Shahid Chamran University of Ahvaz

Irrigation Sciences and Engineering (JISE)
Vol. 44, No. 2, Summer 2021, p. 11-24

Original Paper

Journal homepage: https://jise.scu.ac.ir

Performance Assessment of Wheel Move and Linear Moving Irrigation Systems in Different Climatic Conditions

Z. Bigdeli[1] and H. Ojaghlou[2*]

1- Ph.D. Candidate, Department of Water Engineering, University of Tabriz, Tabriz, Iran
2- Corresponding Author, Assistant Professor, Department of Water Science and Engineering, University of Zanjan, Zanjan, Iran. (*ojaghlou@znu.ac.ir*.)*

ARTICLE INFO

Artlcle history:
Received: 5 September 2020
Revised: 12 March 2021
Accepted: 14 March 2021

Keywords:
Wheel move, Irrigation system, distribution uniformity; application efficiency; wind speed.

TO CITE THIS ARTICLE:

Bigdeli, Z., Ojaghlou, H. (2021). 'Performance Assessment of Wheel Move and Linear Moving Irrigation Systems in Different Climatic Conditions', Irrigation Sciences and Engineering, 44 (2), pp. 11-24. doi: 10.22055/jise.2021.34738.1928.

Abstract
The use of sprinkler irrigation systems have been significantly expanded over the last decades in Iran. Among the sprinkler irrigation systems, solid set systems have recently aroused much attention. However, fewer studies focused on the performance of mechanized sprinkler systems such as wheel move (WM) and linear moving system (LM). In this research, LM system and six WM systems were evaluated under two different climatic conditions, so that 12 and 8 field assessment tests were conducted for the WM and LM systems, respectively. Three indicators including Christiansen's uniformity coefficient (CU), distribution uniformity of low quarter (DUlq), and application efficiency of low quarter (AELQ) were used to describe the performance of the selected irrigation systems. As for WM systems, the calculated CU averages were 77.9% and 64.7% for low and high wind speed conditions, respectively, and also the number for LM system shown to be 81.7% and 72.3%, respectively. Regarding the same conditions, the AELQ averages for WM systems were seen to be 59.9% and 38.6%, respectively, and for LM system were 70.2% and 54.3%, respectively. The increase in the wind speed led to a reduction in water distribution uniformity, and however, wind effect on the performance of the WM systems was more than the LM system. Thus, it deserves to be pointed out that the LM system is an appropriate option compared to the WM system in various climatic conditions. Water pressure, sprinklers distance, and irrigation program were identified as the other factors, affecting the performance of sprinkler irrigation systems.

Introduction

Agriculture plays an important role in ensuring food security and economic growth in developing countries. Irrigated lands produce more than 40% of the total production of food in the world (Postel 1999; Evans and Sadler 2008; Stone et al. 2010). Food production requires a noticeable amount of irrigation water, where higher water use efficiency plays a major role in increasing sustainably (Noreldin et al., 2015). According to the last research, the largest amount of consumption of water resources is allocated to the agriculture sector in Iran. The share of water abstraction in the agricultural sector in the world is 69%, in the Middle East 84% and in Iran 92% (Marzban et al., 2019). One of the most critical obstacles that the country might be faced with might be water scarcity and lack of needed foods. Thus, using sprinkler irrigation systems for reducing water usage needs to be the first priority. Even though sprinkler irrigation systems have been well developed over the last decade, such systems should still be evaluated continuously. Continuous monitoring and evaluation of the sprinklers may lead to an increase in the efficiency of irrigation systems. Linear moving (LM) and wheel move (WM) systems are the most common modern irrigation systems for agriculture and also newly employed systems in Iran. Therefore, more studies are on the call to clarify the performance and evaluation of these systems. The modern sprinkler irrigation systems have attracted many enthusiasts during the last decades. The wind significantly affects the performance of the sprinkler irrigation system since it reduces the amount of water use efficiency and distribution uniformity (Dechmi et al., 2003; Kara et al., 2008; Dukes., 2006; Li et al., 2016). Therefore, developing new ways to increase the efficiency and uniformity of water distribution in windy conditions is of high importance among scientific community. Although more studies about systems evaluation have been accomplished around the world, the results of these researches cannot be generalized to the other parts of the world due to varieties in climates, types of plants, soil, and characteristics