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Optimization of surface irrigation by low-cost water management

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ABSTRACT

Background and Objectives: Surface irrigation is the most common method of irrigation. over 80% of agricultural lands in Iran are irrigated by this method. Generally, this technique has lower investment and energy requirements than pressurized irrigation methods. Many efforts are applied to improve the economic output of water use and to preserve the environment in Iran. Modifying the design and management parameters at the farm level can improve the performance of irrigation systems. The main objective of this study is to optimize surface irrigation efficiency, with low-cost tools, using a simulation model.

Materials and Methods: The study areas were selected fields of the Molla-Sani region in Khuzestan province, located southwest of Iran. Field experiments were carried out in two fields, irrigated using a surface irrigation system. Three irrigation events and three plots (as repeats) were applied per field. Experiments were conducted on the three borders of 150 m in length, 7 m in width, and 0.125 % slope, in Field 1, and on three borders of 200 m in length, 7 m in width, and 0.1 % slope, in Field 2. The inflow rates of 25 and 35 L/s were applied in fields 1 and 2. The Inflow rate was checked using a W.S.C flume. The borders were divided into parts of 10 m distances to measure the advance and recession times. The best combination of parameters was determined with the simulation model. The objective function (OF) including the application efficiency and the distribution uniformity was applied to optimize the irrigation performance.

Results: This study showed that, based on the simulation model, changing the inflow rate, does not affect the best value of an objective function. The optimal inflow rate and cut-off time are recommended as 35 L/s and 30 min in a border with a length of 50 m, in Field 1, and, the best performance in Field 2, is obtained from the inflow rate of 20 L/s and the cut-off time of 48 min and length of 50 m. Field experiments showed that the difference in infiltration rates, was not significant, during this study. Based on the data obtained from three events, in both fields, and analyzed via the simulation model, the average NRMSE (Normalized Root Mean Square Error) index values for the evaluation of the advance curves were 12.7, 12.5, and 11.6%, while the recession curves were 6.9, 6.8, and 6.6%.

Conclusion: Pressurized irrigation has the high investment and energy requirements than surface irrigation. Furthermore, the evaporation rate is much, in the research region. Because the inflow rate and cutoff time are the most effective parameters in improving irrigation, thus, in this region, prediction and selection of the optimum combination of cut-off time and inflow rate are the low-cost tools to improve the surface irrigation performance compared to modifying length and slope in border irrigation or transform of surface to the pressurized system, in the farm level.

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بهینه‌سازی آبیاری سطحی با مدیریت کم‌هزینه آب

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چکیده

مقدمه و هدف: آبیاری سطحی معمول‌ترین روش آبیاری است. بیش از ۸۰ درصد زمین‌های کشاورزی ایران با روش‌های سطحی، آبیاری می شوند. به‌طور معمول، این روش در مقایسه با روش‌های آبیاری تحت فشار نیازمند سرمایه‌گذاری و مصرف انرژی پایین‌تری است. تلاش‌های زیادی برای بهینه‌سازی اقتصادی مصرف آب و نیز حفظ محیط زیست در ایران انجام می‌شود. اصلاح پارامترهای طراحی و مدیریت آب در سطح مزرعه، می تواند به بهبود عملکرد سامانه‌های آبیاری منجر شود. هدف اصلی این پژوهش، بهینه‌سازی بازده آبیاری با کم‌ترین هزینه و به کمک مدل‌های شبیه‌سازی است.

مواد و روش‌ها: منطقه مورد مطالعه شامل مزارع منتخب منطقه ملاثانی خوزستان واقع در جنوب‌غربی ایران است. آزمایش‌های مزرعه‌ای در ۲ مزرعه که به روش سطحی آبیاری می‌گردید، انجام شد. آزمایش‌ها شامل سه نوبت آبیاری و سه نوار آبیاری (به عنوان تکرارهای آزمایش) در هر مزرعه صورت گرفت. آزمایش‌ها بر روی نوارهایی به طول ۱۵۰ متر، عرض ۷ متر و شیب ۰/۱۲۵ درصد در مزرعه ۱ و به طول ۲۰۰ متر، عرض ۷ متر و شیب ۰/۱ درصد در مزرعه ۲ انجام شد. دبی ورودی ۲۵ و ۳۵ لیتر در ثانیه در مزارع ۱ و ۲ اعمال شد. کنترل دبی ورودی با استفاده از فلوم wsc صورت گرفت. جهت اندازه‌گیری زمان پیشروی و پسروی، طول نوارهای آبیاری به قطعاتی با فواصل ۱۰ متری تقسیم شد. تابع هدف (OF) شامل بازده کاربرد و یکنواختی توزیع برای بهینه‌سازی عملکرد آبیاری مورد استفاده قرار گرفت و بهترین ترکیب پارامترهای آبیاری نواری با مدل شبیه‌سازی تعیین گردید.

