-8	75	32/25/38	38 mm lines: 75 m
6	0+000 - 0+085/0+085-0+151	c-5 Ø 2.5"/c-7.5 Ø 1.5"	2.5"	0+085 (H1- H3)-3	59	32/25	2 Quick Coupling Values per hydrant
7	0+000 - 0+066	c-7.5 Ø 1.5"	1.5"	0+037 (H1- H2)-2	59	32/25	2 Quick Coupling Values per hydrant
8	0+000 - 0+192/0+192-0+286	c-7.5 Ø 2.5"/c-7.5 Ø 2"	2.5"	0+0161 (H1- H5)-5	59	32	2 Quick Coupling Values per hydrant
9	0+000 - 0+090	c-7.5 Ø 2"	2"	0+031 (H1- H3)-3	59	32	2 Quick Coupling Values per hydrant
10	0+000 - 0+065	c-7.5 Ø 1.5"	1.5"	0+033 (H1- H2)-2	59	32/25	2 Quick Coupling Values per hydrant
11	0+000 - 0+066	c-10 Ø 2"	2"	0+033 (H1- H2)-2	75	32/25	2 Quick Coupling Values per hydrant
12	0+000 - 0+092	c-10 Ø 2.5"	2.5"	0+031 (H1- H3)-3	75	25	2 Quick Coupling Values per hydrant
13	0+000 - 0+064	c-10 Ø 2.5"	2.5"	0+032 (H1- H2)-2	59	25	2 Quick Coupling Values per hydrant

Source: Own elaboration, based on field data

Topographic Sectorization

Topographic analysis using Google Earth and AutoCAD, validated by field verification, identified 15 distinct slope-homogeneous sectors across the study area (Figure 3). The technical characteristics of each sector including pipe class, diameter, station ranges, hydrant distribution, and mobile line specifications are detailed in Table 10. This spatial segmentation enabled the optimization of hydraulic parameters (flow velocity, Reynolds number, and water consumption) according to site-specific topographic conditions, ensuring uniform water distribution across the heterogeneous terrain.

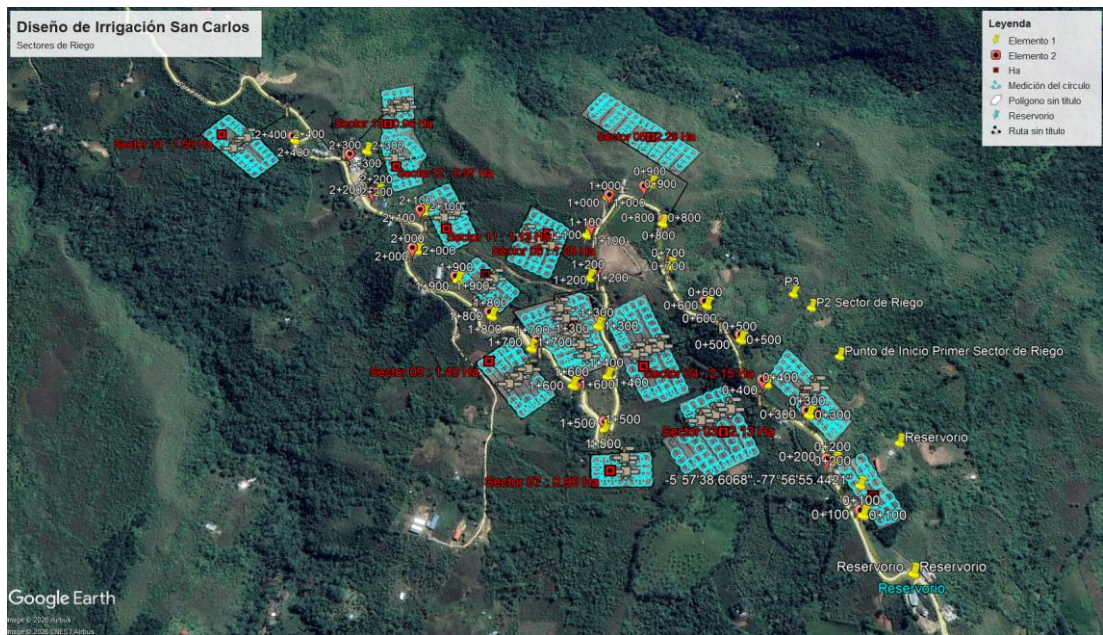


Fig. 3: Topographic-based sectorization of the study area showing the 15 defined irrigation sectors (base map derived from Google Earth and validated through field survey)

Table 10: Technical Characteristics of the Irrigation Sectors

Sector	Slope (%)	Pipe Class	Diameter (mm)	Hydrants (n)	Mobile Line (mm)
1	2–12	PN-10	110	4	38
2	8–18	PN-10	90	3	32
3	10–22	PN-10	90	3	32
4	5–15	PN-10	110	4	32
5	15–28	PN-10	110	4	38
6	12–25	PN-10	90	3	32
7	20–35	PN-10	75	2	25
8	8–18	PN-10	90	3	32
9	10–20	PN-10	110	4	32
10	25–40	PN-10	75	2	25
11	15–30	PN-10	90	3	32
12	18–35	PN-10	90	3	32
13	30–53	PN-10	75	2	25
14	10–25	PN-10	90	3	32

