

# Multi-Criteria Evaluation of Small-Scale Sprinkler Irrigation Systems Using Grey Relational Analysis

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**Abstract** The technical and socioeconomic evaluation of small-scale sprinkler irrigation systems is a multi-criteria problem characterized by complexity and uncertainty. In order to solve that, the application of Grey Relational Analysis (GRA) was presented. An evaluation model with ten sub-criteria under four groups, namely, technical, economic, environmental and social, was established. Among the criteria, calculation method of labor use in the small-scale sprinkler systems was originally addressed, and Life Cycle Cost (LCC) was used as an economic indicator. In the design of GRA, a combination weighting method based on Analytical Hierarchy Process (AHP) and entropy measurement was employed to take into account the experts' knowledge and the inherent information in the experimental data. Six irrigation systems for three field sizes 0.5 ha, 2 ha and 5 ha respectively were considered to verify the model. The systems were optimized with Genetic Algorithms (GAs) first to figure out the optimal combinations of sprinklers and pipes and further, field tests were performed. The discussions show that: the developed approach has successfully provided the ranking of systems for three field sizes. When different types of sprinklers are used, the criteria including atomize index, application efficiency and specific energy consumption change greatly. And the ownership cost, particularly the energy consumption fee, accounts for the largest part of LCC in most of the systems. In comparison, System 5 and System 1 are generally the best. The evaluation model solved by GRA integrated with GAs is effective and can be extended to the comprehensive evaluation and optimization of other irrigation systems.

**Keywords** Evaluation · Irrigation system · Grey relational analysis · Multi-criteria analysis · Life cycle cost

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## 1 Introduction

In an irrigation project, various irrigation systems and different types of sprinklers can be used. This case is the same with small-scale sprinkler irrigation systems applied in developing countries. Therefore, the evaluation of irrigation systems is necessary. However, it is a multi-variant and complicated problem. Many authors have paid attention to the technical evaluation of systems (Burt et al. 1997), which plays an important role in the adequate performance assessment. But in the comprehensive evaluation of a system many other aspects have to be included. The labor use is a good example. As a result of urbanization in China and most parts of developing countries, farm labor is increasingly shrinking. In this context, labor use in the operation and management of small-scale sprinkler irrigation systems has to be reduced. In the resource use or environmental aspect, the application efficiency is most concerned, whereas the energy consumption is often overlooked though energy conservation is emphasized worldwide. In the economic analysis, the repayment period of investment is sometimes used in the calculation of irrigation cost (Srivastava et al. 2010; Atisa et al. 2014). However, it cannot reflect which part of the system can be improved in order to reduce the cost. Therefore, a more comprehensive model for the evaluation of irrigation systems considering the design is required.

Grusse et al. (2009) proposed a method to take into account the technical, agricultural, economic and environmental objectives at the farm level for irrigation systems. Application Efficiency (AE) and Christiansen Coefficient of Uniformity (CU) were taken as the hydraulic performance indicators. The technical objective gains the best consensus among the researchers (Mateos 2006;). In terms of the economic and environmental objective, the economic productivity is often used and in some occasions the energy cost and benefit of the systems are related. Moreno et al. (2010) included annual energy cost per irrigated area (ECS<sub>r</sub>) and energy cost per total annual volume of irrigation water delivered (ECV<sub>T</sub>), and Chen et al. (2011) introduced the energy cost-benefit ratio (EmCBR) in the energy analysis of irrigation delivery systems. Under the social objective, Morankar et al. (2013) expressed the labor employment involved in the irrigation planning in man-days.

Over the years, various indicators have been considered in the evaluation of irrigation systems and districts. Yet most of them were done after the projects had been built. Different schemes or plans were seldom compared in the design process for optimization. The usage of Multi-Criteria Analysis (MCA) in sprinkler systems was rarely reported though some employed in the water resources management (Rodrigues et al. 2013; Brown et al. 2014). The MCA techniques mainly include Analytical Hierarchy Process (AHP), Principle Component Analysis (PCA), Fuzzy comprehensive analysis and Grey Relational Analysis (GRA). They are effective in outlining the best system especially when substantial information is involved in the comparison of different alternatives (Montazar et al. 2013).

By and large, AHP is one of the most commonly used multi-criteria decision-making methods. Besides its flexibility in setting the objectives, AHP can commensurate the tangible and intangible decision attributes (Montazar and Zadbagher 2010). It has been widely used in different fields and it is also a good choice in the weighting required in some other complicated multi-variant evaluation models.

These approaches, such as AHP, PCA and fuzzy theory have their advantages and shortcomings respectively, so they have been employed under different purposes. AHP is more suitable to the qualitative problem and easily influenced by the subjective factors of experts; PCA is more attractive in the selection of major impact factors among the data set with interrelated variables; the appraisal result obtained by fuzzy theory are not precise enough for some problems (Zheng et al. 2012). Comparatively, GRA, a new methodology proposed by Deng (1986), can provide a quantitative analysis and figure out the clear relations between

variables given incomplete information. Therefore, it can be applied in many problems, prediction, multi-response optimization, classification, for instance (Zhai et al. 2009).

Karmakar and Mujumdar (2007) described a two-phase GFWLAM (Grey Fuzzy Waste Load Allocation Model) to capture all alternatives or multiple solutions in the water quality management of a river system in India. Datta et al. (2008) optimized the bead geometry in submerged arc bead-on-plate welding with Grey-based Taguchi method. Khan et al. (2010) coupled GRA with PAC in the optimization design to simplify the process parameters. Akay (2011) concluded that GRA outperformed other seven alternative methods including decision tree, neural networks and Ant Colony Optimization, for the classification of industrial jobs in the range of low risk and high risk. But very few studies have been found on the evaluation of irrigation systems.

The specific objectives of this study were: (1) to establish a comprehensive evaluation model of small-scale sprinkler irrigation systems, in which the indicators were derived mostly according to the experimental results; (2) to employ GRA based on AHP and entropy measurement in the evaluation; (3) to identify suitable sprinkler systems for different field sizes and to recommend appropriate measures to improve the performance of the systems, before that the separate indicator was analyzed and compared for the systems first.

## 2 Methodology

### 2.1 Indicators

An evaluation model consists of ten indicators under four groups, technical, economic, environmental and social, was employed to characterize the performance of the irrigation systems for certain goals such as for different field sizes. Therefore, in the stratum of the evaluation model, Level 1 represents the Target areas; Level two represents the Groups; Level three represents the Sub-criteria and Level four represents the Alternatives of irrigation systems.

