Uniformity of water distribution in sprinkler irrigation mini-cannons in a high Andean community in Peru

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Abstract. The objective of the present work was to determine the uniformity of water distribution through mini-irrigation cannons in conditions of the Peruvian altiplano, applying the formulas for the Christiansen Uniformity Coefficient (CUC) and the Distribution Coefficient (DU) and to interpret the incidence of wind on water distribution at three different times during the day (5:30-7:30, 12-14 and 16-18 hours). Necessary climatological information, field rainfall tests, emitter pressure, and flow, wind speed were collected to evaluate their influence on water application. Variable CUC and distribution uniformity results were obtained at the level of four demonstration plots, the maximum and minimum CUC was 87.42% and 55.34%, while the DU resulted with a maximum of 80.79% and 26. 88% minimum; it is worth mentioning that in the last two schedules, results were obtained that show a poor water distribution; while winds less than 2 m/s favored the uniform distribution of water applied through the sprinklers, affirming that it was possible to obtain an acceptable water distribution uniformity at the plot level considering the irrigation schedule.

1. Introduction

The greatest demand for water use is destined for agriculture [1], however, the current climate conditions require greater water demands; therefore, a technological transformation is necessary to improve its productivity and profitability, implementing irrigation systems that save more water and allow its adequate operation [2,3]. And when rainfall is insufficient to keep crops with available moisture, supplemental irrigation becomes necessary causing an increase in the cost of agricultural operations [2].

Sprinkler irrigation is suitable for most crops in the highlands and is adapted to almost all irrigable soils [4,5]. In addition, there is a wide variety of sprinklers that vary in working pressure and the amount of water they can irrigate in one position [6,7]. However, there are fundamental factors that affect the water distribution process performed by sprinklers, where it is limited by climatic conditions, mainly the wind hindering the uniform distribution of water [8] and others such as the slope of the terrain [9].

The sprinkler irrigation system applies water to the soil simulating rainfall by the pressure that flows the water and thus supplies the water requirements in quantity, quality, and opportunity, which requires the crop for its growth and production; however, the excess as the lack of water resource is essential to avoid losses of water for agriculture, this mainly in the Peruvian highlands, because it is a semi-arid region [10], where climatic conditions are severe, with strong winds and irregular rainfall [11].

This research aims to determine the uniformity of water distribution through mini irrigation cannons in the conditions of the Peruvian highlands, with the specific objectives of determining the pressure, discharge, and characteristics of the mini cannons installed in alfalfa plots to compare the proposed and current design, determine the uniformity coefficient and uniformity of distribution, using the formulas of Christiansen [12] y Merriam & Keller [13], to define the percentage of uniformity of distributed water and determine the influence of wind on the distribution of water.

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2. Materials and Methods

2.1. Study site

The research was carried out in a sprinkler irrigation system with double nozzle mini-cannons (10mm x 4mm), in irrigation blocks A and B, sectors 1-3, 2-4 respectively, in the rural community of Macari in the region of Puno, Peru, located between the coordinates 14° 46' 06" south latitude and 70° 54' 03" west longitude of the Greenwich meridian, above 3900 m.a.s.l.

Fig. 1. Configuration and measurement of water heights in rain gauges

2.2. Evaluation of the uniformity coefficient

To identify the water distribution pattern of the sprinkler, rainfall tests were carried out in columns and rows of 16x16 rain gauges, spaced 2.5 meters apart, with the middle sprinkler as the origin (of a total of 3 sprinklers in a unitary lateral line). In each plot, 3 tests were carried out at the three indicated times. The duration of each test was 2 hours. At the beginning of the operation of each sprinkler, the sprinklers were allowed enough time to stabilize, and the discharge and pressure of each sprinkler were measured. During the process, the correct operation of the sprinklers, wind direction, relative humidity, and temperature were evaluated with the use of a portable anemometer; the spray range was also measured. At the end of the 2-hour test, the volume of water collected in the rain gauges was measured using a graduated test tube (Figure 1).

With the height of water collected in the rain gauges, the uniformity coefficient was calculated using the equation proposed by Christiansen [12], this numerical value is the guaranteed uniformity index, expressed as a percentage of uniformity and defined by equation (1).

$$CU(\%) = 100 \left[1 - \frac{\sum_{i=1}^{n} |X_i - X_m|}{n * m} \right] \qquad (1)$$

Where: CU is the uniformity coefficient (%), X_i is the water height measured in each of the plot containers, X_m is the mean of the water height of all the containers and n is the total number of containers.