نتایج: نتایج این مطالعه نشان داد که با توجه به شبیه‌سازی انجام شده، تغییر در میزان دبی ورودی، تأثیری بر مقدار بیشینه تابع هدف ندارد. بهترین عملکرد سامانه در مزرعه اول، با میزان دبی ورودی ۳۵ لیتر بر ثانیه، مدت زمان آبیاری ۳۰ دقیقه و طول ۵۰ متر و در مزرعه دوم با مقدار دبی ۲۰ لیتر در ثانیه، زمان آبیاری ٤۸ دقیقه، طول ۵۰ متر به‌دست آمد. نتایج نشان داد که

میانگین شاخص ریشه میانگین مربعات خطای نرمال شده (NRMSE) مورد استفاده جهت ارزیابی مدل شبیه‌سازی در دو مزرعه، در مورد منحنی پیشروی برابر ۱۲/۷، ۱۲/۵ و ۱۱/٦ درصد و به مقدار ٦/۹، ٦/۸ و ٦/٦ درصد برای منحنی پسروی است.

نتیجه‌گیری: آبیاری تحت فشار نسبت به آبیاری سطحی نیازمند هزینه سرمایه‌گذاری و انرژی بالاتری است. از طرف دیگر شدت تبخیر در منطقه مورد مطالعه بالاست. به‌دلیل این‌که دبی ورودی و مدت زمان آبیاری از مؤثرترین پارامترهای بهینه‌سازی آبیاری سطحی است، بنابراین، در این منطقه و در سطح مزارع کوچک، پیش‌بینی و انتخاب ترکیب بهینه مدت زمان آبیاری و دبی ورودی، در مقایسه با اصلاح طول و شیب زمین و یا تغییر سامانه سطحی به تحت فشار، ابزار کم‌هزینه‌تری برای بهبود عملکرد آبیاری سطحی است.

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Introduction

Surface irrigation is the most common method of irrigation in Iran and many other countries. For example, over 80% of agricultural lands in Iran are irrigated by surface methods [1, 2]. Generally, this method has lower investment and energy requirements than pressurized irrigation methods, such as sprinkle and drip irrigation. More than 8 million hectares of agricultural land in Iran are irrigated by surface methods. However, the irrigation efficiency in these systems is low. Low efficiencies were not inherent to these methods but were attributable to poor design, implementation, and management of irrigation systems [3, 4]. Non-uniformity of water application and over-irrigation result in water-stressed conditions in parts of the field, as well as wastage of water through runoff at the end of the field and deep percolation below the root zone. Border irrigation is a surface irrigation method that is most widely used for irrigated crops in Iran, such as wheat, alfalfa, barley, etc. Therefore, this irrigation method has an important role in the present and future crop production of Iran.

The flow in surface irrigation (such as border irrigation) is an example of unsteady non-uniform and gradually varied flow over a soil bed. The basic design parameters, such as border length, slope, and inflow rate, as well as infiltration characteristics, interact with each other during an irrigation event. These parameters affect the advance and recession phases in surface irrigation, which determine irrigation efficiency. Hydrodynamic models simulate the different phases of flow in surface irrigation. The application of 1D simulation models started in the 1970s [5]. The zero-inertia model is a simplified model without the acceleration and inertia terms of a full hydrodynamic model. This model was first used to border irrigation by Strelkoff (1972), Katopodes (1974), and Strelkoff and Katopodes (1977) [6, 7, 8]. SRFR [9] and SIRMOD [10] have been the models most widely applied over the years. Bahrami et al. (2010) applied a flood routing method in the simulation of advance time in surface irrigation and compared it with SIRMOD models [11].