#### (1) Technical

*Water application rate*  $\bar{\rho}_s$  and *Irrigation uniformity* are widely used in the evaluation of performances of sprinklers and irrigation systems. Water application rate is the average irrigation depth over the wetted area by a sprinkler. And The Christiansen Coefficient of Uniformity CU was applied.

*Atomize index*  $\rho_d$  is a measurement for general kinetic energy of all the drops emitted out of the nozzle on the soil and plant, defined by Eq. (1) (Li 1995). It is determined by drop diameter, landing velocity and density of raindrops. Different ranges of the atomize index are allowed for specific crops: that for vegetables and flowers is 4,000–5,000, that for field crops is 3,000–4,000.

$$\rho_d = \frac{1000h_p}{d} \quad (1)$$

where,  $h_p$  is pressure head of sprinkler, m(H<sub>2</sub>O);  $d$  is nozzle diameter, mm.

#### (2) Economic

*Life Cycle Cost* LCC is the cost of an asset, or its parts throughout its life cycle, while fulfilling the performance requirements (Tzanakakis 2013). The concept has been applied in the financial analyses concerned in the systems such as sustainable buildings (Halwatura and Jayasinghe 2009). However, it is difficult to predict Life Cycle Cost precisely since the cost for the service life is dependent upon various parameters, and

many uncertainties exist. In this study the total cost of an irrigation system consists of initial cost, operation cost, maintenance cost, disposal cost and salvage value. The operation cost is divided into energy consumption fee and labor cost. Table 1 shows the equations to compute the variable and fixed costs for small-scale irrigation systems (Ribeiro et al. 2012).

In the table,  $C_{pump}$  is the initial cost of pump and motor, US\$;  $n$  is number of sprinklers;  $a$  is sprinkler spacing, m;  $C_{pipe}$  is the unit price of pipeline, US\$/m;  $E$  is fuel price, US\$/ $(kW \cdot h)$ ;  $m$  is irrigation quota, mm;  $T_{sum}$  is annual irrigation time, h;  $A$  is field size, ha;  $T_{p,sum}$  is annual operation time due to labor use, h;  $\rho_1$  is annual maintenance ratio, %;  $N$  is times for transportation in disposal;  $C_{transport}$  is the transportation fee for each time, US\$/time;  $C_{sv}$  is salvage value per kilogram of steel, US\$/kg;  $w_{pump}$  is the weight of pump, kg.

Taking into account the annual discount rate, the Life Cycle Cost is presented in Eq. (2) (Michailidis et al. 2009).

$$LCC = C_{initial} + (C_{energy} + C_{labour} + C_{maintenance})P_{v,sum} + (C_{disposal} - C_{salvage})P_v \quad (2)$$

$$P_{v,sum} = \frac{(1+r)^t - 1}{r(1+r)^t} \quad P_v = \frac{1}{(1+r)^t} \quad (3)$$

where,  $P_{v,sum}$  and  $P_v$  are discount coefficients;  $r$  is interest rate, %;  $t$  is service life, year. The first part in Eq. (2) is also called acquisition cost, the second part is ownership cost and the third is generally disposal cost.

*Irrigation time*  $T$  on each event is related to the operation cost, including the energy consumption and water use, so it is considered as an economic indicator.

(3) Environmental (resource use)

*Specific energy consumption*  $E_p$  is defined as energy consumption per volume water per unit area by Wang et al. (2010), Tu et al. (2012) as shown in Eq. (4). It provides a unified index for the comparison of energy use in different systems.

$$E_p = \frac{H}{36.7\eta_m\eta_p\eta_a} \quad (4)$$

where,  $H$  is pump head, m( $H_2O$ );  $\eta_m$  is motor efficiency;  $\eta_p$  is pump efficiency;  $\eta_a$  is water application efficiency;  $\eta_a = 100AE$  and  $AE$  is application efficiency, %;

*Application Efficiency* ( $AE$ ) is the ratio of the amount of water stored in the subject region to the amount diverted into the subject region (Burt et al. 1997).

**Table 1** Variable and fixed costs of irrigation systems

Cost component	Term	Equation
Initial cost	$C_{initial}$	$C_{initial} = C_{pump} + naC_{pipe} + nC_{sprinkler}$
Energy	$C_{energy}$	$C_{energy} = E_p E m A T_{sum}$
Labor	$C_{labor}$	$C_{labor} = C_{lr0} \cdot T_{p,sum}$
Maintenance	$C_{maintenance}$	$C_{maintenance} = \rho_1 C_{initial}$
Disposal	$C_{disposal}$	$C_{disposal} = N C_{transport}$
Salvage value	$C_{salvage}$	$C_{salvage} = C_{sv}(w_{pump} + n(w_{sprinkler} + w_{riser} + w_{tee} + w_{coupling}))$

## (4) Social

*Labor use* in a small-scale sprinkler irrigation system is different form that in a solid-set irrigation system. The latter mainly includes the time for installation at the beginning, thus it is measured in days. In the small-scale irrigation systems, labor use is employed in the operation at the start and in the disassembly when transferred to the next location at the end in every irrigation event. Therefore, to measure the labor use in the system with days will not be appropriate. And in quantitative calculation it depends on the number of sprinklers and the field conditions. One method was proposed in Eq. (5), the details given in Appendix 1. The time for each component is obtained through statistics in tests and survey. The coefficients are determined according to experiences.

$$T_p = (1 + k_1)(1 + k_2)(1 + k_3) \sum_{i=1}^p T_i \quad (5)$$

*Reliability* refers to the durability and stable performance of sprinklers. The life span of plastic sprinklers is shorter than that of impact sprinklers. Impact sprinklers, that works under lower pressures cause less opposite reaction to the riser pipes in operation and hence are more reliable than the sprinklers working under higher pressures. And *Storage* is related to the management of the system. *Reliability* and *Storage* are measured with 9-point scale.