2.3. Evaluation of distribution uniformity

According to Merriam and Keller [13], it is the mean of the water height of the 25% of the rain gauges that receive the least water in a sampling, divided by the mean of the water height of the sampled plot. Uniformity by irrigation system area can be evaluated using equation (2).

$$DU = 100 \left[\frac{X_{1q}}{X_m} \right] \qquad (2)$$

Where: DU is the distribution uniformity (%), X_{1q} is the water height measured in the lower quartile and X_m is the mean of the water height of all containers.

2.3. Influence of the wind on sprinkler irrigation

Wind distorts precipitation patterns and consequently affects distribution uniformity [4,14]. The higher the wind speed, the greater the losses due to evaporation and dragging of water droplets. Therefore, wind is a factor that negatively affects sprinkler irrigation [15,16]. Table 1 shows some wind speed categories to be taken into account in the design of sprinkler irrigation.

Table 1. Wind speed categories

Category	Wind speed (m/s)
No wind	0.0 to 1.0
Medium winds	1.0 to 2.5
Strong winds	2.5 to 4.0
Very strong winds	Greater than 4.0 (*)

Source: Sprinkler irrigation by Sapir & Sne [17]

3.   Results and Discussion

3.1. *Average flow rates, pressures, wind speed, relative humidity, and temperature*

The data obtained from the rain gauges of water irrigated by three sprinklers in each plot, the operation was carried out for six sprinklers, considering that every certain irrigation time, the lateral should be moved parallel to its initial position making an irrigation frame of 20 m x 20 m, with a complete overlap.

Table 2 shows the flow rates obtained from the 12 sprinklers in the four sectors evaluated, which range from 2.34 m^3/h to 3.67 m^3/h. The highest discharge occurred at 5:30 hours and the lowest at 18:00 hours.

Table 2. Average flows obtained by plots

Plot	Flow rate	Evaluation time			Average
		5:30 – 7:30	12:00 – 14:00	16:00 – 18:00	
Block A-1	m^3/h	2.55	2.53	2.44	2.50
Block A-3	m^3/h	2.42	2.36	2.36	2.38
Block B-2	m^3/h	3.64	3.57	3.55	3.59
Block B-4	m^3/h	2.52	2.41	2.45	2.46
	Average	**2.78**	**2.72**	**2.70**	**2.74**

The flow rates are a function of the pressure, if the pressure is higher, the flow rate increases; however, we have data from technical specifications according to the type of sprinkler, where they indicate that at a pressure of 30 PSI (2.07 bar), there is a discharge of 6.40 m^3/h. It is necessary to mention that according to the proposed project, each sprinkler would work with a nominal flow of 6.36 m^3/h, very similar to the Sime Jolly sprinkler catalog, considering a pressure of 2 bars. Currently, there are sprinklers with 50% less discharge than those proposed. These low values are attributed to the dry season, and the losses that currently exist in the irrigation lateral connections and sprinkler risers; in addition, some users preferably flood their plots with the irrigation laterals during their entire irrigation shift.

The pressures are shown in Table 3, where they maintained values of 2.4 and 2.5 bar; in addition, it is worth mentioning that the topographic slope is sufficient to operate at the level of the entire system, and in the project, the sprinklers will work with pressures not less than 2 bar; therefore, the sprinklers are working with pressures recommended by the project; however, the maximum working pressure has not been mentioned. According to the catalog, Sime Jolly sprinklers with two nozzles (10mmx4mm) work with pressures from 30 to 70 PSI equivalent to 2 to 4.8 bar respectively.

Table 3. Average of pressures measured on the plots

Plot	Pressure	Evaluation time			Average
		5:30 – 7:30	12:00 – 14:00	16:00 – 18:00	
Block A-1	Bar	2.47	2.47	2.47	2.47
Block A-3	Bar	2.43	2.43	2.43	2.43
Block B-2	Bar	2.50	2.50	2.50	2.50
Block B-4	Bar	2.47	2.47	2.47	2.47
	Average	**2.47**	**2.47**	**2.47**	**2.47**

The highest wind speeds occurred from noon onwards, increasing these values in the afternoon, with a westerly direction (Table 4); from 5:30 to 7:30 hours, an average wind speed of 1.28 m/s was obtained, from 12:00 to 14:00 hours there were 4.25 m/s, and 5.05 m/s in the hours from 16:00 to 18:00 hours. The categorization of the winds is from 0 to 1.0 m/s without wind, 1.0 to 2.5 m/s medium winds, 2.5 to 4.0 m/s strong winds, and above 4.0 m/s are considered very strong winds and is not recommended to irrigate above the foliage [18]. On the other hand, CU values increase slightly in low wind speed conditions, values less than 2 m/s wind speed [19].