of irrigation systems (Al-Ghobari, 2010). The distribution uniformity coefficient in low energy precision application (LEPA) irrigation systems was reported in the range of 94% to 97% (Schneider, 2000). Dukes (2006) studied the effect of wind speed and pressure on the LM irrigation system uniformity, revealing that the coefficient of uniformity of the LDN sprinklers was significantly improved at higher wind speeds (5.0-6.6 m/s) and under low operation pressure (<97 kPa) from 70% to 85%. Hence, the Wobbling diffuser (IWOB) sprinklers produced a greater distribution uniformity in comparison to the LDN sprinklers under all experiments. Nine different sprinkler irrigation systems, including solid set and WM systems, were evaluated in the agricultural area located in Arak province, Iran. The values of CU, DU, PELQ, AELQ and ΔP_{max} for the solid set systems were reported as 76.16%, 64.53%, 55.56%, 52.48% and 45.23%, and for WM systems, they were reported as 82.86%, 76.02%, 67%, 67% and 29%, respectively. The WM systems in general work more effectively in comparison to the solid set systems (Boroomand Nasab et al., 2007). Evaluation of different portable sprinkler irrigation systems in Nigeria showed that the water application efficiency was in the range of 86% to 87% (Ahaneku, 2010). Chávez et al. (2010) modeled the motion of a LM system, and developed an algorithm for irrigation variables. The results have shown that irrigation application errors were reduced from 20% to 5% in the subsequent irrigation application. Seyyedi et al. (2011) investigated the dependence of overland rainfall estimated from Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) on the soil moisture conditions at the land surface. The results of the analysis of MESONET-to-TMI ratio values showed that TMI values for surface rainfall intensities with less than 12 (mm/h) were overestimated, so the amount of the overestimation over the wet area was lower than the dry area. Ghorbani and Amini (2011) evaluated sprinkler irrigation system operations in Chaharmahal and Bakhtiari province of Iran. They concluded that the conventional sprinkler system (solid set systems) has a better water application efficiencies and irrigation adequacy in comparison to WM and center pivot systems. Andrés et al. (2014) carried out a demonstration analysis of sprinkler irrigation management in the LASESA district, Monegros in Spain. The results showed an average irrigation efficiency of 76%. The major drawbacks discovered in the irrigation management were low irrigation efficiency for Corn (73%) and high water deficit for Alfalfa (16%). Msibi’s group (2014) evaluated the performance of center pivot system and its effect on the yield of Ubombo sugar cane cultivated in Swaziland. The performance of center pivot systems was so desirable in which the values of CU were 85% and DU values were 75%. Sui et al. (2015) studied the water distribution uniformity of center pivot irrigation system. For the constant application rate, CU was calculated as 86.5% and average CU in the variable rate (30%, 50%, 70% and 100%) was 84.3%. The highest CU 89.2%) was also obtained in the 100% of application rate. Rossi and co-workers (2015) studied efficiency improvement techniques in LM systems through moderate run-off–run-on control strategy. Modeling results indicated that the irrigation efficiencies could be improved by occurrence of runoff–run-on phenomena in a limited compatibility with adequate soil moisture uniformity at the end of the last span. Faria et al. (2016) studied the influence of the wind speed on water distribution uniformity of LM system in the state of South of Rio Grande do Sul, Brazil. Desirable water distribution uniformity was demonstrated in high wind speed conditions. Abedinpour (2017) described field evaluation of center pivot system with different working speeds (S1, S2 and S3) in the North-East of Iran. Based on field observations, CU values were obtained as 80.3%, 82.7% and 86% at the different speeds of S1, S2 and S3, respectively. Application efficiencies (AELQ and PELQ) were under the acceptable standard level of 90% for all speeds. Strip method applied for the SDE prediction of the LM system based on weather parameters by Sadeghi et al. (2017) at Washington State University’s Irrigated Agricultural Research Center. The modeling results showed that temperature, wind speed, and relative humidity as the effective explanatory parameters. In the current study, simultaneous evaluation of several WM irrigation systems were performed where the main focus was on the assessment of each sprinkler machine and its performance was compared to LM irrigation system. The effect of wind speed on the water distribution uniformity and water application efficiency were investigated for both systems.