## 2.2 Evaluation Methods

## 2.2.1 Grey Relational Analysis (GRA)

Grey Relational Analysis utilizes the mathematical method when analyzing correlations between series comprising a grey relational system, and thereby determines the difference in contribution between the reference series and each compared series (Aslan et al. 2012). Data pre-processing is normally required to avoid incorrect results since in different problems the factors, goals and directions are different (Abhang and Hameedullah 2012). Therefore, one has to transfer the original sequence to a comparable sequence, which is called “Grey Relational Generation” or normalization (Khan et al. 2010). In this study a linear normalization is performed. If the expectancy is “larger-the-better”, the original sequence can be normalized in Eq. (6) (Rao and Yadava 2009):

$$y_{ij} = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \quad (6)$$

If the target value is “smaller-the-better”, then the original sequence can be normalized in Eq.(7):

$$y_{ij} = \frac{\max_i x_{ij} - x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \quad (7)$$

However, if a definite value is expected (“nominal-the-best”), the original sequence will be dealt with Eq. (8):

$$y_{ij} = 1 - \frac{|x_{ij} - x_{0j}|}{\max_i |x_{ij} - x_{0j}|} \quad (8)$$

where  $i=1, \dots, m; j=1, \dots, n$ .  $m$  is the number of sequences, exactly, experimental data items or schemes,  $n$  is the number of indicators.  $x_{ij}$  denotes the original sequence,  $y_{ij}$  the sequence after Grey Relational Generation,  $\max_i x_{ij}$  the highest value of  $x_{ij}$ ,  $\min_i x_{ij}$  the lowest value of  $x_{ij}$  and  $x_{0j}$  is the definite value.

Following data pre-processing, a sequence composed of the ideal result  $Y_0=(1, 1, \dots, 1)^T$  will be used as the reference data. Then a Grey Relational Coefficient is calculated to indicate the relationship between the desirable and actual normalized experimental results considering the  $j$ -th indicator, as shown in Eq. (9) (Zhai et al. 2009):

$$\xi_{ij} = \frac{\min_i \min_j |y_{0j} - y_{ij}| + \zeta \max_i \max_j |y_{0j} - y_{ij}|}{|y_{0j} - y_{ij}| + \zeta \max_i \max_j |y_{0j} - y_{ij}|} \tag{9}$$

where,  $\zeta$  is distinguishing coefficient, and its value lies between 0 and 1. Generally  $\zeta=0.5$  is used to fit the practical requirements. The Grey Relational Grade  $\gamma_i$  can then be computed by Eq. (10).

$$\gamma_i = \frac{1}{m} \sum_{j=1}^m w_j \xi_{ij} \quad \sum_{j=1}^n w_j = 1 \tag{10}$$

where,  $w_j$  represents weighting factor for  $j$ -th criteria or response. There are majorly two kinds of approaches to calculate the weighting values, subjective and objective. The subjective weighting method, typically such as AHP and Delphi method, is used based on the knowledge of experts or designers. In contrast, the objective weighting is applied according to the relations among experimental data, PCA (Principal Component Analysis) and entropy measurement, for instance. And there is a new method, combination weighting method to combine both of them in different ways. In this study a combination weighting method based on AHP and entropy measurement is proposed to obtain the weighting values  $w_j$ . All the evaluation processes were carried out on the Matrix and Laboratory (Matlab) R2007a platform.

### 2.2.2 Combination Weighting

Combination of weighting methods can overcome the shortcomings of individual methods and integrate the merits of both. In this regard, the overall weights were determined by Eq. (11) (Jiménez et al. 2006):

$$w_j = \frac{w_{ja} \times w_{jb}}{\sum_{j=1}^n w_{ja} \times w_{jb}} \tag{11}$$

where,  $w_j$  is the overall weight;  $w_{ja}$  is the weight calculated with AHP;  $w_{jb}$  is the entropy weight.

### 2.2.3 Analytical Hierarchy Process

The use of Analytical Hierarchy Process involves developing a hierarchical decision model comprising attributes (criteria) and options. In this case a hierarchy structure in four levels was developed. The weights of criteria were obtained through pair-wise comparison between the elements for each stratum downwards. A semantic 9-point scale is applied in the assignment of priority values. After that each matrix consistency is checked out through calculation of

consistency ratio  $c_r$  (Montazar et al. 2013). The consistency ratio  $c_r$  is expected to be less than 0.1, and correspondingly the weights  $w_{ja}$  will be taken in the determination of combination weighting method. Otherwise the AHP evaluating procedure will be revised.

#### 2.2.4 Entropy Measurement

Entropy, one concept in thermodynamics originally, is the measurement of disorder in a system (Wang and Zhan 2012; Zooho and Vijay 2014). Applying the concept to weight measurement, an attribute with high entropy means it has a great diversity of responses, so the attribute has a more significant influence on the response (Rao and Yadava 2009). The entropy for each criterion is defined in Eq. (12), where  $f_{ij}$  is given by Eq. (13):

$$H_j = -\frac{1}{\ln n} \sum_{i=1}^m f_{ij} \ln f_{ij} \quad (12)$$

$$f_{ij} = \frac{y_{ij}}{\sum_{i=1}^m y_{ij}} \quad (13)$$

The  $j$ -th criteria's entropy weight is determined in Eq. (14). The entropy weight represents the degree of the criterion providing useful information from the viewpoint of information theory.

$$w_{jb} = \frac{1-H_j}{n-\sum_{j=1}^n H_j} \quad \sum_{j=1}^n w_{jb} = 1 \quad (14)$$

### 3 Study Area

#### 3.1 Determination of Field Sizes

Over the years, the small-scale sprinkler irrigation systems has been widely used in some areas due to its low cost, high uniformity, flexibility and compatibility with local low-power engines or tractors in China (Comas et al. 2012). Three scales of irrigation areas, 0.5 ha, 2 ha, 5 ha, are chosen according to the average land per capita in the major farming areas in China.

- (1) 0.5 ha. Irrigated area in one working location for most present small-scale systems is 0.2–0.5 ha. Moreover, according to the authorized statistics, the average land per capita in Henan, Shandong, Anhui provinces where the systems are widely applied is around 0.1 ha per person. Supposing the population in a farming family is 5, the land of a family is then 0.5 ha.
- (2) 2 ha. In the North of China, including Heilongjiang, Jilin, Inner Mongolia, Xinjiang where the system can be extended, the average land per capita is 0.3–0.56 ha, the land of a farming family is 1.5–2.8 ha, so the average 2 ha is taken.

- (3) 5 ha. The lands with 200–250 m length, 150–200 m width, in the area 3–5 ha are popular in the places where collective management is applied. Further, the irrigated area for system with power 8.8 kW, a high value for small holders, is 5 ha.

The meteorological conditions in Taiyuan basin, Shanxi province were taken in the analyses of irrigation systems. In this area, the major plants are wheat and maize. The target wetted depth of soil is 60 mm. The irrigation quota is 33 mm, and the irrigation cycle is 6 days (Niu et al. 2010).

### 3.2 Irrigation Systems

Six systems originally designed by Jiangsu University are selected for the irrigation of three field sizes, 0.5 ha, 2 ha, 5 ha. The parameters of systems are given in Table 2. The optimal configurations, including sprinklers and pipes used, were computed with Genetic Algorithms (GAs) developed by Wang et al. (2010). The hydraulic parameters of sprinklers are listed in Table 3. Irrigation regimes for different systems under three field sizes are shown in Table 4. In the tables, the variables involved in Life Cycle Cost are determined according to market prices and experiences.