Source: Field measurements and AutoCAD spatial analysis

Discussion

Soil Plant Water Relations Under Sprinkler Irrigation

The edaphic characterization of the San Carlos study area revealed a predominance of sandy loam soils (32.14%) with favorable physical properties for sprinkler irrigation. The observed bulk density (1.22–1.35 g cm⁻³), total porosity (40.15–53.60%), and available water capacity (18.38–29.48%) indicate that these soils possess adequate aeration and water retention characteristics to support the cultivated crop species. The measured field capacity (36.7–58.96%) and permanent wilting point (18.32–29.48%) suggest that the soils can store sufficient moisture between irrigation events to buffer crops

against short-term water deficits, a critical advantage in the context of the 10-day irrigation interval employed in this study [29, 30].

The basic infiltration rate (mean 1.5 cm h^{-1}) exceeded the sprinkler precipitation rate (0.36 cm h^{-1}), ensuring that the applied water infiltrated the soil profile rather than generating surface runoff. This hydrological compatibility is essential for maximizing irrigation efficiency and minimizing water losses through overland flow. In steep-slope systems (up to 53%), such compatibility prevents soil erosion and nutrient leaching, which are common constraints in montane agriculture [31-33].

Physiological Basis of Yield Increases

The substantial yield increases observed across all 11 crops ranging from 20% (barley, bean, onion, pea) to 133% (eggplant) can be attributed to the alleviation of water stress during critical phenological stages. Under rainfed conditions, the erratic precipitation patterns and prolonged intra-seasonal dry spells characteristic of the San Carlos region expose crops to soil moisture deficits that trigger a cascade of physiological responses: stomatal closure, reduced CO_2 assimilation, impaired photosynthetic electron transport, and ultimately, diminished biomass accumulation and harvestable yields [2, 3].

The pronounced response of horticultural crops eggplant (133.33%), cucumber (100%), and lettuce (71.43%) reflects their high sensitivity to water stress during reproductive development. In eggplant and cucumber, water deficits during flowering and fruit set are known to induce flower abortion, fruit drop, and reduced fruit size, leading to substantial yield penalties [8, 34]. The supplemental irrigation provided by the sprinkler system effectively buffered these crops against such stress, allowing sustained carbon allocation to reproductive structures.

For cereals and grain legumes corn (75%), barley (20%), and bean (21.43%) the yield gains are likely attributable to improved water availability during the grain-filling period. Soil moisture deficits during this stage accelerate leaf senescence, reducing the duration of photosynthetic activity and impairing starch and protein accumulation in the grain [5]. The irrigation schedule (10-hour applications every 10 days) maintained adequate root-zone moisture throughout this critical window, resulting in increased harvest indices and marketable yields.

The carrot yield increase (50%) and celery yield increase (60%) further highlight the importance of consistent soil moisture for root and petiole development, as turgor pressure and cell expansion are highly dependent on water availability in these succulent tissues [26]. Collectively, these results underscore the biological principle that timely water application tailored to crop phenology is more critical than total water volume for optimizing yield in water-limited agroecosystems.

Comparative Performance and Design Considerations

The hydraulic design employed in this study (NAAN 5022 sprinklers, 0.26 L s^{-1} discharge, 22 m wetted diameter) operated within the manufacturer's recommended pressure range (2–4 atm), achieving adequate uniformity across the heterogeneous terrain. Compared to studies conducted on more uniform topography such as [21], who reported wetted diameters of 23–26 m under homogeneous conditions the reduced wetted diameter observed in San Carlos (22 m) likely reflects the combined effects of steep slopes (up to 53%) and the sandy loam texture, which limits the effective reach of sprinkler streams due to gravitational pull and soil infiltration characteristics [35].

The design's variable flow scheduling distributing 20.8 L s^{-1} across 14 sectors over a 9-day irrigation cycle represents a pragmatic adaptation to the topographic constraints of the Andean environment. This approach aligns with the findings of [36], who demonstrated that non-uniform topography requires careful lateral spacing, pressure regulation, and sector homogenization to maintain application efficiency. In the present study, the implementation of pressure-breaking chambers and strategically sized pipelines (25–38 mm diameters) mitigated friction losses and ensured that all sectors received the design flow rate despite substantial elevation differences.

However, slopes exceeding 50% (Sectors 7, 10, and 13) presented particular challenges, requiring shorter lateral lengths and smaller hose diameters (25 mm) to maintain operating pressures. Future iterations of this system would benefit from the integration of pressure-regulated sprinklers and automated flow control valves to further enhance uniformity in these extreme topographic zones [7].