Materials and Methods

Site descriptions

Six farmlands under WM irrigation systems were selected randomly in Zanjan Province of Iran. Another farm land by Takestan city (location in google maps: 36°11'33.3"N 50°10'10.9"E) was selected to evaluate the performance of LM irrigation system. Regarding the only two existing linear moving systems in the study area, and however, comparing the performance of the sprinkle irrigation systems in the same climatic conditions is acceptable, so the experiments focused on one farm. However, the evaluation tests were performed continuously throughout the growing season to achieve a more reliable result. The annual precipitation and average temperature of the study area are in the range of 250-300 mm and 12-17 °C, respectively. The climatic factors e.g., wind speed are so effective in the performance of sprinkler irrigation systems. Thus, the location of the fields have been selected in a way by which different climatic conditions in terms of wind speed are taken into account. Fig. (1) represents the location of the experimental farms.

Field measurements

Before conducting the evaluation tests, basic information such as a topographic map, crop pattern, meteorological data, physical characteristics of the soil, characteristics of the systems including pump discharge and pressure, main pipes diameters, sprinklers type, lateral pipes diameters and system layout map were collected.

 DOI: 10.22055/JISE.2021.34738.1928

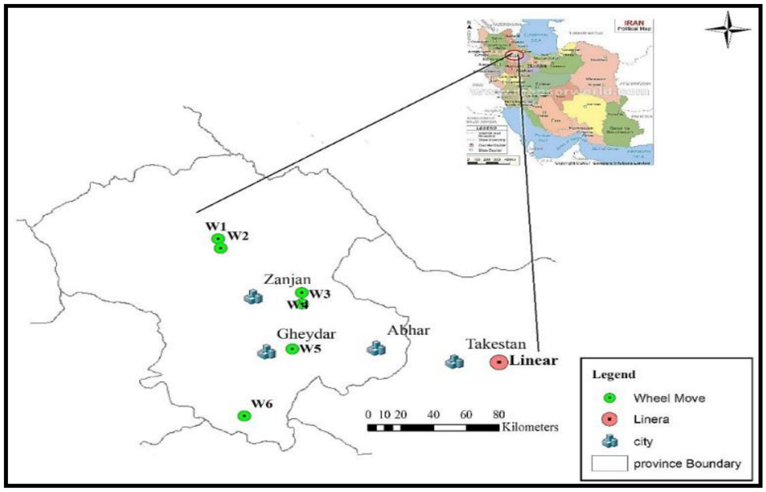

Fig. 1- Location of the experimental farms in Zanjan plain, Iran

In each experiment, water, soil, plant and climate data were measured. The water factors such as sprinklers discharge, water pressure at nozzles, and depth of collected water in the catch cans were measured. Sprinkler discharge was measured by volumetric approach and water jet pressure was gained by a barometer for each test. Soil features such as bulk density, texture, moisture content before irrigation to estimate soil moisture deficit (SMD), soil moisture content at field capacity and permanent wilting point as well as infiltration rate were determined for experimental farms. The most important plant measured parameter in this research was the depth of developed root (depending on the type of plant between 0 and 120 cm) to determine net water requirements of the plants. Climate parameters such as air humidity, evaporation from the surface of the water and wind speed were collected from nearest meteorological stations and also measured during the tests. In order to determine the uniformity of water distribution, the catch cans were installed at a 3 m distance from each other in a rectangular grid. Catch can test were performed by ASABE (2007), Keller and Bliesner (1990), and Merriam and Keller (1978). As can be seen in Table 1, the important data of experimental farms under WM systems illustrated. Soil physical properties of farms under WM systems are presented in Table 2. During the irrigation season, 12 evaluation tests were conducted for low (≤3 km/h) and high (≥10 km/h) wind speed conditions at the farms under the WM system. Wind speed was the main criterion in choosing the irrigation events for evaluation tests. The experiments under low and high wind speed conditions were performed from the 2nd to 3^{d} and from 7th to 9th irrigation events, respectively. The physical properties of LM system were measured as well. The length of LM machine was 330 m, including six spans with the exception of the last one with 50 m length. The distance between the sprinklers was also 5 m. The irrigation frequencies in this farm was between 2 and 4 days which varied during the growing season. Similar to fields under the WM system, the obtained data for the farm under LM system also were grouped in two general sections of fixed-form data and variable-from data. The fixed-form data included the physical characteristics of the soil, system layout map and the physical characteristics of the LM system. This data was collected before performing the evaluation tests. Variable-form data included soil moisture (before and after applying irrigation), plant’s developed root depth, the depth of collected water in catch cans, sprinklers discharge and pressure, evaporation from water surface and wind speed. At each assessment, the wind speed and evaporation from the water surface were determined by an anemometer and three test catch cans. The catch cans were installed in three rows with 3 m of intervals (Fig. 2). After passing the machine through the catch cans, the depth of collected water was measured by a scaled cylinder. The properties of the LM irrigation system are shown in Table 3. Table 4 presents the physical characteristics of the soil of the farm for Sharif Abad area. Overall, eight evaluation tests were conducted in the farm under LM system during the irrigation season. The time of the experiments was chosen in a way that enabled the examination of the system for different wind speeds. Four evaluation tests were performed in low wind speed conditions (2-4 km/s) and four tests in high wind speed conditions (≥10 km/h).

Table 1- Some important characteristics of selected farms under WM system

Experimental fields	Production	Sprinkler model	Sprinkler spacing (m×m)	Sprinkler discharge (l/s)	Operation pressures at the beginning of the lateral (atm)
UW	Alfalfa	LANCER	15×12	2.67	4
UW	Alfalfa	VYR	15×12	2.67	4
PW	Wheat	ZHALE -5	12.5×8.5	2.67	4
PW	Potato	ZHALE -5	10×16	2.67	4
BWvw	Wheat	VYR-35	18×12	2.67	4
GWvw	Wheat	VYR-35	18×12	2.67	4

Table 2- Physical properties of the soil at farms under wheel move systems

Farm	Depth (cm)	Texture	Clay(%)	Silt(%)	Sand(%)	Soil bulk density (gr/cm^3)	θ_{FC} (cm^3/cm^3)	θ_{PWP} (cm3/cm^3)
W1	0-30	silty clay loam	36	48	16	1.31	25.9	13.1
	30-60	sandy loam	19	14	67	1.33	27.8	10.5
W2	0-30	silty clay loam	29	53	18	1.28	26.9	11.7
	30-60	sandy clay	35	5	60	1.37	29.5	11.1
W3	0-30	silty clay	45	45	10	1.29	24.4	13.4
	30-60	silty clay loam	34	50	16	1.21	24.9	13.0
W4	0-30	silty clay loam	32	49	19	1.20	28.9	13.7
	30-60	silty clay	41	42	17	1.32	24.4	13.4
W5	0-30	sandy clay	43	7	50	1.40	23.9	10.8
	30-60	sandy clay	44	9	47	1.43	22.5	10.6
W6	0-30	sandy clay	40	14	46	1.33	21.9	11.4
	30-60	silty clay loam	37	46	17	1.27	24.9	12.8

Table 3- characteristics of farm with LM irrigation system

Experimental fields	Production	Sprinkler model	Sprinkler Spacing (m×m)	System Discharge (l/s)	Average Sprinkler ischarge (l/s)	›eration pressures : the beginning of the lateral (atm)
Sharifabad	Forage corn	Spray	6	30	0.35	2.9

Table 4- Physical properties of the soil at farm under linear moving system

Depth (cm)	Texture	Clay(%)	Silt(%)	Sand(%)	Soil bulk density (gr/cm^3)	θ_{FC} (cm^3/cm^3)	θ_{PWP} (cm^3/cm^3)
0-30	Silt Loam	18.7	53.83	27.47	1.59	28.2	11.9
30-60	Silt Loam	18.2	50.33	31.47	1.75	27.4	11.8
60-90	Silt Loam	22.2	54.44	21.36	1.74	29.85	0.13