The experiments to test the hydraulic performances of these systems and to validate the optimization results were performed on the grassland in the west of Jiangsu University, Zhenjiang, China, as illustrated in Fig. 1. When the irrigation of the area covered by the system is finished, the system is shifted to the next location.

In the field tests, the pump head, the pressure heads of sprinklers along the pipeline and the irrigation uniformities were measured. A vacuum gauge in precision grade 1.6, normal pressure gauges (YB-150) in grade 0.4 and a tachometer typed DT-2234B were used. In the irrigation uniformity test, catch cans in diameter 200 mm with 220 mm weight were placed in intervals 2 m×2 m. An anemometer AR826 was used to test the wind speed and a thermohygraph WS-A3 to test the air temperature and humidity. Each test lasted for one hour.

## 4 Results

### 4.1 Test Results

Different numbers of sprinklers were used to get the optimal design for each system. Practices show that pipe diameters calculated from GAs model are more reasonable (Wang et al. 2010; Tu et al. 2012; Kalita et al. 2014); a smaller diameter for all pipes will lead to a higher head loss and finally the rise in the energy use. A bigger pipe diameter promises more sprinklers that can be used and a larger area irrigated. The numbers of sprinklers provided in Table 2 prove to be the best among the trials, with the lowest energy consumption and proper pressure deviation of sprinklers. And water distribution contours between two adjacent sprinklers of the systems are presented in Fig. 2.

Irrigation uniformity was calculated for each of the overlapped sprinkler systems shown in Fig. 2 in view of the lateral spacing demonstrated in Fig. 2c. The operation time on each location is shown in Appendix 1. All the performances of the systems for an irrigation event (operation on each location) are shown in Table 5. Supposing annual irrigation time of system 2 for 5 ha is 300 h, the irrigation time of other systems can be derived in proportion. Then the results for the field sizes, 0.5 ha, 2 ha and 5 ha, are figured out. In order to analyze the



**Table 2** Parameters and configurations of irrigation systems

No.	System		Pump				Design		
	Type	Power $N$ (kW)	Size of pump	Discharge $Q$ (m <sup>3</sup> /h)	Head $H$ (m)	Speed $r$ (r/min)	Cost $C_{\text{pump}}$ (US\$)	Pipe diameter $D$ (mm)	Number of sprinklers
1	2.2QP-30	2.19	50ZB-30Q	15	30	3,600	247.8	65	16×10PXH <sup>1</sup>
2	2.7DP-25	2.66	50ZB-25D	25	25	2,850	264.2	80	20×15PY <sup>2</sup>
3	7.5DP-65	7.5	50ZB-65QJ	20	65	2,850	434.9	80	3×30PY
4	5.9CP-40	5.9	65ZB-40C	30	40	2,900	372.6	80	12×20PY
5	2.2CP-30	2.2	50ZB-30C	16	30	3,000	242.9	65	16×10PXH
6	4.4CP-45	4.41	50BP-45	20	45	2,600	313.5	65	7×20PY

1 “PXH” refers to fluidic sprinklers; 2 “PY” refers to impact sprinklers

**Table 3** Hydraulic parameters of sprinklers

Size	Pressure $p$ (MPa)	Discharge $q$ (m <sup>3</sup> /h)	Range/ Spraying radius $R$ (m)	Cost $C_{\text{sprinkler}}$ (US\$/set)
10PXH	0.25	0.973	10.7	11.5
15PY	0.20	1.52	15.0	19.7
20PY	0.35	2.92	19.0	27.9
	0.40	3.18	19.5	27.9
30PY	0.40	6.66	25.9	46.0

economic status of the systems in detail, the components of Life Cycle Cost are presented in Fig. 3. The ownership costs (energy, labor use and maintenance) were multiplied by the sum of discount coefficient  $P_{v,\text{sum}}$  in Eq. (3) and the disposal cost was adjusted with discount coefficient  $P_v$ .

### 4.2 Evaluation Results

#### 4.2.1 AHP

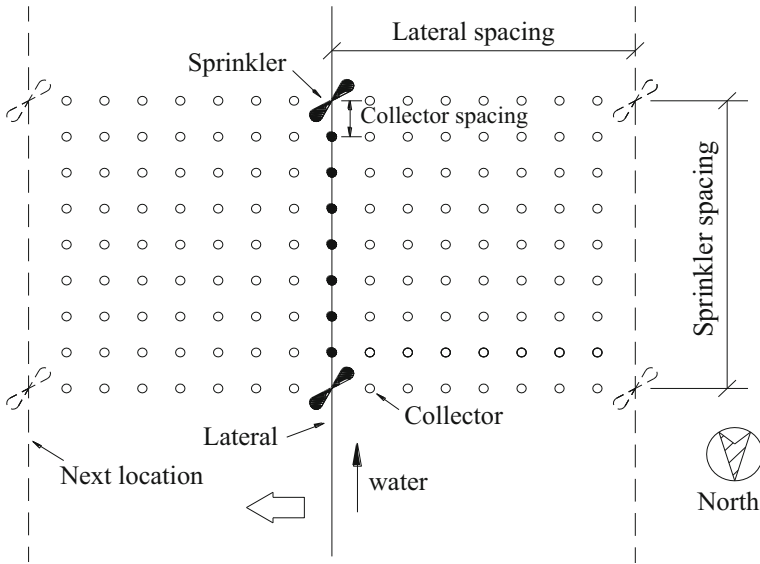
AHP was performed to get the subjective weight,  $w_{ja}$ . The relative importance of indicators was determined considering the consistency required in AHP and experiences in the evaluation and practice of irrigation. Table 6 shows the matrix of pair-wise comparisons for the second level Groups. Table 7 gives the matrixes of pair-wise comparisons of sub-criteria for each group, technical, economic, environmental and social respectively.

