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Ant Colony Optimization for the Design of Small-Scale Irrigation Systems

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Abstract The optimal design of sprinkler irrigation systems is a complicated nonlinear programming problem that is related to the performance of the system and meanwhile an economic problem to farmers in developing countries. Ant colony optimization (ACO), a meta-heuristic algorithm with the strategies inspired by foraging ants, was considered. Exactly an Ant Cycle System was proposed to solve this problem. The performance of ACO was compared to that of Genetic Algorithm (GA), and the optimal results were further validated by field tests on four small-scale irrigation systems. In the optimization model, the objective function was minimizing the specific energy consumption subject to the constraints of pipe diameters, number of sprinklers and working pressure of the end sprinkler along the pipeline and pump-pipeline cooperation conditions. In the design of ACO, head loss between adjacent sprinklers was introduced in the heuristic function to represent the distance between two cities in a Travelling Salesman Problem (TSP). And the fitness composed of the specific energy consumption dealt with penalty function was taken instead of the total length of a route in the pheromone updating. The results indicate that the specific energy consumption has been decreased in average by 12.45 % through ACO, 10.27 % through GA and 11.27 % from field tests compared to that in the initial configurations with irrigation uniformities higher than 75 % in the field tests. ACO implementation outperforms genetic algorithm in efficiency and reliability especially in larger systems. The ACO may provide a promising approach for the optimization of irrigation systems.

Keywords Ant colony optimization · Irrigation systems · Genetic algorithm · Energy consumption

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1 Introduction

The optimal design of a sprinkler irrigation system is a combinational optimization problem that consists of sizing the pipes and equipping proper number of sprinklers so as to convey water from the source to the sprinklers with lower cost or lower energy consumption. It is a non-linear, constrained and multi-modal problem included in the category of NP-hard (Non-deterministic Polynomial-time hard) problems. Over the years, it is solved under the suggestions from the extensive research contributions on the water distribution systems (WDSs) or the trickle irrigation systems where a large number of methods have been employed (Yildirim 2009; Izquierdoa et al. 2008; Dercas and Valiantzas 2012). Inspired by the finite element method (FEM) used in the trickle irrigation systems, for a sprinkler irrigation system Trung et al. (2007) applied the back step method in the basic part based on unsteady-flow analysis, while employed the forward step method in the determination of distribution of the pressure head along each lateral (Mohtar et al. 1991; Wu et al. 2010). In general, most of these hydraulic models were designed for exact problems or solved by the step-by-step (stepwise) method which is time-consuming and requires high skills (Singh 2012; Zhao et al. 2006).

Genetic Algorithm (GA) is a kind of heuristic method that is computationally simple, adaptive and robust. It is effective in solving the optimization problems. Earlier application of GA in irrigation was centered on the irrigation scheduling, channel irrigation, or the pipe work layout (Raju and Kumar 2004; Pais et al. 2010; Singh 2014). It was also utilized in the optimal design of tapered diameter pipeline with multiple outlets on different slopes (Bai and Wang 2005). But the disadvantages of GA include the chance-dependent outcome and lengthy computation time.

Recently, Gil et al. (2011) observed that a new Ant Colony Optimization (ACO) implementation with the objective function of minimal total investment cost subject to pressure constraints, obtained better results than the Genetic Algorithm and scatter search implementations in the design of typical Alperovits-Shamir and Hanoi networks. Similarly, in the multi-purpose reservoir operation, ACO model was found to perform better than GA model in terms of higher annual power production, especially in the case of long-time horizon reservoir operation (Kumar and Reddy 2006). Ant Colony Optimization is currently a new alternative in the design of delivery systems (Hossain and El-shafie 2013; Hassanzadeh et al. 2011). And it has been widely used in variety of combinational optimization problems such as sequential ordering and scheduling (Dorigo 1992; Dorigo and Blum 2005; Moeini and Afshar 2012). Maybe due to proper availability of traditional methods, the application of ACO in the optimization of sprinkler irrigation systems is neglected and few contributions are found.

Though much attention has been paid to the optimization of water distribution systems (WDSs) and trickle irrigation systems, the design of sprinkler irrigation systems still differ from the former two systems in many aspects. Firstly, optimization of sprinkler irrigation systems involves the sizing of pipe diameters and numbering of sprinklers while the optimization of WDSs focuses on the routing of water in different pipelines connecting consumers. Secondly, in WDSs, several pumps or reservoirs operate simultaneously, but in the average sprinkler irrigation systems, only one pump works, so the pump-pipeline cooperation should be considered (Wang et al. 2010; Tu et al. 2012). Compared with the design of drip tapes or laterals, the optimization of sprinkler systems aims at the least cost or the minimal energy consumption. In drip irrigation, where energy consumption is fairly low, and hence neglected, is however targeted at lowering head loss along the pipeline to ensure the emission uniformities through the spacing design of outlets.

Further, most previous studies of sprinkler irrigation systems focused upon performances of sprinklers, indicators for irrigation quality or hydraulic calculations of pipelines (Colaizzi et al.

2010; Fátima et al. 2013; Khan et al. 2008; Martinez et al. 2004). Few discussions were found on the optimal design of small-scale sprinkler irrigation systems with the advantages of low cost, homogeneity, mobility and good adaptability to different topographies and crops (Tu et al. 2012).

Main contributions of this study contain to employ two methodologies, GA and originally designed ACO, in the design of four small-scale sprinkler irrigation systems, and then to compare the optimal results with the experimental findings obtained from the field tests.

2 Problem definition

In the design of an irrigation system, the type of sprinklers to choose depends on the soil, plant and meteorological information of environment. Whereas the number of sprinklers, the pipeline and pipe fittings are equipped according to the hydraulic parameters of the pump (Tu et al. 2012). In a small-scale sprinkler irrigation system shown in Fig. 1, the power of the pump is usually less than 11 kW and the working pressures of sprinklers are lower than 0.4 MPa. The pipelines are plastic-coated pipes in order that the system can be moved more easily and more suitable to sloping lands. Moreover, they are cheaper than aluminum pipes. Therefore, this kind of system have been widely used by small-scale farmers. The pipelines are often laid in one line with rotating sprinklers of identical sizes. They will be shifted to the next location for the irrigation of a larger area when one patch of land is watered. The optimization model first developed by Wang et al. (2010) was introduced.