Table 4. Average wind speed per plot

Plot	Wind speed	Evaluation time			Average
		5:30 – 7:30	12:00 – 14:00	16:00 – 18:00	
Block A-1	m/s	0.70	2.80	2.5	1.75
Block A-3	m/s	2.00	5.30	7.40	4.90
Block B-2	m/s	0.50	3.80	3.10	2.47
Block B-4	m/s	1.90	5.10	7.20	4.73
	Average	**1.28**	**4.25**	**5.05**	**3.46**

The relative humidity is inversely proportional to temperature, where its minimum value corresponds to the hottest hours and the maximum value in the early morning, varying according to the time of day and the climatic conditions of the day (Table 5); in general, the altiplano maintains low relative humidity due to the dry air, typical of the Peruvian Andes. From December through April, relative humidity averages 66%, and 49% during May through November, divided into two seasons (rainy and dry).

High relative humidity values (RH=59.7%) were recorded at 5:30 hours, these values tend to decrease until reaching 29.8% at noon, then progressively increase again at 16:00 hours to 18:00 hours reaching 42.5%.

Table 5. Average temperature and relative humidity per plot

Test plot	Evaluation time					
	5:30 – 7:30		12:00 – 14:00		16:00 – 18:00	
	°C	R.H. (%)	°C	R.H. (%)	°C	R.H. (%)
Block A-1	8.50	75.80	15.55	52.37	13.40	42.00
Block A-3	13.95	60.40	16.15	16.37	8.30	25.83
Block B-2	14.35	65.47	17.15	35.17	7.95	76.60
Block B-4	13.80	37.13	17.45	15.13	9.40	25.57
	12.65	**59.70**	**16.58**	**29.76**	**9.76**	**42.50**

The temperatures are typical of the area and season of the year (winter). Table 5 shows minimum temperatures of 9.76°C after 16:00 hours, at midday maximum temperatures of 16.58°C; on the other hand, in the first hours of the day, the average temperature was 12.65°C.

3.2 Uniformity coefficient and distribution coefficient

The figures below describe the behavior of uniformity coefficients and distribution uniformities of the experimental plots (called blocks A and B).
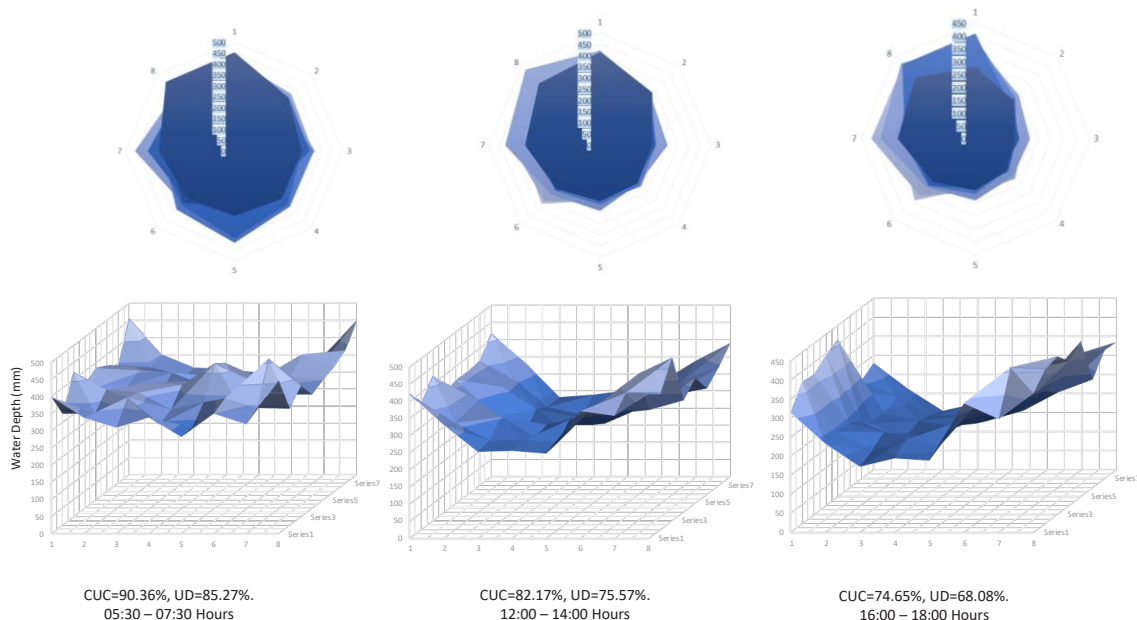