#### 4.2.2 Entropy Measurement

Entropy measurement was carried out to derive the objective weights,  $w_{jb}$ , in Eq. (14). Before that, the standardization of values by Eq. (6) to Eq. (8) was performed. Among the indicators, lower values of LCC, irrigation time  $T$ , specific energy consumption  $E_p$ , operation time  $T_p$  are desirable. Higher values of Christiansen

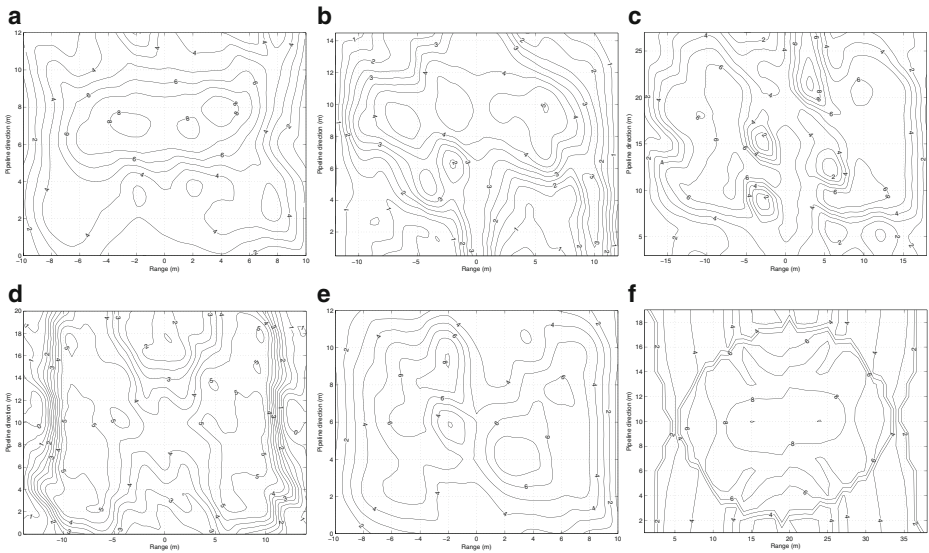
**Table 4** Irrigation regimes of systems

System No.	Design	Sprinkler spacing (m)	Irrigation Area on each location (ha)	Irrigation time on each location (h)	Maximum locations	Shifting times (Number of locations)		
						0.5 ha	2 ha	5 ha
1	16×10PXH	10	0.15	2.9	18	3	13	–
2	20×15PY	15	0.43	4.4	12	1	5	11
3	3×30PY	30	0.18	4.1	12	2	8	–
4	12×20PY	20	0.44	4.1	12	1	5	11
5	16×10PXH	10	0.15	2.9	18	3	13	–
6	7×20PY	20	0.24	3.8	12	2	8	–



**Fig. 1** Schematic layout of pipeline

uniformity  $CU$ , water application rate  $\bar{\rho}_s$ , application efficiency  $AE$ , *Reliability* and *Storage* are expected. And medium atomize index  $\rho_d$  is ideal, and the average value is taken as the definite value. Figure 4 shows the normalized values for three field sizes. After data pre-processing, the entropy matrixes  $H$  and the entropy weights were calculated,

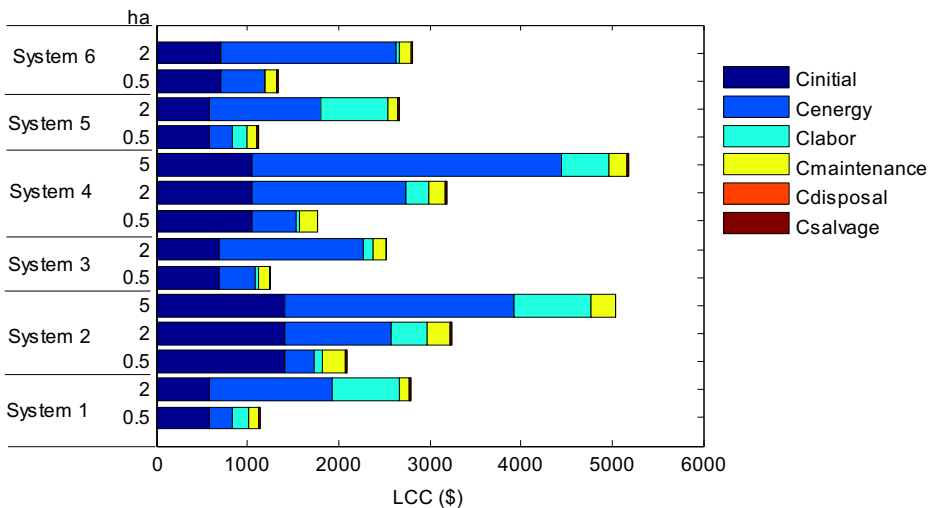


**Fig. 2** Water distribution contours between two adjacent sprinklers in six systems (wind speed lower than 1.0 m/s, according to the test every 10 min in an hour). **a** System 1: 2.2QP-30. **b** System 2: 2.7DP-25. **c** System 3: 7.5DP-65. **d** System 4: 5.9CP-40. **e** System 5: 2.2CP-30. **f** System 6: 4.4CP-45

**Table 5** Performances of irrigation systems for different field sizes

System No.		1	2	3	4	5	6
<b>Technical</b>							
CU (%)		80	79.7	79.2	79.5	78.7	76.8
$\bar{p}_s$ (mm/h)		7.01	5.32	6.52	6.10	7.11	6.49
$\rho_d$		5,500	4,762	3,850	5,950	6,200	6,417
<b>Economic</b>							
LCC (US\$)	0.5 ha	1,126.4	2,074.3	1,247.6	1,764.0	1,110.0	1,323.3
	2 ha	2,777.9	3,224.4	2,515.0	3,172.3	2,657.7	2,800.0
	5 ha	–	5,033.8	–	5,163.0	–	–
T (h)	0.5 ha	8.7	4.4	8.1	4.1	8.7	7.5
	2 ha	37.9	22.2	32.4	20.5	37.9	30.2
	5 ha	–	48.8	–	45.2	–	–
<b>Environmental</b>							
$E_p$ (kW·h·mm <sup>-1</sup> ·ha <sup>-1</sup> )	Theoretical	3.53	2.72	7.64	4.61	3.39	5.99
	Test	3.45	2.64	5.5	4.57	3.53	5.41
AE (%)	75.2	78.8	88.9	80.5	75.6	81.9	
<b>Social</b>							
$T_p$ (h)	0.5 ha	3.5	1.9	0.5	1.0	3.5	1.1
	2 ha	15.0	9.7	2.2	4.9	15.0	4.3
	5 ha	–	21.4	–	10.7	–	–
Reliability	5	9	3	7	5	7	
Storage	5	7	9	7	5	7	

listed in Table 8. Entropy weights in the table  $w_{jb1}$ ,  $w_{jb2}$ ,  $w_{jb3}$  were averaged as the objective weights  $w_{jb}$ .