2.1 Objective function

Previous research shows that the specific energy consumption, defined as energy consumed per depth of water sprayed over a hectare, can be used as the objective function to design the system, presented in Eq. (1). It reflects the working conditions of components included in the system directly and helps to forward the control of fuel consumptions in agricultural systems. In this work, the optimization of the system involves minimizing the specific energy consumption by selecting the pipe diameters, adjusting the pressure heads and flow rates of sprinklers as well as controlling efficiency and working condition of the pump.

$$E_p = \frac{H}{36.7\eta_b\eta_d\eta_p} \tag{1}$$

where, E_p is the specific energy consumption of the system, kW·h/(mm·hm^2); H is the pump head, m(H_2O); η_b is the pump efficiency; η_d is the motor efficiency; η_p is the efficiency of water application in the field, exactly, from the pump outlet to the land wetted.

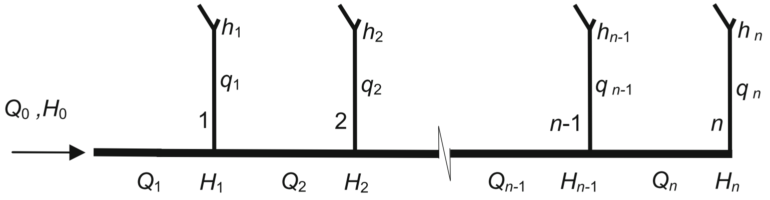


Fig. 1 Layout of the pipeline in a small-scale sprinkler irrigation system

2.2 Constraints

In the problem, constraints are formed to guarantee the performance of the whole system. Minimal working pressure of sprinkler, sprinkler working pressure deviation range, number of sprinklers and the pump-pipeline operating conditions are chosen as the constraint conditions (Tu et al. 2012). Range of flow velocity and decreasing pipe diameters along the pipeline for instance, are integrated in the optimization procedure.

The optimization constraints include: (1) according to the current standard in China "GB/T 50085-2007 Technical Code for Sprinkling Engineering", any sprinkler should work under the pressure no lower than 90 % of the design value; (2) pressure difference between any two sprinklers along the line should be lower than 20 % of the design pressure of sprinkler to ensure the normal operation of sprinklers and irrigation uniformities (Carrión et al. 2014); (3) the maximal or minimal number of sprinklers is decided in reference to the lateral design with multiple outlets on the flat ground (Zhang GX 1990); (4) the actual working condition of sprinkler irrigation system is determined by the intersection point of the characteristic curves of the pipeline and the pump, which means the agreement between the working conditions of them. Therefore, the discharge of pump Q obtained from the characteristic curve provided by the factory, is equal to the flow rate Q_0 at pipe inlet through hydraulic calculation of the pipeline. The relationship between the pump head identified on the curve and the inlet pressure of the pipeline calculated can be expressed in Eq. (2) (Tu et al. 2012).

$$H_0 = H - h_b \tag{2}$$

where, H_0 is inlet pressure of the pipe network, m(H_2O);h_b is head loss from the inlet of suction pipe to the pump outlet (or the inlet of pipeline), plus elevation between them, m(H_2O).

In the hydraulic calculation of the pipeline, the back step method is introduced in view of assuring the pressure head of the end sprinkler h_n, considering there is usually no pressure regulators in a small-scale sprinkler irrigation system (Kang and Nishiyama 1996). Hence the pressure head and discharge at the sprinklers and pipe nodes respectively are calculated from the end to the inlet of the pipeline, interpreted in Fig. 1. The discharges from all the outlets are assumed to be identical. Darcy-Weisbach Formula is used in the calculation of friction loss and equivalent length in the local loss. And the relationship between flow rate and pressure head of an impact sprinkler is considered in Eq. (3) based on orifice flow equation.

$$q_n = \mu \frac{\pi d_p^2}{4} \sqrt{2gh_n} = 0.01252 \mu d_p^2 h_n^{0.5} \tag{3}$$

where, q_n is the sprinkler discharge at the Node n, the end of pipe, m^3/h; h_n is the pressure head of sprinkler at the end of the delivery pipeline, m(H_2O); μ is the discharge coefficient of sprinkler; d_p is the orifice diameter of nozzle, mm.

Based on these above, when the pressure head of end sprinkler is input and the pipe diameters are determined, the flow rates and pressure heads at all the sprinklers and pipe nodes can be obtained sequentially from the end to the inlet along the pipeline and finally coupled with the characteristic curve of the pump.

3 Methodology

Two types of meta-heuristic algorithms were utilized: ACO and GA.

3.1 Ant colony algorithm

ACO algorithm, exactly an Ant Cycle System operated on Matlab (Matrix Laboratory) R2007a , was applied in the design of sprinkler irrigation systems for the first time.

An ACO model of a combinational optimization problem consists of: a search space S defined over a finite set of discrete decision variables, namely, solutions for the problem, a set Ω of constraints and an objective function f to be minimized (Blum 2005; Dorigo and Blum 2005).

The search space S in the optimization of sprinkler irrigation systems is defined as follows: A set of pipe diameters d_i^j for n sections of pipe are given in Eq. (4):

$$d_i^j \in D_i = \left\{ d_i^1 \ldots d_i^{D_i} \right\}, i = 1 \ldots n \tag{4}$$

Different diameters chosen will result in different working pressures of sprinklers. And the number of pipe sections n is equal to the number of sprinklers which is further decided by the pressure head at the end sprinkler. Therefore, the decision variables are the number of sprinklers, the pipe diameter and the pressure head at the end sprinkler. A feasible solution, s ∈ S, is a complete assignment that satisfies the constraints. The set of constraints Ω and objective function f have been stated earlier.