Fig. 2- Determining the uniformity of water distribution - LM system

Indicators of evaluation

In order to evaluate the performance of WM and LM irrigation systems, wind drift and evaporation losses, Christiansen's uniformity coefficient (CU), distribution uniformity of low quarter (DUlq) and application efficiency of low quarter (AELQ) were applied. The percentage of spray losses were determined by calculating the difference between the volumes of water sprayed from the collected sprinklers in the catch cans. The other indicators were estimated using the following equations:

$$CU = \left[1 - \frac{\sum |D_i - \overline{D}|}{\overline{D} \times n}\right] \times 100 \quad (1)$$

$$DU_{lq} = \frac{D_{lq}}{\overline{D}} \quad (2)$$

$$\mathrm{SMD} = (\theta_{fc} - \theta_i).\rho_b.dr \quad (3)$$

$$\begin{cases} AELQ = \dfrac{D_{lq}}{D_{app}}, if : D_{lq} \prec SMD \\ AELQ = \dfrac{SMD}{D_{app}}, if : D_{lq} \geq SMD \end{cases} \quad (4)$$

Where: D_i is depth of water measured in the catch cans (mm), $\overline{D}$ delineates average depth of water measured from catch cans (mm), n is the number of catch cans used in the evaluation, D_{lq} shows average low quarter depth of water caught (mm), D_{app} and SMD are also the average depth of applied water and soil moisture deficit (mm), respectively. θ_{fc}, θ_i, and ρ_b are soil moisture at field capacity point (%), soil moisture before irrigation (%), Soil bulk density (gr/cm^3), respectively. Also, d_r is Plant root depth (mm).

Results and Discussion

Evaporation and wind drift losses: The discharge rate of sprinklers, the average depth of water application, the average depth of collected water in catch cans and spray losses for WM systems are illustrated in table (5). For each farm, the amounts of applied water depth were kept the same for both evaluation tests. The water depth varied between 25.84 mm and 54.67 mm for various fields. The depths of applied water were the same for two climatic conditions, which is an indication of no flexible and optimal management in the farms. The average amount of water depth reached the ground for two different climate conditions (low and high wind speed) were 33.91 mm and 26.75 mm, respectively. Increasing the wind speed in the second evaluation tests resulted in an increase in the spray's losses. The minimum and maximum wind draft losses for the evaluation tests under low wind speed were 9.07% and 18.38%, and for high wind speed were 26.63% and 34.76%, respectively. On average, increase in wind speed resulted in a wind draft loss of 18.5%. The applied water depth, wind drift and evaporation losses in the LM system are presented in Table (6). In the LM, unlike the WM systems, the amount of applied water varied during the crop season (in the range of 33.8 to 75.0 mm). The wind drift losses in the LM system were observed as 4.8% to 16.7%, with an average of 9.5%. The average wind drift and evaporation losses in both low and high wind speed conditions were calculated as 7.1% and 13.6%, respectively. Thus, increase in the wind speed caused a higher wind drift and evaporation losses by 6.5%. The results showed that the wind drift and evaporation losses in the WM systems were more than those of the LM system in both low and high wind speed conditions. On average, the amount of water losses by wind drift and evaporation in the LM system was 11.5% less than the WM systems. Results indicated that, the water losses in the WM systems were more than those of the LM system in any climatic conditions.

Table 5- Water balance parameters in evaluation tests of WM systems

Farms	Sprinkler discharge (l/s)		Average of applied water depth (mm)		Average of collected water in catch-cans (mm)		Wind drift and evaporation losses (%)	
	High wind	Low wind	High wind	Low wind	High wind	Low wind	High wind	Low wind
W1	0.65	0.65	39.23	39.23	28.78	35.44	26.63	9.66
W2	0.43	0.43	25.84	25.84	17.92	23.5٠	30.66	9.07
W3	0.44	0.44	51.33	51.33	23.86	26.1١	32.68	10.99
W4	0.41	0.41	54.67	54.67	30.57	48.96	34.76	10.42
W5	0.65	0.65	32.69	32.69	22.6٠	28.4٠	30.87	13.13
W6	0.43	0.43	50.26	50.26	36.78	41.02	26.8٠	18.38
Minimum	0.41	0.41	25.84	25.84	17.92	23.5٠	26.63	٠9.07
Maximum	0.65	0.65	54.67	54.67	36.78	48.96	34.76	18.38
Average	0.50	0.50	42.34	43.34	26.75	23.91	30.40	11.94

Table 6- Water balance parameters in evaluation tests of LM systems

Irrigation Event	Wind speed (km/h)	Applied water depth (mm)	depth of collected water in Catch-cans (mm)	Wind drift and evaporation losses (%)
Second	3.6	38.1	35.53	6.7
Third	10.8	41.3	36.58	11.4
Fourth	12.3	40.7	35.53	12.7
Fifth	4.1	43.1	40.18	6.8
Seventh	3.5	75.0	71.38	4.8
Eighth	9.8	33.8	28.17	16.7
Ninth	3.9	52.4	48.5	7.4
Eleventh	5.4	44.7	40.38	9.7
Minimum	3.5	33.8	28.2	4.8
Maximum	12.3	75.0	71.4	16.7
Average	6.7	46.1	42.0	9.5

Water distribution uniformity

Christiansen's uniformity coefficient (CU) and distribution uniformity of low quarter (DUlq) were utilized for the descriptions of water distribution uniformity. Fig.3 demonstrates the CU coefficients in the WM systems. The values of this indicator were obtained in the range of 61.2% to 86.6% for low wind speed condition, and also obtained for high wind speed conditions between 49.5% and 75.6%, respectively. The average values of CU indicated in two climate conditions were calculated as 77.9% and 64.7%, respectively. Boroomand Nasab et al. (2007) reported the average of CU and DUlq coefficients in WM systems as 82.8% and 76%, respectively. The increase in wind speed has led to a reduction in water distribution uniformity by 13.2%. Based on the obtained values, the uniformity of water distribution in the WM systems was evaluated moderate to good in low (1-3 km/hr) and moderate in high (10-15 km/h) wind speed conditions. The distribution uniformity of low quarter in the WM systems can be seen in Fig. 4. DUlq index values for low and high wind speed conditions were measured in the range of 54.6% to 81.5% and 33.6% to 76.4%, respectively. The average values of the indices were also gained as 67.9% and 55.0%, respectively. The amount of uniformity dropped by 12% due to an increase in wind speed from 3 to 12 km/h. In general, by increasing the wind speed, both the CU and DUlq indicators decreased by a similar ratio. Fig. (5) Shows the water distribution patterns in the WM systems. Water pressure changes in lateral were also identified as the second reducing factor in the uniformity of water distribution in the WM systems, so the average variation of water pressure was measured as 19.7%.