According to the studies of Raine et al. (1997), Smith et al. (2005), Bautista et al. (2009), Moradzadeh et al. (2013), Lalehzari et al. (2014), and Morris et al. (2015), the inflow rate and cut-off time are the most effective parameters in surface irrigation efficiency [12, 13, 14, 15, 16]. Gonzalez et al. (2011), Chen et al. (2012), Reddy et al. (2013), Morris et al. (2015), Anwar et al. (2016), Kifle et al. (2017), and Mazarei et al. (2020) used different indicators such as application efficiency, distribution uniformity, deep-percolation, and runoff volume, as irrigation performance indicators [2, 15, 17, 18, 19, 20]. Modifying the design and management parameters at the farm level can improve the efficiency of irrigation systems. Hydrodynamic simulation models are useful tools for the design and management of surface irrigation systems. These models develop solutions to the problems related to water logging, wastage of water, and salinity. Field characteristics and inflow rate values are applied to optimize the efficiency of surface irrigation by simulation models. Thus, the aims of this study are as follows:

a. To achieve the best irrigation management parameters that result in optimum performance of irrigation without making geometric changes in the field.
b. To determine the best combination of geometric parameters of the border, such as length and slope, which result in the optimum performance of irrigation.

Materials and Methods

The study areas were selected fields of the Molla-Sani region in Khuzestan province located in southwest Iran (31.4°-31.6° N and 48.8°-48.9° E). Field experiments were carried out in two alfalfa fields (3 and 7 years after planting, respectively) irrigated using a surface irrigation system (border irrigation). Three irrigation events and three plots (as repeats) were applied per field. Experiments were conducted on three borders of 150 m in length, 7 m in width, and 0.125% slope in field 1, and on three borders of 200 m in length, 7 m in width, and 0.1 % slope in field 2. Inflow rates of 25 and 35 L/s were applied in fields 1 and 2, respectively. The inflow rate was measured using a W.S.C. flume. The borders were divided into 10 m distances to measure the advance and recession times. Infiltration variations were not significant during the study. The best combination of surface irrigation parameters was determined with the simulation model.

WinSRFR is a software package for the hydraulic simulation of surface irrigation systems, developed by the USDA-Agricultural Research Service. It is an integration of the surface irrigation (basin, border, and furrow) program SRFR, level basin design program BASIN [21], and sloping border-strip program BORDER (Strelkoff et al., 1996) [22]. Input data for analyzing irrigation performance with winsrfr4.1 [23] are inflow rate, infiltration properties, geometric properties, and the depth of irrigation requirement. In this study, the Kostiakov-Lewis equation was applied to simulate the infiltration phase [2]:

$$Z= kt^{a} +f_0t \qquad [1]$$

where Z is cumulative infiltration (mm), t represents elapsed time of infiltration (min), f_0 is the basic infiltration rate (mm min^{-1}), and k and a are empirical coefficients. In the current study, infiltration properties in Kostiakov-Lewis parameters (a and k) were determined with the double-ring method, and then the advance and recession data were used to calibrate the infiltration parameters. The precision of the estimated coefficients can be achieved via a trial-and-error method, which is used to calculate the infiltration coefficients [23].

In addition, irrigation performance under different slopes and lengths was simulated using Physical Design World in the software. Furthermore, the Operation Analysis World was used to determine the best combination of inflow rate and cut-off time [12]. Five normal inflow rates in the Molla-Sani region (i.e., 20, 25, 30, 35, and 40 L/s) were considered in the performance analysis. In this study, the Zero-Inertia model of winsrfr4.1 software was used to simulate irrigation scenarios [2, 24]. The inflow rate, geometric properties (such as length, width, and slope of the border), and depth of water application are required for simulation. In the current study, the Event Analysis World was used to estimate and calibrate the infiltration parameters. The advance and recession curves, and irrigation performance under different inflow regimes were simulated using Simulation World. The Physical Design World evaluated different geometric scenarios, such as changing field length and slope. Finally, Operation Analysis World determined the best combination of inflow rate and cut-off time. The analysis is conducted using performance contours as a function of inflow rate and cut-off time [2, 12].