Comparing the optimization of sprinkler irrigation systems with the real ant foraging behavior or typical Travelling Salesman Problem (TSP), the available pipe diameters of each section connecting two pipe nodes are the paths between two cities, number of sprinklers or pipe sections is the number of cities, as shown in Fig. 2 (Xu et al. 2006). The specific energy consumption dealt with penalty function, presented in Eq. (5), is the total length of the route in TSP. It makes the fitness (Fit_1) and it is used in the pheromone updating. Head loss in each pipe section representing distance between two cities in TSP, is introduced in the heuristic function since it is related to pipe diameter, and sum of the head loss will add to the pump head and further the specific energy consumption E_{p}.

$$Fit_1 = E_p + \mu_1 |H_0 - H| + \mu_2 \left| \min\left(0, h_{\min} - 0.9 h_p\right) \right| + \mu_3 \left| \max\left(0, \frac{h_{\max} - h_{\min}}{h_p} - 0.2\right) \right| \tag{5}$$

where, Fit_1 is the fitness for ACO algorithm; μ_1, μ_2,μ_3 are the penalty factors; $h_{\min}$ is the minimum pressure head of sprinkler, m (H_2O); h_{p} is the design working pressure head of sprinkler, m(H_2O); .

ACO introduces a rule of transition depending on a parameter, which determines the relative importance of exploitation versus exploration (Zecchin et al. 2006). Every time an

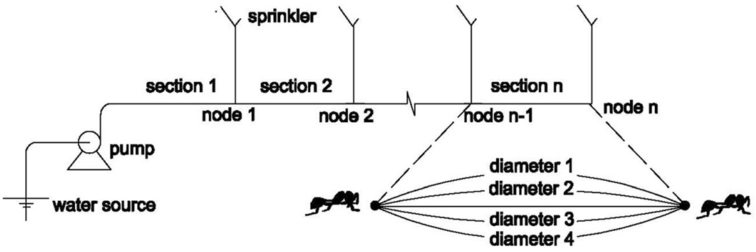


Fig. 2 Ant colony optimization for branched irrigation systems

ant at node *i* selects pipe diameter d_i^j in Eq. (4) for section *i* according to the following transition probability (Chebouba et al. 2009; Mohan and Baskaran 2012) in Eq. (6).

$$p_{ij}^k(t) = \begin{cases} \dfrac{\left(\tau_{ij}(t)^{\alpha}\left(\eta_{ij}(t)\right)^{\beta}\right.}{\sum_{u\in J_i^k}\left(\tau_{ij}(t)^{\alpha}\left(\eta_{ij}(t)\right)^{\beta}\right.} & for J \in J_i^k \\ 0 & for J \notin J_i^k \end{cases} \tag{6}$$

where the parameter α controls the relative importance of the pheromone intensity and β controls the function of heuristic value; $\eta_{ij}(t)$ is the heuristic function, or called visibility, guides the ants to move on section *i* through D_i. In this work the heuristic function is given by:

$$\eta_{ij}(t) = \frac{1}{h_{ij}} \tag{7}$$

where, h_{ij} is the head loss on the pipe section *i* between two nodes, shown in Eq. (8):

$$h_{ij} = f\frac{Q_i^m}{D_i^b}L_i \tag{8}$$

where, Q_i is the flow rate at pipe section *i*, m^3/h; L_i is the length of section *i*, m; *f*, *m*, *b* are the calculation coefficients of head loss considering the pipe material.

In the process of pheromone updating we use an Ant Cycle System (Dorigo 1992). In this system the pheromone trail associated with section *i* joining node *i* and *j* is updated by global updating after the traversal of all the sections, as in Eq. (9):

$$\begin{cases} \tau_{ij}(t+1) = (1-\rho)\cdot\tau_{ij}(t) + \rho\cdot\Delta\tau_{ij}(t) \\ \Delta\tau_{ij}(t) = \sum_{k=1}^{m}\Delta\tau_{ij}^k \end{cases}, \Delta\tau_{ij}(t) = \frac{Q_a}{Fit_1} \tag{9}$$

where, $\tau_{ij}(t)$ is the pheromone intensity on section *i* at the moment *t*; ρ ($0<\rho<1$) is the evaporation coefficient; *m* is the number of ants; $\Delta\tau_{ij}(t)$ is the total pheromone deposited by all the ants passing section i through D_i included in the best route; Q_a is an adjustable parameter; Fit_1 is expressed in Eq. (5) to represent the total length of the best route within the past total iterations (Moeini and Afshar 2012; Afshar 2006).

3.2 Genetic algorithm

The GA is a global search method that imitates the mechanism of "survival competitions where the superior survive while the inferior are eliminated." The main steps in the design of the GA include initialization, selection, reproduction crossover and mutation to mimic the biological evolution, cross-breeding and trail solution (Whitley 1994). Only the best solutions will be chosen and propagate to successive generations. The coding and design of genetic operators are the major parts which decide the efficiency of procedure and to what kinds of problem it is applicable. In this work, a standard GA was employed where the 2-tournament selection was used in the selection operation, an arithmetic crossover considered in the crossover operation and a real-valued mutation operator in the mutation operation to meet the characteristics of the problem involved. The objective function and constraints were the same as those in ACO. The difference was that we used a new fitness Fit_2 shown in Eq. (10) to satisfy the maximization principle needed in the design of a Genetic Algorithm.

$$Fit_2 = \frac{1}{Fit_1} \tag{10}$$

And the elitism was introduced to maintain the population diversity to avoid early maturity and local optima. The algorithm was written with Visual Basic 6.0. In the previous studies by Wang et al. (2010) and Tu et al. (2012) GA was implemented under different objective functions for the optimization of irrigation systems. In this work GA was employed as a reference to check the feasibility and performance of ACO.