**Fig. 3** Comparison of the components of Life Cycle Cost in six systems

**Table 6** Pair-wise comparison matrix of criteria with respect to the goal: selection of irrigation systems

	Technical	Economic	Environmental	Social	Weight
Technical	1	1	1/3	1	0.1725
Economic	1	1	1	2	0.2700
Environmental	3	1	1	4	0.4225
Social	1	1/2	1/4	1	0.1350

Consistency ratio = 0.04 < 0.1 OK

### 4.2.3 GRA Result

Subjective weights obtained with AHP and objective weights with entropy measurement were integrated in Eq. (11). The final overall weights are presented in Eq. (15).

$$w = (0.0636, 0.0507, 0.0513, 0.2213, 0.0448, 0.2388, 0.1814, 0.078, 0.0458, 0.0243)^T \quad (15)$$

The overall weights and normalized values for three field sizes were then used in the GRA procedure. Figure 5 illustrates the variation of Grey Relational Grade with system number.

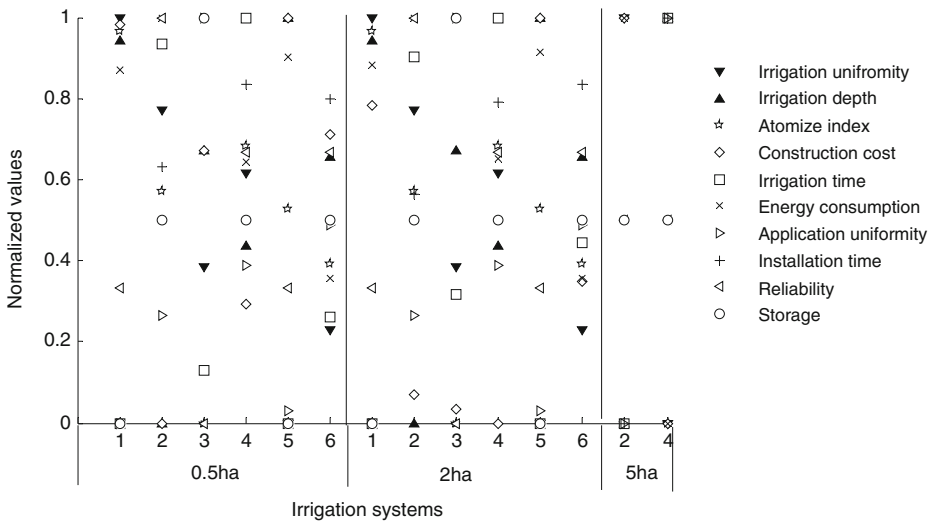
## 5 Discussion

Comparing Table 2 and 5, the Genetic Algorithms have successfully provided the optimal configurations for systems, verified by the field tests. In Table 5, the differences of specific energy consumption  $E_p$  obtained theoretically and experimentally in System 1, 2, 4, 5 respectively are less than 3 %. The experimental specific energy consumption  $E_p$  in System 3 is 28.0 % lower than the theoretical value because we use the submerged pump in an ordinary pond in depth less than 3 m. The behaviors of all the systems are good. And the indicators will be analyzed separately.

**Table 7** Pair-wise comparison matrixes of 10 criteria under each group

	Technical			Economic		Environmental		Social			Weight
	$\bar{\rho}_s$	CU	$\rho_d$	LCC	T	$E_p$	AE	$T_p$	Reliability	Storage	
$\bar{\rho}_s$	1	2	1								0.067
CU	1/2	1	1								0.053
$\rho_d$	1	1	1								0.053
LCC				1	5						0.148
T				1/5	1						0.121
$E_p$						1	1				0.245
AE						1	1				0.177
$T_p$								1	1	3	0.065
Reliability								1	1	2	0.045
Storage								1/3	1/2	1	0.025

Consistency ratio for the first matrix is  $c_{rA} = 0.08 < 0.1$  OK, for the fourth matrix  $c_{rD} = 0.05 < 0.1$  OK



**Fig. 4** Normalized values relative to the prioritization systems adopted when considering different field sizes

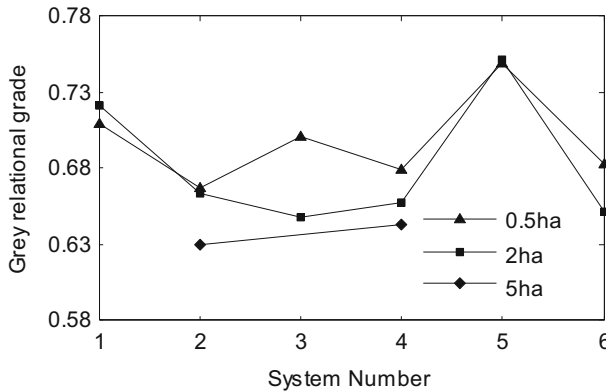
### 5.1 Performances of Irrigation Systems

#### 5.1.1 Technical and Environmental Indicators

Irrigation uniformity is most addressed in the evaluation of an irrigation system. Figure 2 indicates that water distributions of all the systems are symmetrical along the pipeline, slightly impacted by the wind and pressure difference between overlapping sprinklers. An area of high irrigation depth near the farther sprinkler in System 1 and 2 presented in Fig. 2a and b may be caused by the higher pressure of the farther sprinkler compared to that of the closer sprinkler in test. In Fig. 2c, several areas of low irrigation depth in the central of the test zone may be due to the wind and different discharge profile of sprinkler 30PY compared to sprinkler 10PXH used in the first system. According to Fig. 2 and Table 5, the irrigation uniformities of System 1, 2, 4 are the highest, around 80 %. In System 6 where the pressure at sprinkler 20PY is a little higher than the normal pressure used in System 4 with the same sprinklers adopted, the irrigation uniformity is the lowest, 76.8 %.