The objective function (OF), including the application efficiency (AE) and the distribution uniformity (DU), was applied to optimize irrigation performance [2]:

$$OF= (0.5\times AE) + (0.5\times DU) \qquad [2]$$

In this research, Normalized Root Mean Square Error (NRMSE), Relative Error (RE) criterion, and Mean Absolute Error (MAE) were the evaluation criteria used to analyze the software accuracy [2, 25]:

$$NRMSE = (\frac{1}{\bar{O}}\sqrt{\frac{\sum_1^N (O_i-P_i)^2}{N}}) \times 100 \qquad [3]$$

$$RE = \frac{P_i-O_i}{O_i} \times 100 \qquad [4]$$

$$MAE = \frac{\sum_1^N |P_i-O_i|}{N} \qquad [5]$$

where O_i and P_i are the observed and predicted values, respectively, N is the number of measurements, and $(\bar{O})$ is the average measurement.

Results and Discussion

Soil properties of the experimental fields are given in Table 1. There was a low variation in cumulative infiltration amount in double-ring tests; therefore, the mean values of infiltration parameters were applied in each field simulation.

Table 1. Soil properties of the experimental fields.

Soil depth	Field	
	1	2
0-30 cm	Silty clay loam	Silty clay loam
30-60 cm	Clay loam	Silty clay loam
60-90 cm	Silty loam	Clay loam
90-150 cm	Silty loam	Clay loam
Mean field capacity %	18	17.5
Mean permanent wilting point %	8	8.5
Infiltration equation	$2.98t^{0.55}+19t$	$3.55t^{0.6}+13t$

After the calibration of infiltration parameters, the accuracy of the simulation model in the advance and recession trajectory curves was evaluated using the measured data. The evaluation of simulation in the advance and recession times indicated good accuracy of the field measurements. The data obtained from three events in both fields were analyzed via the simulation model. The NRMSE (Normalized Root Mean Square Error) index values for the evaluation of the advance and recession times are shown in Table 2. The average values of NRMSE for advance time simulations were 12.43% and 12.23% in field 1 and field 2, respectively, while the recession times were 7% and 6.5% in field 1 and field 2, respectively. These results are in agreement with those of Chen et al. (2012), Anwar et al. (2016), Araujo et al. (2019), Mazarei et al. (2020), and (Xu et al., 2019) [2, 17, 18].

Table 2. The accuracy of simulated advance (adv) and recession (rec) times.

	FIELD 1		FIELD 2	
	NRMSE		NRMSE	
	adv	rec	adv	rec
Irrigation event 1	12.1	7.3	13.3	6.4
Irrigation event 2	13.5	7.2	11.5	6.5
Irrigation event 3	11.7	6.7	11.9	6.5

The accuracy of the simulated values of application efficiency and irrigation distribution uniformity is shown in Table 3. The average values of NRMSE, MAE, and RE for the AE were 7.6, 8.6, and 8.9% for first 1, and 6.4, 6.5, and 8.7% for field 2, respectively. The average values of NRMSE, MAE, and RE for DU were 8.6, 10, and 10.7% in fields 1, and 8, 8.5, and 10.5% in field 2, respectively. This result shows that the Zero-Inertia model has a good performance in estimating the irrigation efficiency of these fields. These results are in agreement with Boroomand Nasab et al. (2006), Mazarei et al. (2020), and Nie et al. (2019) [2, 26].

Table 3. The accuracy of simulated performance indicators.

	FIELD 1						FIELD2					
	NRMSE		MAE		RE		NRMSE		MAE		RE	
	AE	DU	AE	DU	AE	DU	AE	DU	AE	DU	AE	DU
Irrigation event1	7.3	10.1	8.9	11.1	9.3	12.2	5.6	7.9	6.2	8.7	8.3	10.2
Irrigation event2	8.5	8.7	9.2	10.8	9.1	10.1	7.5	8.4	6.9	7.9	9.1	11.2
Irrigation event3	6.9	7.1	7.8	8.1	8.5	9.9	6.2	7.7	6.5	8.8	8.6	10.2