4 Case study

4.1 Sprinkler irrigation systems

In order to test the ability of proposed ACO and outline the differences between it and GA in the optimization of sprinkler irrigation systems, four small-scale systems were considered. The pumps used are external-mixing self-priming pumps, originally designed by Jiangsu University in China. They are superior with shorter self-priming time and higher efficiencies compared to the traditional internal-mixing type, thus widely applied in agriculture in China. The parameters of pumps and sprinklers are described in Tables 1 and 2 (Li et al. 2011). The indoor test for the four systems suggest that in Eq. (1) the motor efficiency can be η_d=40 %. Based on the technical code (GB/T 50085-2007) and field condition the efficiency of water application η_p= 90 % can be used. And the pump efficiency η_b is decided through the hydraulic calculation when the pump-pipeline cooperation condition is considered. The available pipe diameters D_i are 50 mm, 65 mm and 80 mm. The length of each pipe section L_i in Fig. 2 is equal to the sprinkler spacing in Table 1. For the plastic-coated pipes, the calculation coefficients of head loss in Eq. (8) can be f=94,800, m=1.77, b=4.77.

Table 1 Parameters of small-scale irrigation systems (Tu et al. 2012, 2014)

No.	(a)	(b)	(c)	(d)
Pump Type	50ZB-35Q	50ZB-25D	65ZB-40C	50ZB-30C
Power N (kW)	2.19	2.66	5.9	2.16
Fuel	Gasoline	Electricity	Diesel	Diesel
Discharge Q (m^3 /h)	15	25	30	16
Head H (m(H_2O))	30	25	40	30
Speed r (r/min)	3600	2850	2900	3000
Outlet Diameter D_0 (mm)	50	50	50	65
Sprinklers	10PXH[a]	15PY[b]	20 PY	10PXH
Initial number of sprinklers	14	20	10	14
Sprinkler spacing (m)	10	15	20	10

[a] "PXH" refers to the fluidic sprinkler controlled by the Coanda Effect

[b] "PY" refers to the impact sprinkler

Table 2 Performances of sprinklers

Sprinkler	Orifice size d_p (mm)	Inlet diameter d_s (mm)	Pressure p (MPa)	Discharge Q (m^3/h)	Range / spraying radius R (m)
10PXH	4	20	0.25	1.03	10.7
15PY	4.2	25	0.20	0.894	14.8
20PY	6	30	0.35	2.189	19.0

4.2 Optimization parameters

The parameters of ACO and GA used in the empirical executions are listed in Table 3. Penalty coefficients for objective function are $\mu_1=100$, $\mu_2=1$, $\mu_3=50$. The penalty coefficients evolved were selected according to the average optimal results among the experimental iterations while the other parameters for the two algorithms were taken based on the empirical rules by other researchers.

4.3 Test area

The sprinkler irrigation experiments were done on the grassland in the west of Jiangsu University, Zhenjiang, China from August 11 to 17, 2010 (Fig. 3). The pressures at the inlets and outlets of pumps were recorded with a vacuum gauge YB-100 in precision grade 1.6 and a normal pressure gauge YB-150 in grade 0.4, respectively. The speed of pump was read by a tachometer typed DT-2234B (Tu 2011). In the system powered by the 50ZB-25D pump the pipeline was laid in two parallel lines, for the number of sprinkler was relatively large, while pipes in the other three systems were laid in one line.

Apart from the specific energy consumption, the irrigation uniformity is another indicator to evaluate a sprinkler irrigation system, which may vary greatly if the working pressure of sprinkler is lower than 90 % of the design pressure. It is influenced by many factors besides the pressure head. Therefore it is hard to be included in the optimization model. Hence it was tested in the experiments to confirm the feasibility of the optimization results. According to the terrain conditions of the grassland, flat land between sprinklers No.2 and No.3 was chosen as the test area, shown in Fig. 3c. The catch cans 200 mm in diameter were arranged in intervals of 2 m in squares. And temperature and humidity of the air were measured.

Table 3 Parameters used in the empirical executions

Technique	Parameter	Value
GA	Pop-size M	200
	Maximum number of generations $N_{\_max}$	30
	Crossover probability P_c	0.8
	Mutation probability P_m	0.05
ACO	Number of ants m	40
	Pheromone importance α	1
	Heuristic Importance β	2
	Maximum number of iteration $t_{\_max}$	50
	Evaporation rate of pheromone ρ	0.3
	Adjustable parameter Q_a	1

(a) Pump 50ZB-35Q (b) Pump 65ZB-40C (c) Test area

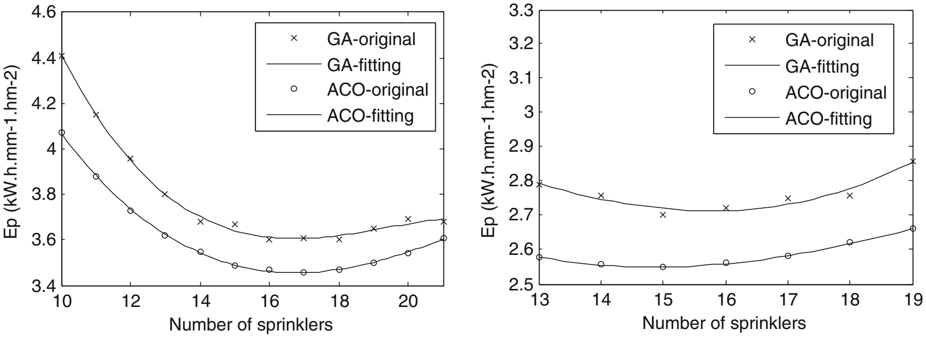
Fig. 3 Self-priming pumps and the test area (**a**) Pump 50ZB-35Q; (**b**) Pump 65ZB-40C; (**c**) Test area