**Table 8** Entropy matrixes and Entropy weights for three field sizes 0.5 ha, 2 ha, 5 ha

		CU	$\bar{p}_s$	$\rho_d$	LCC	$T$	$E_p$	AE	$T_p$	Reliability	Storage
0.5 ha	$H$	0.778	0.776	0.772	0.767	0.760	0.753	0.777	0.689	0.755	0.769
	$w_{jb1}$	0.0923	0.0931	0.0949	0.097	0.0999	0.1027	0.0926	0.1293	0.1019	0.0962
2 ha	$H$	0.778	0.776	0.772	0.777	0.767	0.753	0.777	0.694	0.755	0.769
	$w_{jb2}$	0.0931	0.094	0.0957	0.0936	0.098	0.1038	0.0934	0.1285	0.1028	0.097
5 ha	$H$	0.301	0.300	0.298	0.301	0.301	0.291	0.301	0.289	0.301	0.301
	$w_{jb3}$	0.0996	0.0998	0.1	0.0997	0.0997	0.1011	0.0996	0.1013	0.0996	0.0996
	$w_{jb}$	0.0950	0.0956	0.0969	0.0968	0.0992	0.1025	0.0952	0.1197	0.1014	0.0976



**Fig. 5** Variation of Grey Relational Grades with system number for different field sizes

In Table 4, sprinklers 15PY are used for System 2, 10PXH for System 1 and 5, 20PY for System 4 and 6, and 30PY for System 3. The pressure at sprinklers rises and correspondingly, the specific energy consumption of systems comes in this order, shown in Table 5. The use of various sprinklers led to different performances of the systems. In systems 1, 2 and 5, the atomize indexes of sprinklers  $\rho_d$  are comparatively high with an average 5,487, which means the drops are fine. As a result, the application efficiencies AE are relatively low, in the average 76.5 %, so the drift losses cannot be neglected. In System 4 and 6, the atomize indexes are also high (the average 6,183), maybe due to the higher pressure of sprinklers 20PY compared to sprinklers 10PXH and 15PY. It will lead to a higher kinetic energy of raindrops on the ground. The application efficiencies are medium. In System 3, the atomize index is the lowest, 3,850, but the value is acceptable for field crops. It indicates the jet emitted out of the nozzle was not well separated compared to the former three types of sprinklers, thus the drift loss might be less. Hence, the application efficiency is the highest, 88.9 %.

### 5.1.2 Economic and Social Indicators

In Fig. 3, the ratio between the ownership cost (operation and maintenance cost) and the initial cost increases from less than once for the area 0.5 ha to more than twice for 5 ha. Therefore, the Life Cycle Costing is necessary, and the optimization and scientific management of small-scale irrigation systems are very important. The relationship between Life Cycle Cost and field size is not linear. LCC in 2 ha is only around twice of that in 0.5 ha. LCC in 5 ha is one and a half of that in 2 ha. Hence to expand the irrigation area in some range with the systems is economically promising. The energy consumption fee  $C_{\text{energy}}$  accounts for the largest part in LCC, followed by initial cost  $C_{\text{initial}}$ , then labor use  $C_{\text{labor}}$  and maintenance cost  $C_{\text{maintenance}}$ . Typically, the difference in energy consumption fee between System 4 and System 2 contributes to the higher LCC in System 4 compared to that in System 2 for the irrigation of 5 ha. The disposal cost  $C_{\text{disposal}}$  and salvage value  $C_{\text{salvage}}$  are comparatively fairly low, and they are offset by each other. For each field size, LCC in System 2 and System 4 is the highest, and that in System 3 is the lowest.

According to Tables 1 and 5 and Fig. 3, the initial cost and labor use are mainly dependent on the capacity of the system and the number of sprinklers. The more sprinklers are used, the shorter irrigation time will be spent on a definite area, but the longer operation time is needed for each event and the higher initial cost will be, typically verified by System 2.

The *Reliability* and *Storage* are related to the type and number of sprinklers. In Table 5, though the irrigation uniformity and water application rate are good, the sprinkler 10PXH may easily get clogged and stop running due to the relatively small nozzle. On the other hand, *Reliability* is also likely to be influenced by the working pressure. Such as sprinkler 30PY, the pressure is high, the discharge and momentum is large, sometimes enough to cause the inclining or falling of the riser. And it is easier to be effected by the wind. However, its storage is simple. Obviously, more sprinklers will result in more work on the management, hence less *Storage* value. As a consequence, the maintenance ratio in LCC is taken the same for all systems.

In view of the complicated relations between the configurations of systems and their performances, an evaluation method that can integrate both the subjective and objective aspects is required.

## 5.2 Effectiveness of AHP-GRA Method

A multivariate analysis method, GRA combined with AHP and entropy measurement, was implemented in the evaluation of 6 irrigation systems. It performed well. In the weighting of indicators using AHP, the consistency is achieved for the matrixes at all levels. The weight of environmental group is the highest, 0.4225, followed by the economic group, 0.2700, then by the technical group. It reflects the requirements of farmers in developing countries, or for field crops. In terms of the industrial crops in some other situations, the weights of technical group and environmental group may be the highest.

In the entropy measurement, according to Fig. 4, the normalized values of all systems change just a little in the field sizes 0.5 ha and 2 ha. The entropy weights provided in Table 8 are closely equal for 10 indicators, in the range 0.095–0.1194. The even weights may imply the good feasibility of the equations for the ten criteria in characterizing the systems. In another perspective, it also illustrates that every system has its own strengths and hard to assess just according to several individual indicators. In this regard, a mere objective method, entropy measurement is not adequate for the comprehensive evaluation.

By combination of AHP weights and entropy weights, the overall weights were obtained to supplement the individual weaknesses. The final weights were used in the Grey Relational Analysis. Figure 5 demonstrates that the proposed approach is effective in ranking the performances of 6 systems for the three field sizes.

Comparing Fig. 5 with Fig. 4, we can see that, System 1 and 5 are the best, with the Grey Relational Grade around 0.71 and 0.75 respectively for both 0.5 ha and 2 ha. It is correlated with the high normalized values. The values in System 6 are the medium, so the overall ranking is also good. In System 2, 3 and 4, the normalized values of all the criteria are almost evenly distributed, thus the Grey Relation Grades are the lowest, around 0.660. In Table 2, System 2 with only one third of the power in System 4, can however be used in the 5 ha. These results may validate that the advantage of AHP is in the over-specification of judgment, and that of entropy measurement is in the extraction of inherent information in the data, and that of GRA is in the integration of various aspects.

## 5.3 Adaptability of Systems for Each Field Size

Comparing Fig. 5 with Table 5, the differences between System 1 and 5 lie in that: the water application rate  $\bar{\rho}_s$  and application efficiency AE in System 5 are 1 % higher than, atomize index  $\rho_d$  12.7 % higher than, and the specific energy consumption  $E_p$  4 % lower than that in System 1. Similarly, the higher energy consumption and lower irrigation uniformity in System



6 compared to System 4 lead to its lower Grey Relational Grade in 2 ha. In 5 ha, the evaluation result tends to be mainly decided upon the balance between the energy consumption and labor use when System 2 and System 4 are involved. The falling of Grey Relational Grades in System 3 and 6 for 2 ha compared to that for 0.5 ha may be related to more shifting times, longer operation time when a smaller area is covered for each location due to less sprinklers compared to that in other systems. The rising of Grey Relational Grades in System 1 for 2 ha, 0.7215, compared to that for 0.5 ha, 0.7101, may be caused by its absolute lower Life Cycle Cost divided in a larger area. The constant low grade of System 2 may be caused by its high LCC and particularly the high labor use, twice of that in System 4 and 6, due to largest number of sprinklers used.