Socio-Economic and Sustainability Implications

The economic indicators particularly the social NPV (S/. 877,689.11), IRR (95%), and B/C ratio (5.07) strongly support the viability of this intervention. Beyond the financial metrics, the yield increases translate directly into improved food security and

household income for the 20 participating families. In the context of rural-to-urban migration pressures in the Amazonas region, such productivity gains may serve as a countervailing force, strengthening the economic attractiveness of agricultural livelihoods and stemming the outflow of youth to urban centers [37-39].

The preservation of ecological flow in the Kaká and Calché streams, coupled with watershed reforestation using *Alnus glutinosa*, ensures the long-term sustainability of the water supply. This integrated approach combining hydraulic engineering, agronomic management, and watershed conservation provides a replicable model for other high-altitude communities facing similar water scarcity and topographic constraints. Moreover, the adoption of efficient irrigation technologies, as recommended by the (1), can increase productivity by up to 30% while reducing water losses by more than 40%, reinforcing the global relevance of the system designed in this study.

Limitations and Future Research Directions

While the findings are compelling, several limitations should be acknowledged. First, the before-after comparison design lacks a contemporaneous control group, which could confound the yield improvements with other environmental or management variables. Second, the study was conducted over a single agricultural season, and inter-annual climatic variability particularly ENSO-related fluctuations may influence the consistency of the observed yield responses. Third, the soil and yield measurements were confined to 14 sectors within a single community, limiting the generalizability of the findings to other Andean regions with differing edaphic and climatic conditions.

Future research should address these limitations through:

- (i) Multi-season replicated trials to assess inter-annual yield stability
- (ii) Inclusion of physiological measurements (e.g., stomatal conductance, leaf water potential, chlorophyll fluorescence) to elucidate the mechanistic basis of yield responses
- (iii) Assessment of the system's performance across a broader range of soil types and slope gradients
- (iv) Evaluation of the long-term socio-economic impacts, including household income diversification, nutrition outcomes, and community resilience to climatic shocks [40-42].

Conclusion

This study demonstrates that the implementation of a sprinkler irrigation system in the high-Andean community of San Carlos, Peru, significantly enhances the productivity of 11 key crops through the alleviation of phenological-stage water stress. The principal conclusions are as follows:

Biological productivity gains: Sprinkler irrigation resulted in statistically significant yield increases ranging from 20% (barley, bean, onion, pea) to 133% (eggplant), with the most pronounced responses observed in horticultural crops that are highly sensitive to water deficits during flowering and fruit set. These gains are attributable to sustained stomatal conductance, photosynthetic activity, and carbon allocation to harvestable organs under optimal soil moisture conditions.

Edaphic compatibility: The sandy loam soils predominant in the study area characterized by adequate porosity (40.15–53.60%), available water capacity (18.38–29.48%), and infiltration rates (mean 1.5 cm h⁻¹) are well-suited to sprinkler irrigation, provided that application rates do not exceed the soil's infiltration capacity.

Hydraulic feasibility: The designed system (20.8 L s⁻¹, 14 sectors, 9-day irrigation cycle) operates effectively under challenging topographic conditions (slopes up to 53%), achieving adequate water distribution through careful lateral sizing, pressure regulation, and sector-specific flow scheduling. The preservation of ecological flow and watershed reforestation ensure long-term water sustainability.

Socio-economic viability: The project is economically robust, with a social IRR of 95% and a B/C ratio of 5.07, translating to improved livelihoods, food security, and reduced out-migration pressures for the 20 beneficiary families.

Replicability and policy implications: The integrated framework combining hydraulic design, agronomic management, and watershed conservation provides a transferable model for sustainable agricultural intensification in other high-altitude, water-limited environments. Strengthening community participation, water governance, and capacity-building initiatives is essential to maximize the long-term development impact of such interventions.

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Author's Contributions

Juan Eduardo Suárez Rivadeneira: Conceptualization; Methodology; Investigation; Project administration; Writing – original draft; Writing review and edited; Supervision; Funding acquisition.

Freddy A. Manayay: Conceptualization; Methodology (agronomic protocols); Investigation (crop yield assessment); Writing review and edited; Validation.

Juan Francisco Robles Ruiz and Edgar Virgilio Bedoya Justo: Methodology (hydraulic design); Investigation (flow measurements, pipeline sizing); Data curation; Visualization (Figures 2 and 3).

Wilfredo Ruiz Camacho, Daniel Olivier Carranza Lizana and Eduer Blandimiro Bermilla Rodriguez: Investigation (field installation, soil sampling); Resources; Project administration (community liaison).

Daniel Carranza Montenegro and Angel Wilmer Paredes Guerrero: Conceptualization (pressure regulation strategy); Validation; Formal analysis (hydraulic modeling); Writing review and edited.

Edilbrando Vega Calderón, Juan Alberto Rojas Castillo: Formal analysis (economic evaluation: NPV, IRR, B/C); Data curation; Writing original draft (economic section); Visualization (Tables 8 and 9).

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