CUC=90.36%, UD=85.27%.
05:30 – 07:30 Hours

CUC=82.17%, UD=75.57%.
12:00 – 14:00 Hours

CUC=74.65%, UD=68.08%.
16:00 – 18:00 Hours

Fig. 2. Irrigation distribution in the plot in block A-1

CUC=90.10%, UD=85.98%.
05:30 – 07:30 Hours

CUC=71.40%, UD=55.57%.
12:00 – 14:00 Hours

CUC=63.41%, UD=45.27%.
16:00 – 18:00 Hours

Fig. 3. Irrigation distribution in the plot in block A-3

CUC=81.96%, UD=75.20%.
05:30 – 07:30 Hours

CUC=83.62%, UD=71.77%.
12:00 – 14:00 Hours

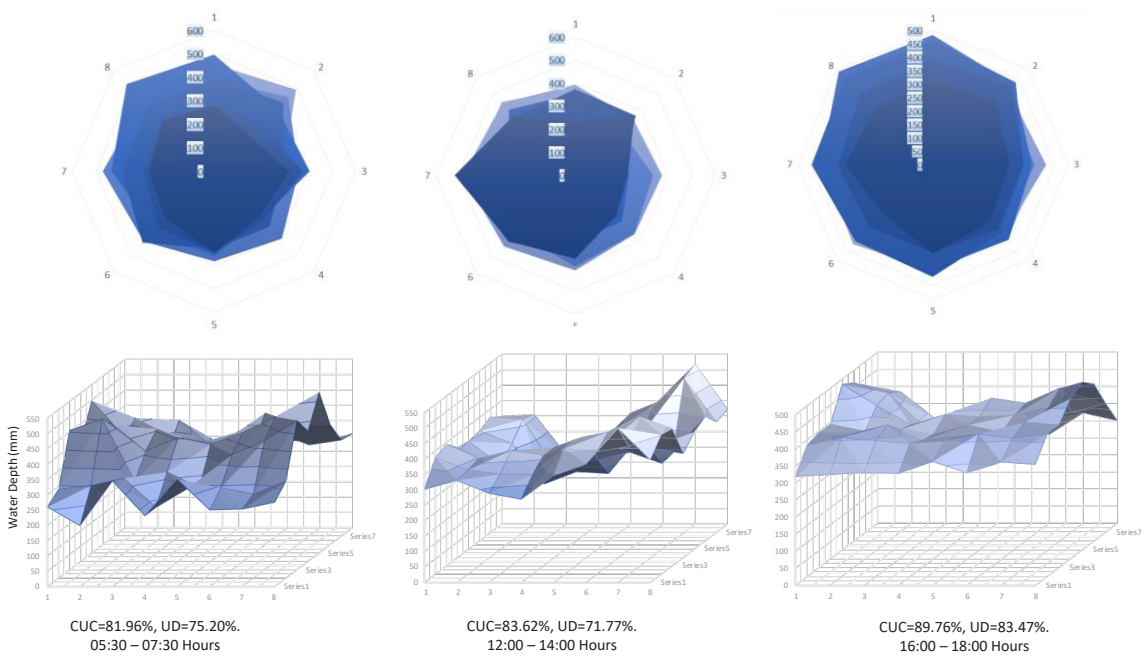CUC=89.76%, UD=83.47%.
16:00 – 18:00 Hours
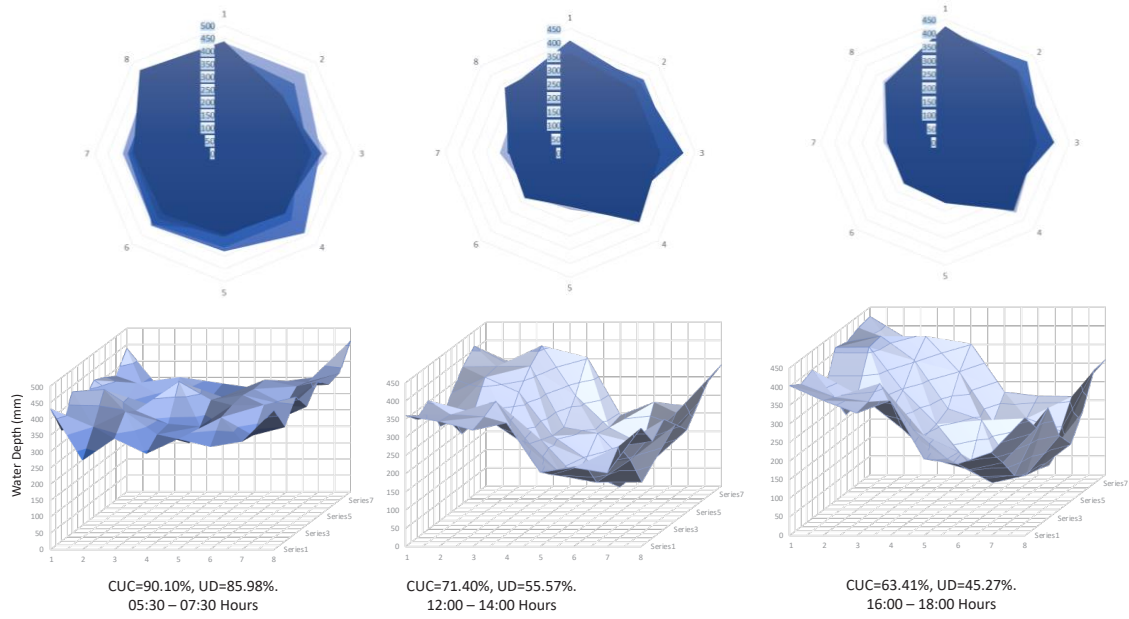
Fig. 4. Irrigation distribution in the plot in block B-2