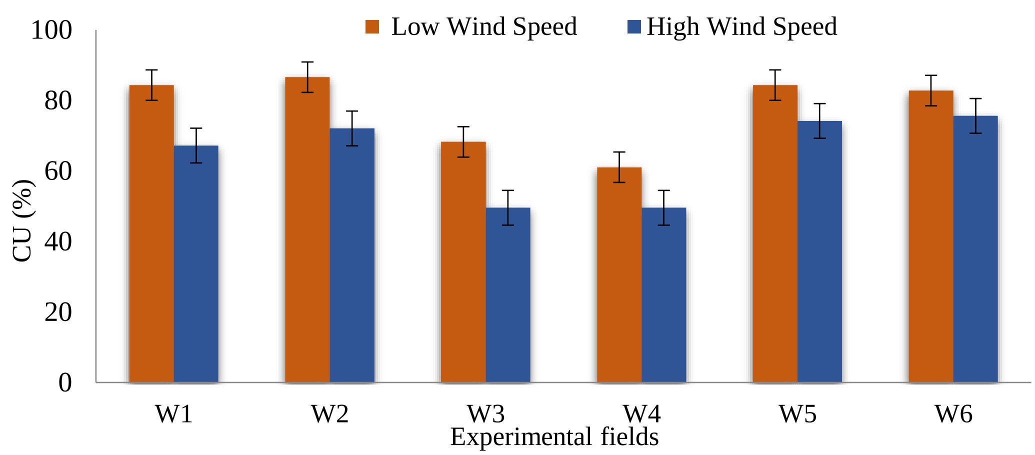

Fig. 3- Christensen uniformity coefficient for WM systems

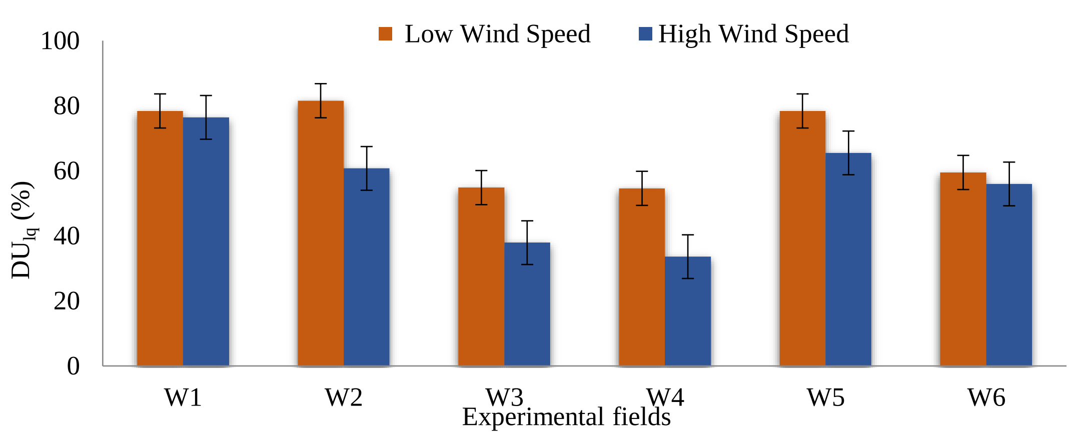

Fig. 4- The values of distribution uniformity of low quarter for WM systems

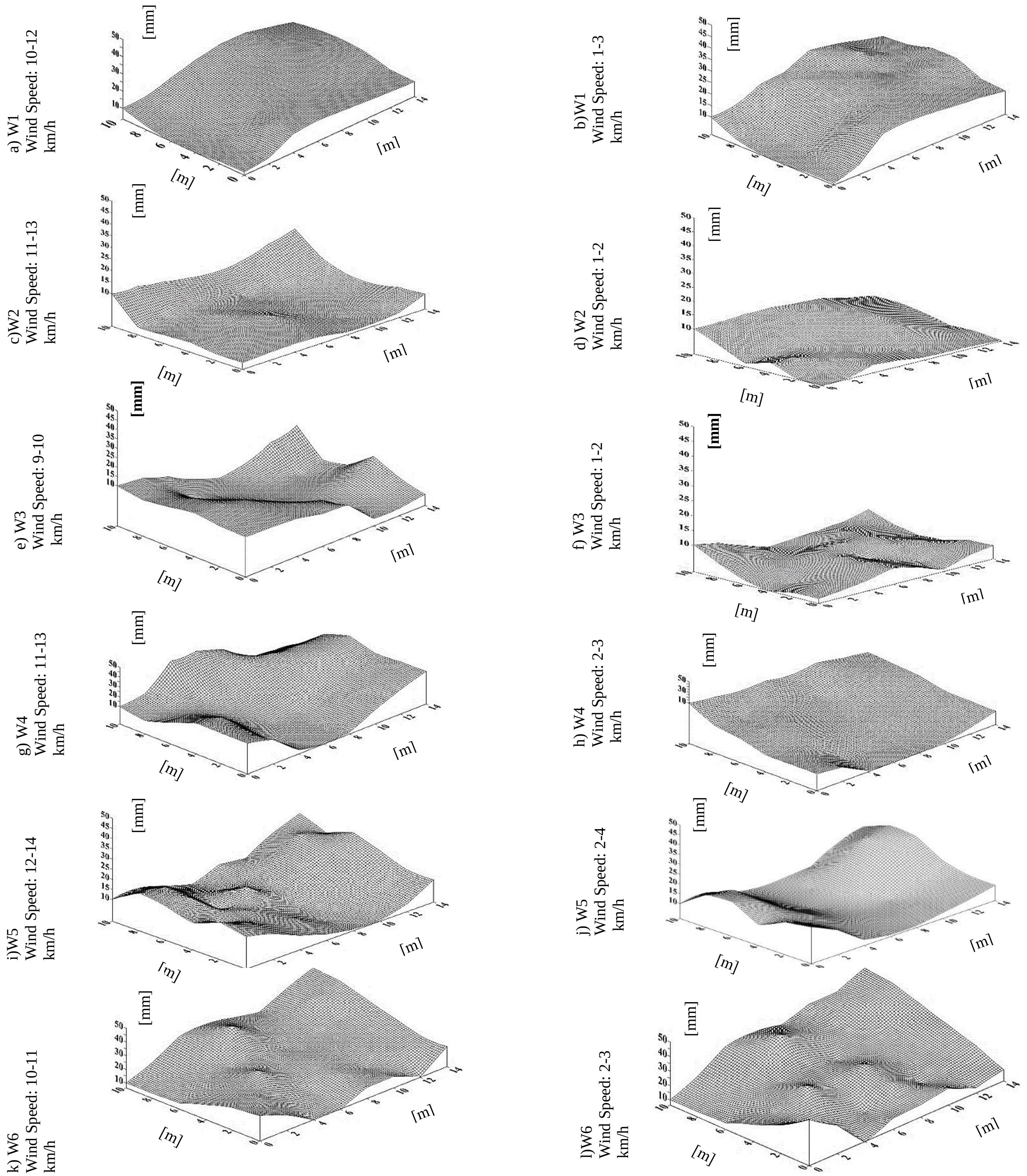

Fig. 5- The pattern of water distribution under two climatic conditions –WM Systems

 DOI: 10.22055/JISE.2021.34738.1928

The values of the CU and DUlq coefficients for the LM systems are presented in Fig. 6 and Fig. 7. Based on measured values of water depth in catch-cans, the values of CU were 70.55% to 91.3% and their average was 78.2%. According to the NBR 14244 norm (ABNT 1998) (the Brazilian Association of Technical Standards), the values of CU coefficients in low and high wind speeds were classified as “good to great or best” and “moderate to good”, respectively. Moreover, the averages of CU indexes for the low and high wind speed conditions were calculated as 81.7% and 72.3%, respectively. Wind speed also caused a decrease by 9.3% in the CU indicator. Dukes (2006) reported the coefficient of uniformity in the LM system at higher wind speeds (5.0-6.6 m/s) in the range between 70% and 85%. On the other hand, the minimum and maximum values of DUlq were 60.2% and 85.5%, with an average of 70.7%. The wind speed caused a decrease of 12.7% in the DUlq indicator, which was significantly higher than that of the CU index. The water distribution patterns for the LM system is shown in Fig. 8. As is seen in Fig. 8, the amount of collected water in some catch-cans was significantly lower than the others. because of the variation of topography, so it changes the water pressure. The lateral slope varied depending on the different positions and ranged from 1 to 4%. The damaged sprinklers in some places, which reduced flow rates and spray radius, could be the other reason for the variability of water depth in the catch cans. With a comparison between the results of water distribution uniformity, it can be concluded that the LM system has a better performance than the WM system because the Dulq value in the LM system was 9.3% higher than that of the WM system with the same climate condition. Thus, the negative impact of wind speed on the uniformity of water distribution in the WM system was significant.