From Figs. 4 and 5 and Table 8, in the area 0.5 ha, the most suitable systems in decreasing order are System 5, System 1, System 3 and System 6; in 2 ha, the proper systems in decreasing order are System 5, System 1, System 2 and System 4; in the area 5 ha, they are System 4, System 2. Therefore, System 1 and 5 are good for both 0.5 ha and 2 ha; System 3 and 6 perform better in 0.5 ha, System 2 behaves well in 2 ha, and System 2 and 4 can be used in 5 ha.

## 6 Conclusions

A multi-criteria evaluation method, Grey Relation Analysis (GRA) using combination weighting was proposed for the evaluation of irrigation systems. In the combination weighting, AHP was applied to get the subjective weights, and entropy measurement employed to derive the objective weights in order to avoid the limits of separate methods. Four groups of criteria, technical, economic, environmental and social criteria with ten sub-criteria in total were considered in the evaluation model. Six small-scale sprinkler irrigation systems with four types of sprinklers involved were used to validate the approach. Three target field sizes, 0.5 ha, 2 ha, 5 ha were summarized according to the average farming land per capita in China. The configurations of systems were calculated with Genetic Algorithms (GAs) first and compared with experimental results in field. The indicators of the systems were analyzed separately and aggregated with GRA afterwards. The conclusions may be drawn as follows.

- (1) The optimization design of irrigation systems with GAs is reliable. The differences between the theoretical specific energy consumption  $E_p$  obtained with GAs and the experimental values are less than 3 % if the systems are correctly installed. The generally even weights for all the ten sub-criteria computed in entropy measurement indicate that the equations for the criteria have described the characteristics of each system well.
- (2) The performances of six systems are good, but when different sprinklers are used, the criteria are quite different. The water distributions of all the systems are symmetrical along the pipeline, rarely influenced by the wind. In Systems 1, 2 and 5 where sprinklers work in lower pressures, the atomize indexes  $\rho_d$  are higher, and the application efficiencies  $AE$  and energy consumption  $E_p$  are lower.
- (3) The ownership cost, particularly the energy consumption fee  $C_{\text{energy}}$  accounts for the largest part of LCC for most of the systems. And the ratio of it to the Life Cycle Cost increases with the field size. In this regard, to optimize the configuration and to reduce the energy consumption of small-scale irrigation systems are very important. The initial cost, labor use and social indicators of the systems are to an extent related to the number of sprinklers. The more sprinklers are used, the shorter irrigation time is spent on a certain area, but the higher initial cost, and the longer operation time are needed for each event, and the less value of *Storage* will be.

- (4) The GRA integrated with AHP and entropy measurement has provided a good alternative in the assessment of different performances for the six systems. System 5 and 1 are suitable in both 0.5 ha, 2 ha, with Grey Relational grades higher than 0.7; System 3 and 6 perform better in 0.5 ha; System 2 shows great potential in 2 ha; and System 2 and 4 can be used in 5 ha. The results are reasonable and may benefit designers, farmers and managers in choosing the proper systems according to the plant, field, economic and social conditions.

In terms of the evaluation method concerned in this work, the combination weighting can be modified to adapt to different problems in the evaluation of irrigation systems or some other water distribution systems. The matrix of pair-wise comparison in AHP was decided upon the designer's experience, thus it was a little subjective. More experts or customers are needed to be questioned in order to get a reasonable weighting matrix in AHP in the future.

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## Appendix

### Labor use (Operation time)

The operation time of a small-scale sprinkler irrigation system can be calculated using Eq. (16) in reference to the formula of manufacture time involved in the fire-fighting (Du and Xu 2011) and surgery (Garg et al. 2010).

$$T_p = (1 + k_1)(1 + k_2)(1 + k_3) \sum_{i=1}^p T_i \quad (16)$$

where,  $T_p$  represents the operation time of irrigation system on each location, min;  $k_1$  is coefficient of experience of workers;  $k_2$  is coefficient of weather condition, temperature and humidity for instance, influencing the efficiency of workers;  $k_3$  is the coefficient related to the muddy ground;  $p$  is the number of components, or items included;  $i$  indicates the  $i$ -th part, including the operation time of pump and motor, pipes, sprinklers and walking time in the field;  $T_i$  is the operation time for the  $i$ -th part, min. All the time is summarized according to experiences and statistical data in field tests and the questionnaire among users.

#### (1) Pump and motor

The operation time spent on the pump and motor  $T_m$  includes three items: carrying them to the water source, connecting the suction pipe and checking the parts before start.

#### (2) Pipes

The time for laying and connecting the delivery pipes,  $T_d$  shown in Eq. (17) can be divided into two parts: the operation time and walking time for transportation.

$$T_d = n[T_{d1}(1 + k_d) + T_{d2}] \quad (17)$$

$$T_{d2} = k_t t_d a \quad (18)$$

where,  $Td1$  is the operation time for each pipe connecting two sprinklers;  $kd$  is coefficient related to pipe diameter;  $Td2$  is walking time for allocating and installing the pipes, min;  $kt$  is coefficient of walking times,  $k=1, 2$ , for the initial time,  $k=2$ , others,  $k=1$ ;  $td$  is the walking time per meter, min.

(3) Sprinklers

The operation time of sprinklers  $T_s$  can be described with Eq. (19).

$$T_s = nT_{s0} \quad (19)$$

where,  $T_{s0}$  is the operation time for each set of sprinkler, riser pipe and supporter, min.

(4) Walking time or transportation time

The walking time or transportation time in distributing the sprinklers, pipes and couplings is related to the area of the field in each irrigation event. Supposing all the facilities are placed at one end of the field while the end sprinkler is arranged at the other end. The walking time  $T_l$  is then presented:

$$T_l = t_a \frac{n(n-1)}{2} a \quad (20)$$

The coefficients used in these equations are listed in Table 9 (Du and Xu 2011).

**Table 9** Values of coefficients

Coefficient	Bad	Medium	Good
Experience	Not very experienced	Medium	Very experienced
$k_1$	0.03	0.02	0.01
Weather condition	Hot, 28–35°, high humidity	Warm, 14–28°, medium humidity	Chilly, 0–14°, low humidity
$k_2$	0.015	0.01	0.015
Ground condition	Muddy	Wetted	Dry
$k_3$	0.03	0.01	0
Pipe diameter (mm)	80	65	50
$k_4$	0.03	0.02	0.01

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