Figures 2, 3, 4, and 5 show the processing of the data obtained through the rainfall tests, thus obtaining the CUC and DU for the demonstration plots. Working with a total of 128 data from rain gauges (water collected), in the three proposed schedules, to verify the incidence of wind speed on water distribution.
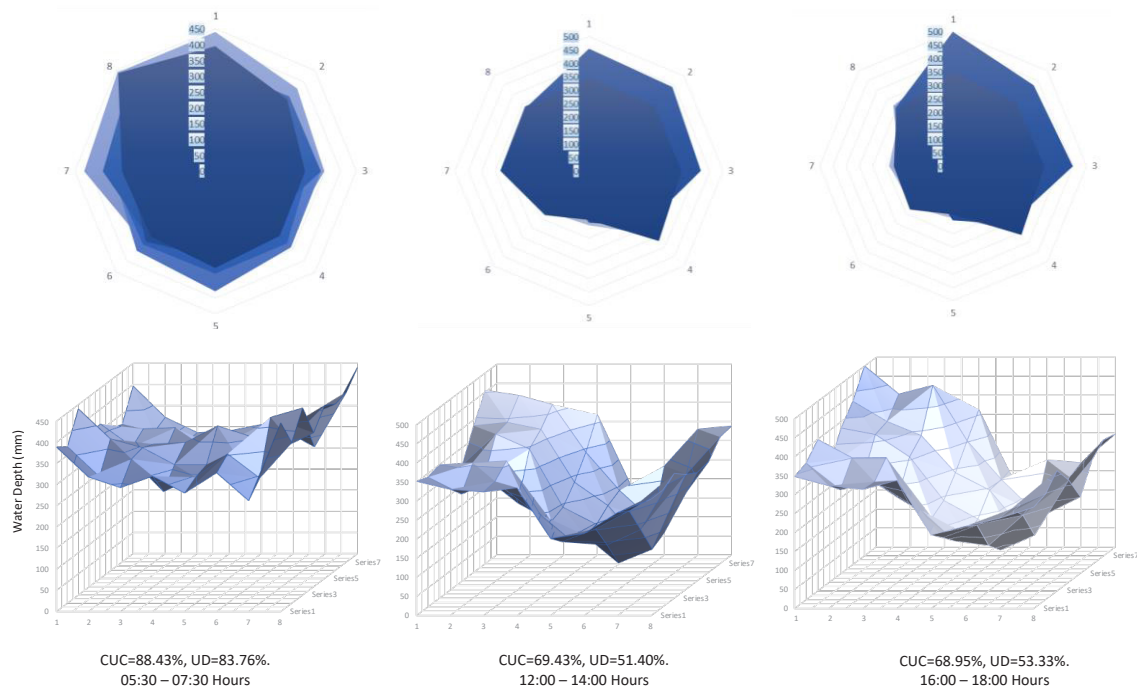
CUC=88.43%, UD=83.76%.
05:30 – 07:30 Hours