5 Results and discussion

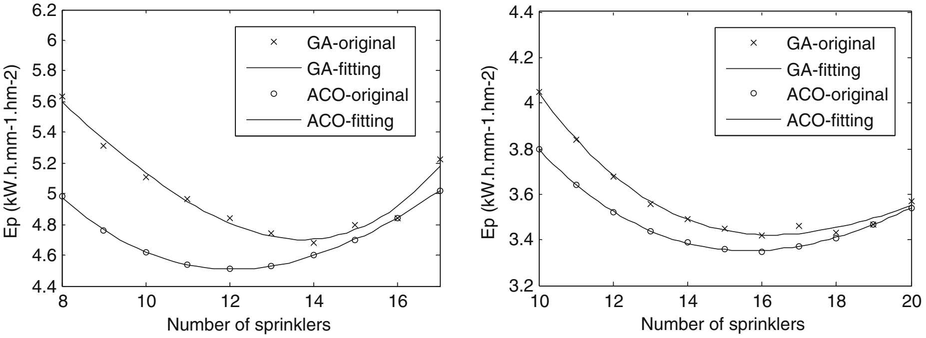
5.1 Evolution of results

Firstly, comparisons of specific energy consumptions E_p over the numbers of sprinklers n from GA and ACO are shown in Fig. 4.

In the design of systems, too few or too many sprinklers used will lead to high energy consumptions, so optimization is necessary. In Fig. 4, ACO provides smoother curves of specific energy consumption E_p over number of sprinklers n in similar shapes and generally



(a) 50ZB-35Q (b) 50ZB-25D

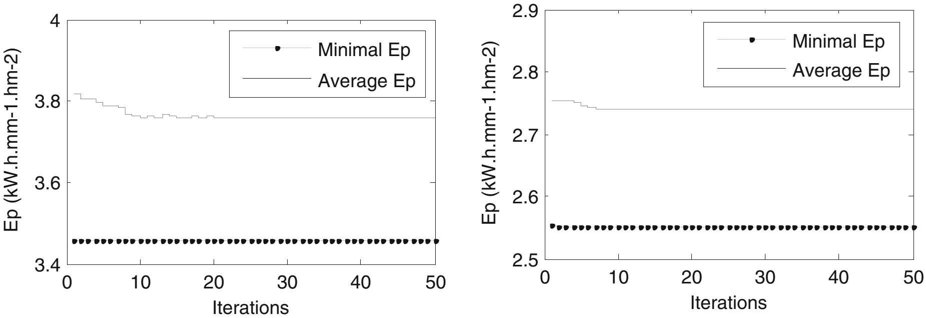


(c) 65ZB-40C (d) 50ZB-30C

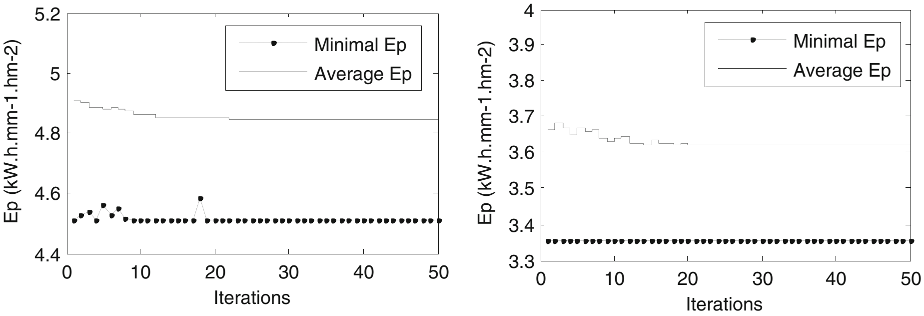
Fig. 4 Comparisons of specific energy consumption E_p over number of sprinklers from GA and ACO (**a**) 50ZB-35Q; (**b**) 50ZB-25D; (**c**) 65ZB-40C; (**d**) 50ZB-30C lower values than GA in the same system. The deviation between the two approaches at the optimal number of sprinklers for all the systems except System (c) is in the lower range. The average difference of E_p values obtained by two methods is less than 1 % in System (a) and System (d), 5 % in System (b), and the highest deiviation 10 % is found at the number of sprinkler $n=8$ in System (c). These may confirm the feasiblity of the new approach ACO. Slopes of the curves E_p over n obtained in GA are sharper than those in ACO for Systems (b) and (c), exactly, the systems with higher pressures or larger number of sprinklers. Comparatively, in the other two systems slopes of the curves in ACO are slightly sharper than those in GA. It may indicate that GA is more suitable in problems of smaller scale and ACO performs better in those of larger scale.

Under the optimal number of sprinklers, the evolutions of the minimal and average specific energy consumptions E_p gotten by the artificial ants over different iterations are given in Fig. 5.

The runtime of GA written in Visual Basic with no codes for drawing pictures is 8–16 s in different systems, and that for ACO written in Matlab with functions for drawing all the curves discussed later is 13–30 s. Results including the optimal numbers of sprinklers and lowest E_p in GA fluctuate slightly in different operations, whereas the results in ACO are almost stable with E_p varying only less than 1 %. A larger searching space due to random selection and reproduction in GA and the heuristic function introduced in ACO to narrow the range of paths may explain the difference of efficiencies concerning runtime. The role of evaporated pheromone may lead the artificial ant to the right answer which may contribute to the stable results from ACO.



(a) 50ZB-35Q (n = 17) (b) 50ZB-25D (n = 30)



(c) 65ZB-40C (n = 12) (d) 50ZB-30C (n = 16)

Fig. 5 Evolutions of minimal and average E_p in different iterations under the optimal number of sprinklers with ACO procedure (**a**) 50ZB-35Q ($n=17$); (**b**) 50ZB-25D ($n=30$); (**c**) 65ZB-40C ($n=12$); (**d**) 50ZB-30C ($n=16$)

Figure 5 shows a good convergence in ACO for all the systems with only 50 iterations. The average and minimal values of E_p become stable around 20 iterations. The difference between them is 8.5, 6.9, 6.8 and 7.7 % for the four systems respectively, showing the steady performance of ACO.