As noted above, inflow rate, cut-off time, slope, and border length are the most important variables that effectively increase border irrigation performance and efficiency. Simulation models can be used to improve irrigation performance by considering performance evaluation indicators, such as application efficiency and distribution uniformity. To achieve this goal, the counter curves were created by the zero-inertia model, and then the best pair of the inflow rate and cut-off time was extracted by considering three slopes and five border lengths. The performance of the border irrigation system was evaluated assuming that the required depth was provided at the end of the border (100% irrigation adequacy). Inflow rate and cut-off time are the most effective parameters compared to geometric ones (length and slope) and have significant effects on irrigation performance [12]. Thus, it is simpler to optimize the inflow rate and cutoff time than to modify soil characteristics and field geometry. The Operation Analysis World in the software simulates different inflow rates and cut-off times to improve irrigation performance. The optimization is conducted using performance contours, which display the variation of selected performance measures as a function of the inflow rate and cut-off time [12]. To identify an acceptable combination of the inflow rate, and the cut-off time, a range of 20-40 l/s was selected for the inflow rate.

The Physical Design World of the simulation model was used to evaluate different geometric scenarios, such as changing field length and slope. The lengths of 50, 100, 150, 200, and 300 m, with slopes of 0.06, 0.125, and 0.2% for field 1 and 0.05, 0.1, and 0.2 % for field 2, were evaluated to improve irrigation performance. The effects of inflow rate, cut-off time, slope, and border length changes on oF using model simulation are presented in Figures 1 and 2.

The simulation showed that the application efficiency decreased with increasing slope, resulting in the decreased oF in Field 1 (Figure 1). It is also observed that the efficiency decreased by increasing the border length from 50 to 200 m. However, the efficiency increased in a length of 300 m compared to that of 200 m. Furthermore, the simulation model showed the highest efficiency in a length of 50 m. The simulation result showed that the efficiency decreased with increasing the inflow rate in the borders by a length of 300 m, but there were no considerable changes in the other lengths.

Figure (2) shows a similar trend in Field 2. The application efficiency and, consequently, oF decreased with the increasing slope in different border lengths and inflow rates. The simulation also showed that the efficiency decreased by increasing the border length from 50 to 200 m. However, the efficiency increased in the border with a length of 300 m compared to that of 200 m. The highest efficiency was achieved at 50 m, and unlike the other lengths, the efficiency decreased for a length of 300 m with the increasing flow rate, but the efficiency did not show marked changes in the other lengths. These results are in agreement with some studies, such as Morris et al. (2015), Anwar et al. (2016), Akbar et al. (2016) Mazarei et al. (2020), and Nie et al. (2019) [2, 15, 17, 26, 27].