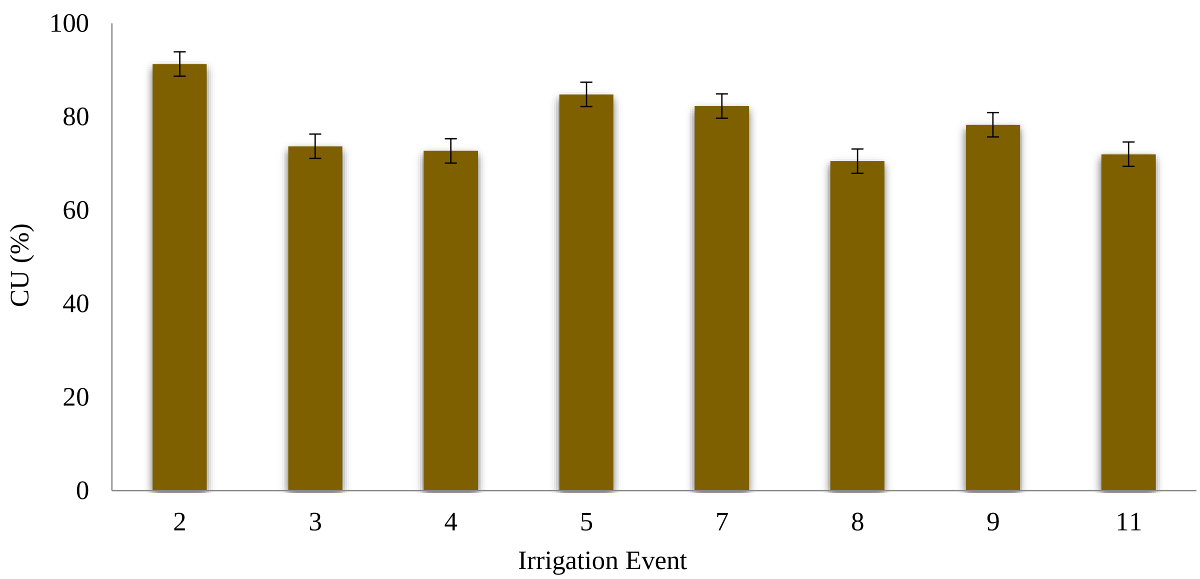

Fig. 6- Christensen uniformity coefficients for LM system

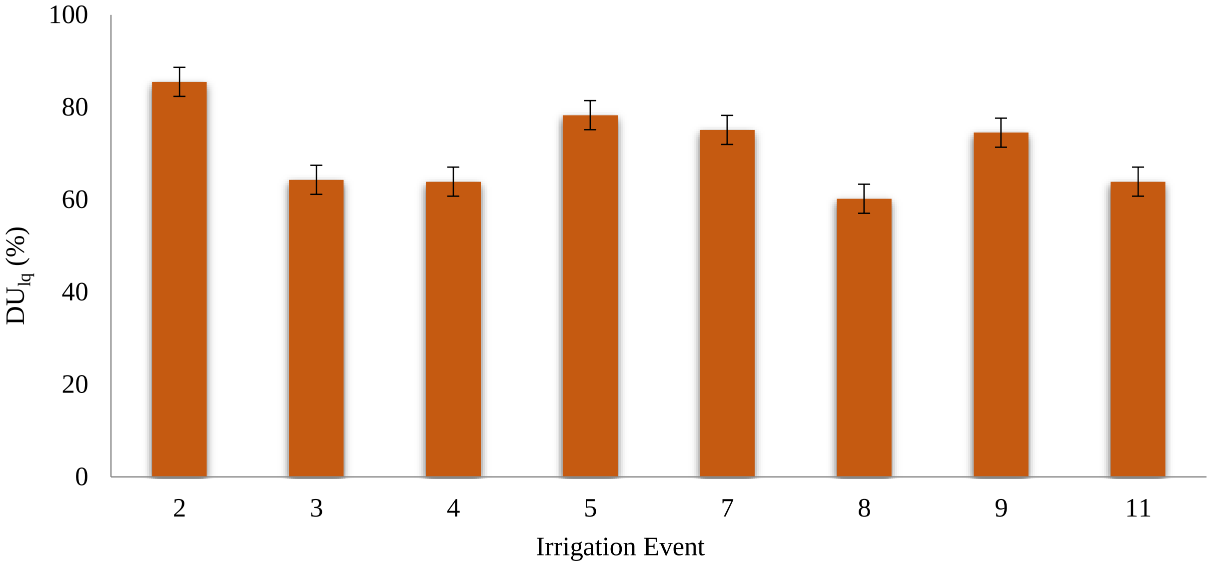

Fig. 7- Distribution uniformity of low quarter for LM system

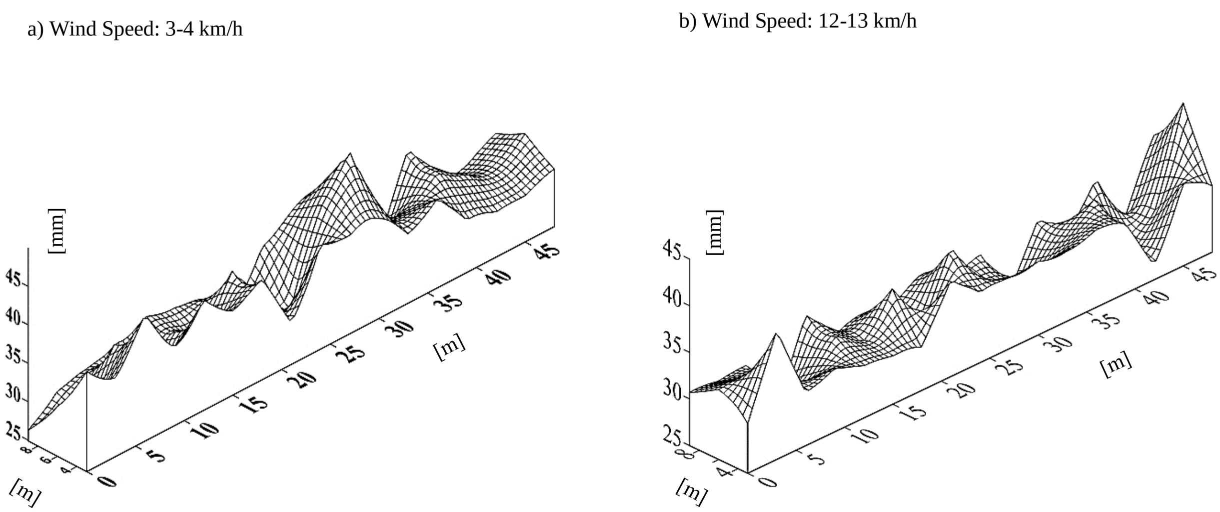

Fig. 8- Water distribution patterns under two climatic conditions – LM system

Application efficiency of low quarter: Fig. (9) demonstrates the application efficiency of low quarter (AELQ) for the WM systems. The values of AELQ index for low and high wind speed conditions were determined as 48.5 to74.1% and 21.9 to56.1%, respectively. The average values of AELQ for two above mentioned situations were calculated as 59.9% and 38.6%. Wind speed has led to a decrease by 21.3% of this index in the WM systems. Fig. 10 shows the values of AELQ for experiments under the LM system. The range of the indicators was obtained as 57.7% to 79.7% (with an average of 70.2%) and 50.2% to 57.0% (with an average of 54.3%) for low and high wind speed conditions, respectively. The wind speed effect on this indicator for the LM system was less than that of the WM system, so the reduction was 15.9%. Comparing the results for the two types of evaluated systems indicated that application efficiency (AE) for the LM system was better than the WM system in various climatic conditions.