5.2 Pressure heads along the pipeline

When different numbers of sprinklers or pipe diameters in the system are applied, not only the specific energy consumption will vary, but the pressures and flow rates at sprinklers and pipes along the pipelines may differ. Further, working condition and thus irrigation uniformity of the system will change. Therefore, the pressure heads along the pipelines need to be investigated in the optimization. Comparisons of pressure heads at sprinklers and pipes along the pipelines in the four systems under optimal configurations obtained from GA and ACO are illustrated in Fig. 6.

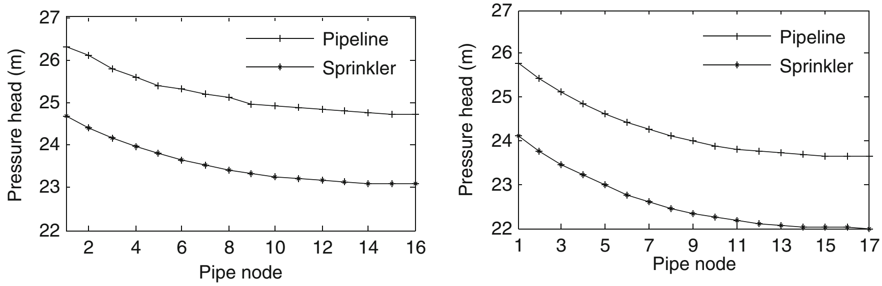
In Fig. 6, pressure heads at sprinklers and pipes along the pipeline gained from ACO are lower with smoother curves than those from GA, but the pressure differences between the sprinklers and the pipes at the same nodes for the two methods are generally the same. In Fig. 6(a1), 6(a2), 6(d1), 6(d2), pressure differences between the first and the end sprinklers calculated with GA are smaller than those with ACO in Systems (a) and (d). However, in Fig. 6(b1), 6(b2), 6(c1), 6(c2), they are smaller with ACO in Systems (b) and (c). This confirms that GA may be excellent for combinational optimization problems in smaller scales while ACO is more efficient for those in larger scales. All the pressure differences are lower than 20 % of the design pressure of sprinklers.

The relationships between specific energy consumptions and numbers of sprinklers for the systems presented in Fig. 4 are hard to be carried out with actual experiments. The reasons are that: firstly, high pressure heads at sprinklers due to fewer sprinklers equipped may destroy structures of sprinklers; secondly, far low pressure heads at sprinklers may impair the irrigation uniformities greatly which leads to no necessity in field tests. Thirdly, the field tests on movable sprinkler systems are labor intensive and something unexpected may happen after frequent installation and disassembly, so that validation tests on the optimization results from algorithms cannot be assured. In this respect, only the optimal configurations for the four systems were taken into account in the field tests performed in Jiangsu University. To make ssure the pressure head at the end sprinkler higher than 90 % of the design value, the optimum pipe diameters were used first and the number of sprinklers was tried and adjusted accordingly. The experimental optimal number of sprinklers and pressure heads along the pipelines are drawn in Fig. 7.

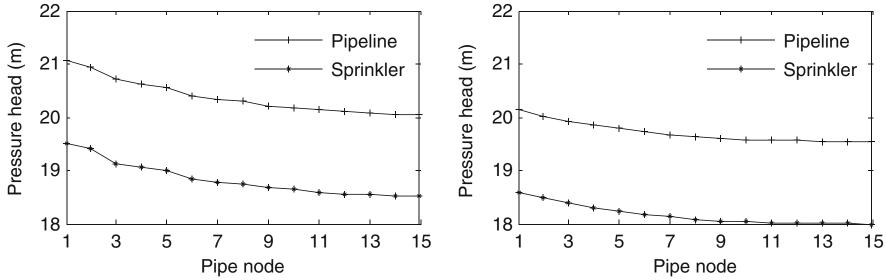
During the experiment, every system ran for one hour after its operation was stable and the rotation speed of pump, pressure heads at pipes were tested every 10 min. In the sprinkler system powered by the pump 50ZB-25D, the number of sprinklers $n=28$ was the maximum in which pressure head at the end sprinkler was already 90 % of the design pressure.

In comparison of Fig. 6 with Fig. 7, pressure heads at the pipelines in field tests for the sprinkler systems (a), (b) and (d) are closer to those with ACO method, with a deviation of 1.0, 1.0, 2.0 % respectively at the first node, and a deviation of 1.0, 3.7 and 1.0 % respectively at the end. However, for pressure heads at the pipelines in System (c), the values in ACO at the first node and the end node are 5.1 and 1.0 % respectively lower than those in field tests (Fig. 7c); in GA, the values are 2.4, 3.4 % higher, respectively.

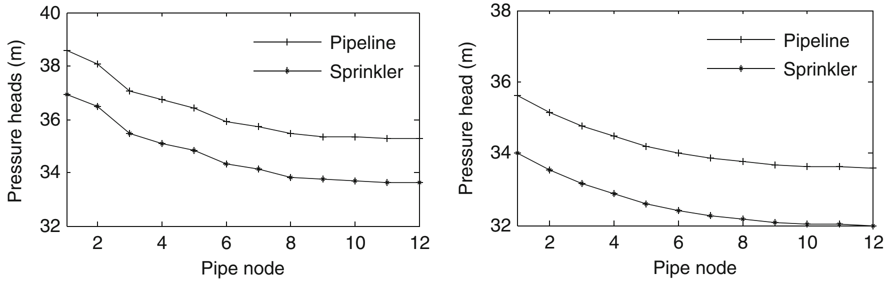
Slight fluctuations on the curves in Fig. 7c and d may be caused by the small terrain differences on the land Since the experiments on the four systems could not be finished within 1 day, the position for the installation of each system might vary. System (c) and System (d) were placed almost in the same line with the elevation decreased a little at the distance 150 to