CUC=69.43%, UD=51.40%.
12:00 – 14:00 Hours

CUC=68.95%, UD=53.33%.
16:00 – 18:00 Hours

Fig. 5. Irrigation distribution in the plot in block B-4

Table 6. Summary of CUC and DU values as a function of wind speed

Plot	Test time	Cristiansen (1942)				Merrian & Keller (1978)				Wind speed	
		CU (%)	Average/ plot	Average/ test time	Max/min	DU (%)	Average / plot	Average/ test time	Max/mi n	(m/s)	Average/ test time
Block A-1	5:30–7:30	81.86		81.49	87.42	75.94		73.56	80.79	0.7	1.28
	12:00–14:00	76.90	76.31	70.53	55.34	67.24	68.71	52.14	26.88	2.8	4.25
	16:00–18:00	70.18				62.94		52.09		2.5	5.05
Block A-3	5:30–7:30	84.00				77.04				2	
	12:00–14:00	65.44	68.26			40.26	48.06			5.3	
	16:00–18:00	55.34				26.88				7.4	
Block B-2	5:30–7:30	77.80				66.53				0.5	
	12:00–14:00	75.21	80.14			64.98	70.77			3.8	
	16:00–18:00	87.42				80.79				3.1	
Block B-4	5:30–7:30	82.29				74.72				1.9	
	12:00–14:00	64.56	69.92			36.08	49.52			5.1	
	16:00–18:00	62.90				37.75				7.2	

Table 6 shows the values obtained for the Christiansen uniformity coefficient and distribution uniformity for each schedule, averages per plot and test hour, as well as the recorded wind speeds.
A variety of values of uniformity coefficients and distribution uniformity were obtained from the different evaluations according to test schedules as shown in Table 10, the minimum CUC is 55.34%, while in DU the minimum value was 26.88%, which results in wind speeds of 7.4 m/s; in the schedule from 16 to 18 hours. The average Christiansen uniformity coefficient calculated from 5:30 to 7:30 hours was 81.49%, which is considered a good water distribution, with a distribution uniformity of 73.56%, the DU value is below the recommended by Merriam and Keller (80%);

however, it would still be considered a regular water application; as for the average CUC from 12 to 14 hours, it is 70.53% and 52.14% for the 12 to 14 hours. 53% and 52.14% of DU, on the other hand in the schedule from 16 to 18 hours the average CUC and DU are 68.96% and 52.09% respectively, it is necessary to emphasize in the last two schedules that results were obtained, indicating a low distribution of water at plot level.

The CUC and DU values obtained are estimated at acceptable values considering the irrigation schedule. For the Christiansen uniformity coefficient, there is no record of neighboring areas; however, there are evaluations made with emitters of similar flow and current pressure of the mini-cannons. Durand [20] in 4 Technified Irrigation Business Management Groups of the Huambo-Caylloma district, obtained values of 72.35% of CUC, for VYR-36 sprinklers and a CUC of 48.91 in RC-235/2 sprinklers, in both cases these values are lower than those recommended by Christiansen, where there was a clear incidence of wind speed. For De La Cruz [21], in the district of Socos-Huamanga, the result of his evaluation of the CUC, with Silver BR ¾" sprinklers, was from 78.90% to 80.75%, in a schedule from 9 to 10:30 hours with absent winds, and according to Poma [22], 61.04% as distribution uniformity considered as a low value, in the elevation with VYR50 sprinklers in the experimental station Choquenaira, Bolivia. This suggests us to take into consideration various factors and better ways to control and/or optimize the operation of sprinkler irrigation [16,18,23].

4. Conclusions

2. The research proposed only one sprinkler characteristic in the initial design, in the discharge of the emitters it was determined that the Sime Jolly mini aluminum sprinklers with double nozzles (10 mm and 4 mm), discharge flows from 2.36 m^3/h to 3.67 m^3/h, according to the proposed design, with losses of 42.3% to 62.9% of the sprinkler flow; also, pressures of 2.4 to 2.5 bars were recorded, these values are within the range of operation of these emitters.

3. Acceptable CUC and DU values were obtained during the first hours of the day for the most part; however, water distribution has been distorted by the presence of strong winds after midday; nevertheless, water distribution uniformity is acceptable at the plot level considering specific irrigation schedules.

4. Wind speed had an effect on water distribution, causing low uniformities in the evaluation; minimum values of 0.3 m/s were obtained, and the most abrasive winds were up to 10.7 m/s, with a predominant westerly direction; wind speeds lower than 2 m/s had no effect on the uniformity of water application.

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