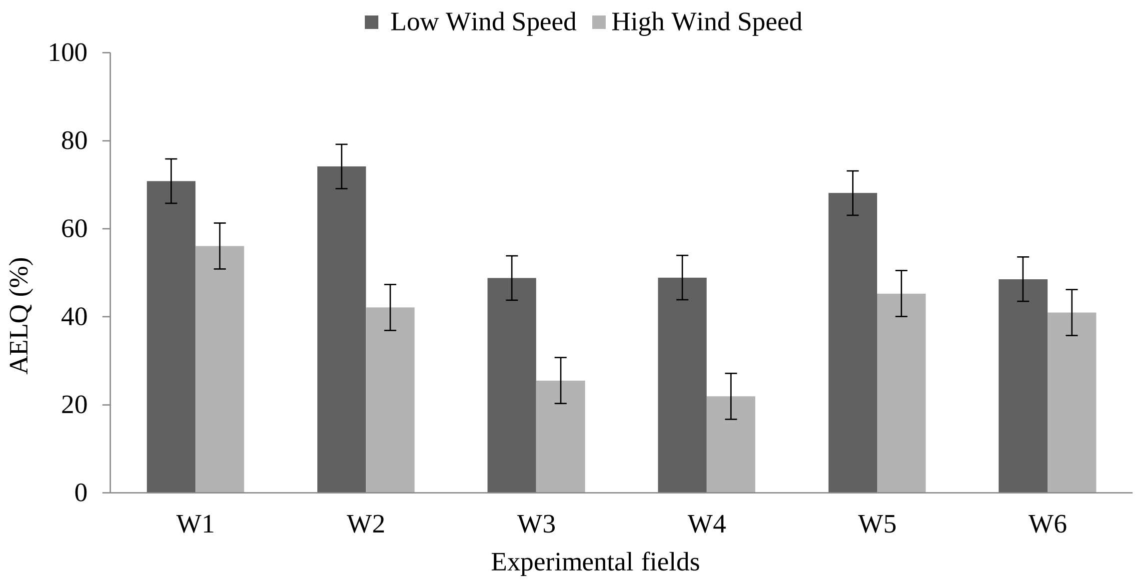

Fig .9- Application efficiency of low quarter – WM systems

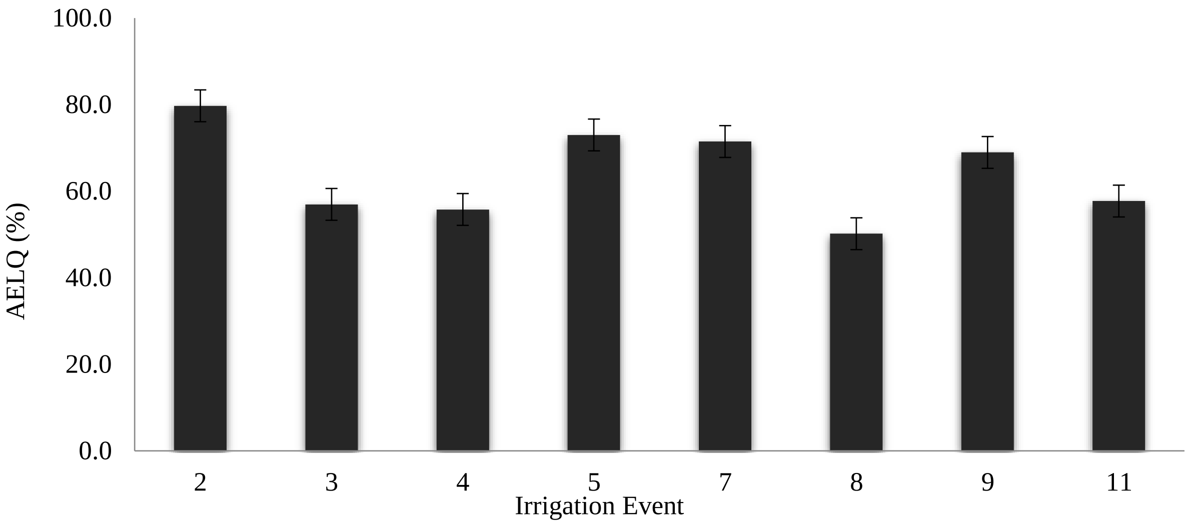

Fig.10- Application efficiency of low quarter – LM system

Conclusions

The performance of Linear Moving (LM) irrigation system and Wheel Move (WM) irrigation systems were compared in terms of water distribution for different climatic conditions. An increase in wind speed, significantly reduced the efficiency and the uniformity of water distribution for both systems. It needs to be noted that the reduction in water distribution was lower for LM system compared to WM system. It was concluded that the flexible irrigation plan was the main reason for the high irrigation efficiency for the LM system compared to the WM system. The results showed that the performance of the LM system in terms of water distribution efficiency is more effective than the WM in different climatic conditions. The main factor for obtaining the optimal water distribution performance of the irrigation systems, in fact, is the appropriate selection irrigation system for different climate conditions e.g., climate and topography.

Acknowledgement

The authors would like to thank the Agricultural Jahad Organization of Zanjan Province for their support and providing a part of the data.

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