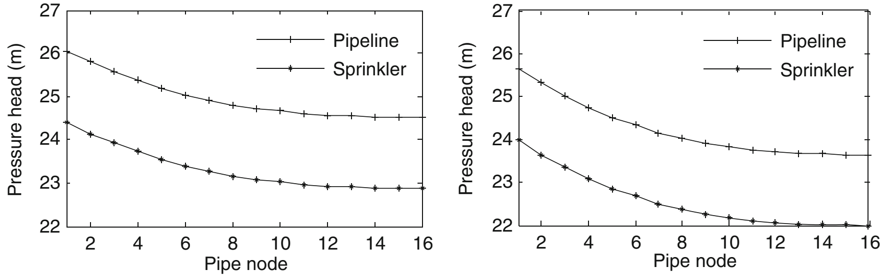
(a1) 50ZB-35Q (GA, n = 16, one pipeline) (a2) 50ZB-35Q (ACO, n = 17, one pipeline)



(b1) 50ZB-25D (GA, n = 30, two pipelines) (b2) 50ZB-25D (ACO, n = 30, two pipelines)



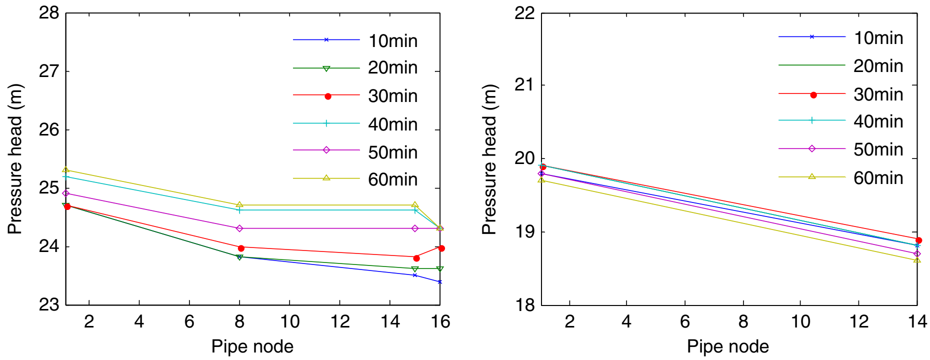
(c1) 65ZB-40C (GA, n = 12, one pipeline) (c2) 65ZB-40C (ACO, n = 12, one pipeline)



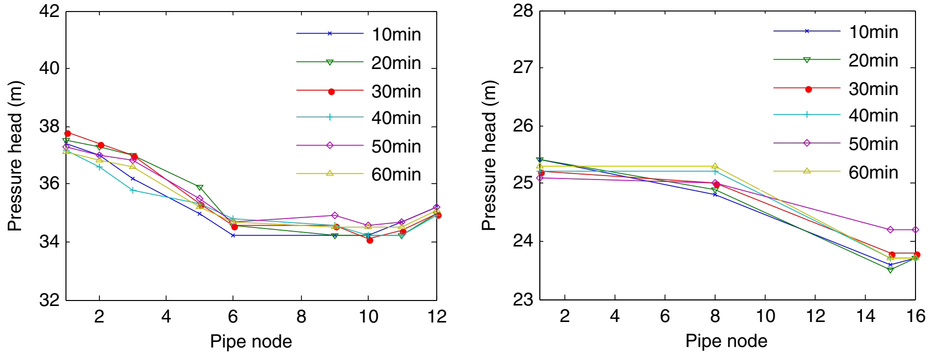
(d1) 50ZB-30C (GA, n = 16, one pipeline) (d2) 50ZB-30C (ACO, n = 16, one pipeline)

Fig. 6 Pressure heads at sprinklers and pipes along the pipelines with GA and ACO (*a1*) 50ZB-35Q (GA, n=16, one pipeline), (*a2*) 50ZB-35Q (ACO, n=17, one pipeline); (*b1*) 50ZB-25D (GA, n=30, two pipelines), (*b2*) 50ZB-25D (ACO, n=30, two pipelines); (*c1*) 65ZB-40C (GA, n=12, one pipeline), (*c2*) 65ZB-40C (ACO, n=12, one pipeline); (*d1*) 50ZB-30C (GA, n=16, one pipeline), (*d2*) 50ZB-30C (ACO, n=16, one pipeline)

180 m from the inlet of the system. Therefore, the pressure head at the end of the pipeline in System (c) and System (d) increased correspondingly caused by the Bernoulli equation. To



(a) 50ZB-35Q (Test, $n = 16$) (b) 50ZB-25D (Test, $n = 28$)



(c) 65ZB-40C (Test, $n = 12$) (d) 50ZB-30C (Test, $n = 16$)

Fig. 7 Pressure heads at pipes along the pipelines of systems (**a**) 50ZB-35Q (Test, n=16); (**b**) 50ZB-25D (Test, n=28); (**c**) 65ZB-40C (Test, n=12); (**d**) 50ZB-30C (Test, n=16)

exclude this effect, the pressure head at pipes deceased abruptly at the upper stream of the pipeline and then came to be stable at the downstream, just like the tendency in System (a) or Fig. 7 in the study by Trung et al. (2007).

5.3 Irrigation uniformities

Catch can tests were performed in the area between sprinklers No. 2 and No. 3. The water amounts collected in catch cans were measured. The irrigation uniformity, represented by Christiansen Coefficient was calculated and then overlapped to get the overlapping irrigation uniformity C_u considering the square arrangement when the system was moved to next location. The average water application rates ρ_0 and overlapping irrigation uniformities of systems are listed in Table 4.

In Table 4, overlapping irrigation uniformities C_u in the four systems with optimal configurations are all higher than 75 % required by the national standard (GB/T 50085-2007).

5.4 Comparisons of GA, ACO and field tests

Based on the established GA and ACO techniques, the optimal configurations and specific energy consumptions E_p of the irrigation systems, together with the working conditions of

Table 4 Average water application rates and overlapping irrigation uniformities of systems

System	50ZB-35Q	50ZB-25D	65ZB-40C	50ZB-30C
ρ_0 (mm/h)	7.01	4.32	6.10	6.93
C_u (%)	80	79.7	78.7	79.0

pumps have been obtained. In the field tests, the working conditions of pumps were identified on the characteristic curves first and the E_p was then calculated using Eq. (1). Comparisons of results from three methods above are provided in Table 5.