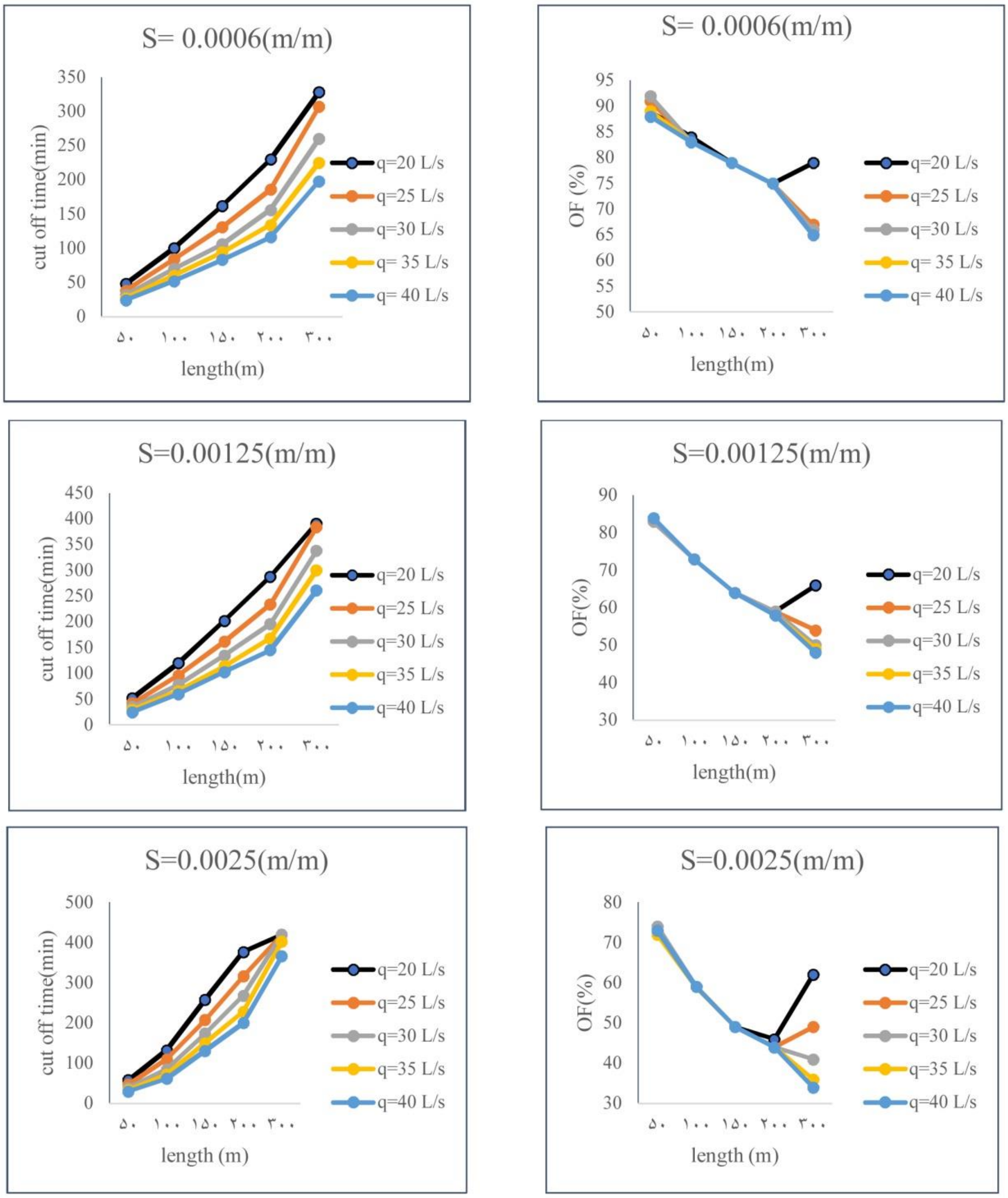

Figure 1. Optimum design and management scenarios with different slopes, lengths, and inflow rates in Field 1.