In the table, "combination" mainly refers to the type and number of sprinklers equipped; η_b is the pump efficiency, %; r is the reduction rate of specific energy consumption in the optimal configuration compared to that of initial design. The group of data "INITIAL" shows the results in the initial design, Group "TEST" gives the results from field tests.

In Table 5, the optimal numbers of sprinklers and working conditions of the systems gained from GA and those from ACO are similar, seen also from Figs. 4 to 6. The specific energy consumption is reduced in average by 10.27 % through GA, 12.45 % through ACO. In the field tests, the reduction rate is 11.27 %, a value between that from these two approaches. With the same number of sprinklers and proper pipe diameters equipped, the specific energy consumption E_p in ACO method is closer to that in field test compared to that in GA. In Fig. 4b and c and Table 5, we are clear that the optimal number of sprinklers gained by ACO is more reliable.

Comparing Table 2 with Table 5, we can see that, the pressure of sprinklers is for a large amount correlated to the energy consumption. E_p in System (c) with sprinklers typed 20PY is the highest, E_p in System (a) or (d) with sprinklers typed 10PXH the second, System (b) with sprinklers typed 15PY comes the last. Optimal configurations for these systems are 12 sprinklers 20 PY, 16 sprinklers 10PXH and 28 sprinklers 15PY, respectively.

The minimal pressure heads h_n are higher than 90 % of the design working pressure for all the three methods, and pressure deviations between any two sprinklers not listed in the table are lower than 20 % of the design pressure. Pump efficiencies are approximately 60 %, a high value for self-priming pumps. These combine to confirm the feasibility of the mathematical model used and the correction of results from both GA and ACO techniques.

6 Conclusions

An Ant Colony Optimization (ACO) algorithm for the optimization of sprinkler irrigation systems was built for the first time. The objective function was specific energy consumption. The pressure head loss between adjacent sprinklers was applied in the heuristic function to represent the distance between two cities. In the hydraulic calculation model the back step method was employed. Results from the ACO approach were compared to those from Genetic Algorithm (GA) previously used and experimental results on four sprinkler irrigation systems. In the field tests, pressure heads at pipes along the pipelines and the irrigation uniformities were measured.

Results indicate that the ACO algorithm proposed can be applicable in the optimization of irrigation systems and shows quick convergence, robustness, with the runtime 13–30 s in different systems. Comparing ACO and GA, ACO provides smoother curves of specific energy consumption over number of sprinklers with lower values than GA, and the minimum E_p in ACO is closer to that in field tests. The pressure heads at pipes along the pipelines

Table 5 Comparisons of results from GA, ACO and field tests

No.	Pump size	Combination		D (mm)	Q (m^3/h)	H (m(H$_2$O))	η_b (%)	h_n (m(H$_2$O))	E_p (kW·h·mm^{-1}·hm^{-2})	r (%)
(a)	50ZB-35Q[a]	INITIAL	14 * 10PXH	50	13.57	31.19	58.83	21.9	4.02	–
		GA	16 * 10PXH	65/50	15.11	29.11	61.13	22.7	3.6	10.3
		ACO	17 * 10PXH	65/50	16.65	28.65	62.73	21.6	3.46	13.8
		TEST	16 * 10PXH	65	18.86	27.7	59.4	21.1	3.45	14.1
(b)	50ZB-25D[b]	INITIAL	20 * 15PY	65	17.75	24.46	61.9	19.2	2.99	–
		GA	30 * 15PY	80/65	26	24.24	68	18.1	2.70	10.0
		ACO	30 * 15PY	80/65	25.56	22.88	67.9	17.7	2.55	14.7
		TEST	28 * 15PY	80	35.72	23.3	69.95	18.1	2.52	15.7
(c)	65ZB-40C[a]	INITIAL	10 * 20PY	65	21.71	41.88	63.34	32.9	5.01	–
		GA	14 * 20PY	80/65	30	40.64	65.76	32.0	4.68	6.5
		ACO	12 * 20 PY	80	25.34	38.62	64.77	31.4	4.51	9.9
		TEST	12 * 20 PY	80	36.21	40.5	67.02	32.7	4.57	8.7
(d)	50ZB-30C[a]	INITIAL	14 * 10PXH	50	13.14	30.67	61.39	21.9	3.78	–
		GA	16 * 10PXH	65/50	15.03	28.84	63.85	22.5	3.42	9.5
		ACO	16 * 10PXH	65	15.66	28.53	64.4	21.6	3.35	11.4
		TEST	16 * 10PXH	65	16.29	28.89	60.9	23.0	3.53	6.6

[a] The pipes weree laid in one line

[b] tthe pipes were laid in two parallel lines

obtained through ACO change gradually, more in accordance with those measured in field tests. The pressure differences at the first and the end pipe nodes obtained with ACO are higher than those with GA in the systems powered by pumps 50ZB-35Q and 50ZB-30C. The trends are contrary in the systems powered by 50ZB-25D and 65ZB-40C. And in the latter two systems the optimal numbers of sprinklers calculated through ACO are closer to the experimental results. These suggest GA may be excellent for smaller combinational optimization problems while ACO is more efficient in larger problems.

The optimal configurations of four systems were selected. The specific energy consumption was reduced in average by 10.27 % through GA, 12.45 % through ACO and 11.27 % in field tests. In the test case, the overlapping irrigation uniformities are higher than 75 %, so the performances of systems are ensured and the optimization results are reliable.

ACO developed in this paper may provide an efficient method for the optimization of irrigation systems. The results from ACO and GA in four systems reinforce the good performance of Ant Colony System in the water distribution network or pipelines by other authors. For further comparison of capabilities with GA and ACO for problems of different scales in irrigation, more samples are needed.

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