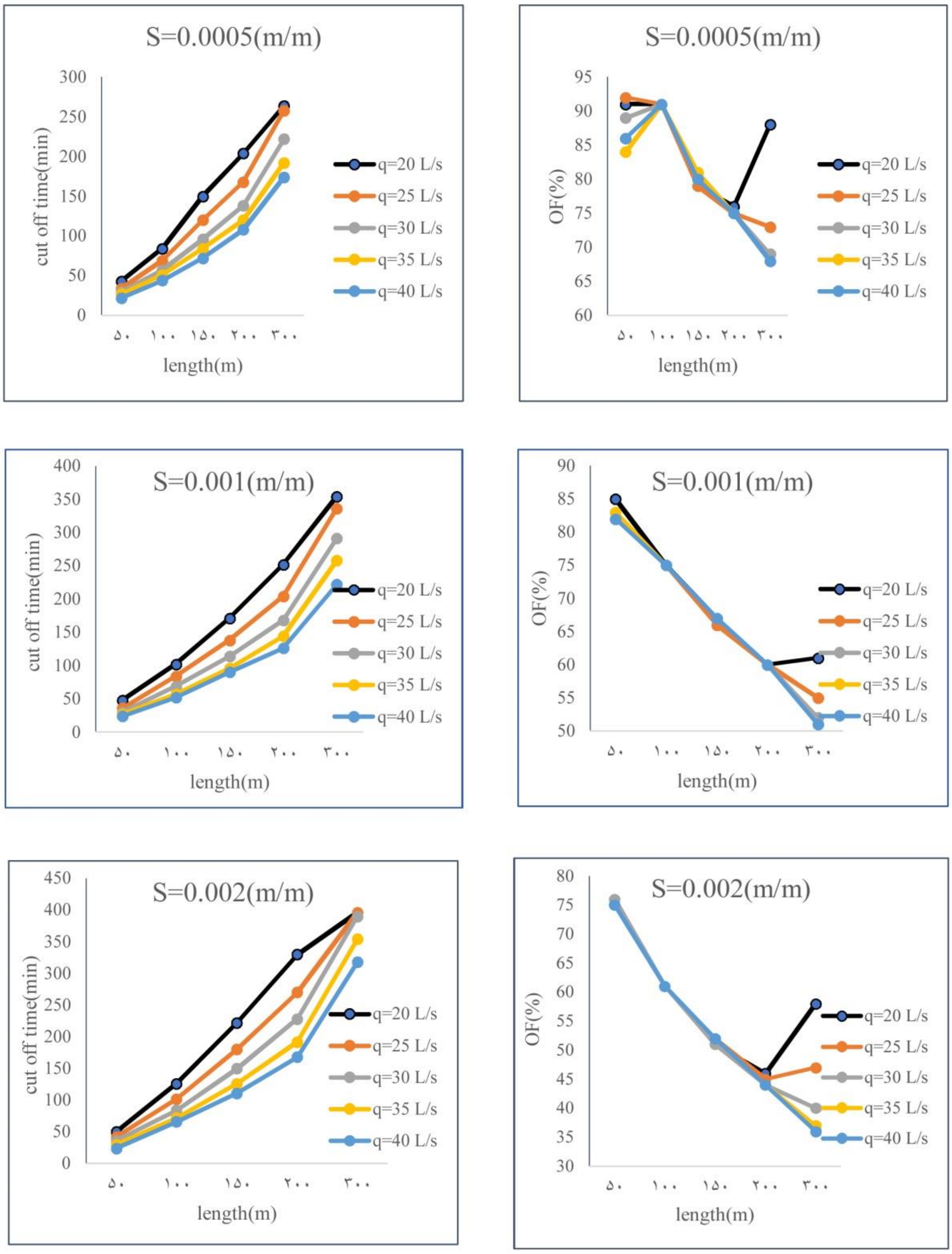

Figure 2. Optimum design and management scenarios with different slopes, lengths, and inflow rates in Field 2.

Conclusion

In this study, the optimum inflow rate, cutoff time, and physical parameters of border irrigation were determined to improve irrigation performance with a simulation model. Two irrigation performance indicators (AE and DU) were evaluated under field and simulation studies. Compared to length and slope, determining the optimal combinations of inflow rate and cutoff time are simple and low-cost means to improve irrigation efficiency. According to the results of the simulation model, the application efficiency decreased in the two fields with increasing the slope of the irrigation border in all inflow rates. The decrease of border slope in fields 1 and 2, increased from 64% to 79% and 60% to 75%, respectively. At inflow rates of 20 and 25 L/s, a length of 50 m, the lowest slope led to the highest efficiency in all fields. At inflow rates of 30, 35, and 40 L/s, a length of 50 m, in Field1, and a length of 100 m in the second Field, resulted in the highest efficiency on low slopes, respectively. However, a length of 50 m yielded the highest efficiency on high slopes. The application efficiency was 65-92% in different lengths and inflow rates with a slope of 0.05%, in Fields 1 and 2. Because of a low infiltration rate, if it is not possible to change the longitude slope of the border, the end of the border could be opened to reuse the outlet runoff in other parts. Furthermore, the application efficiency could be increased if it is possible to use the cut-back method. It is suggested to apply the simulation model for other fields in the Molla-Sani region, and even in other crops. Moreover, the performance tables or figures (e.g. Figures 1 and 2) for each farm should be prepared and used by farmers, which would be useful when the ground is leveled well and carefully. Because of the high evaporation rate in the study area, the application efficiency of surface irrigation is expected to be comparable with sprinkle irrigation. Pressurized irrigation also has a high investment and maintenance cost. Furthermore, the inflow rate and cutoff time are the most effective parameters in improving irrigation compared to modifying length and slope in border irrigation. Therefore, the prediction and selection of an optimum combination of cutoff time and inflow rate are low-cost tools for improving surface irrigation performance at the farm level.

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Data: Experimental data were obtained from 2 fields, located in Molla-Sani, Khuzestan, Iran, during the 2019-2020 years, under the Applied Research Program.

Conflicts of Interest: The author declares no conflict of interest.

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