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Research on Resource Optimization Path of Agricultural Water-saving Irrigation Management Supported by Intelligent Algorithms

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ABSTRACT

In order to improve the efficiency of agricultural irrigation industry and ensure the economy and environmental protection in the production process. The study proposes an agricultural water-saving irrigation path optimisation method based on the NGSA-III algorithm, and establishes a multi-objective water-saving optimal allocation model for the agricultural water source irrigation system. The NGSA-III algorithm is used to obtain the optimal solution of the model and achieve the path optimisation of agricultural water-saving irrigation resources. The results show that the running time of the article method to get the optimal path result is 0.31s, which can improve the economic and environmental benefits of the agricultural irrigation industry, the model in this paper can achieve the effect of smaller environmental objectives when the economic objectives are larger, and three solutions are selected to trade-off the analysis of economic and environmental objectives. Among the three different optimal solutions, the decision maker can choose the decision scheme according to the actual situation, which provides reference for agricultural water saving path planning.

Keywords: ngsa-iii algorithm, water saving irrigation management, multi-objective optimisation; agricultural irrigation

1. Introduction

As China's water resources become increasingly strained and serious water shortages are occurring in many areas, water conservation measures must be taken to improve the efficiency of water use for sustainable development. Water-saving irrigation not only provides the water needed for crop growth to promote crop growth, but also reduces water wastage and soil erosion. Advances in science and technology have led to continuous improvements and innovations in water-saving irrigation management techniques, which are capable of precisely controlling water and improving irrigation efficiency, and are also of far-reaching significance for improving agricultural aquaculture [1-2].

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Agricultural irrigation is an important part of agricultural development, and water-saving irrigation is the key to agricultural irrigation. In the process of innovative water-saving irrigation ideas, intelligent irrigation technology using sensors and computer technology to achieve automatic irrigation is gradually applied to farmland water conservancy projects. Intelligent irrigation technology can use sensor technology to perceive real-time soil moisture status, meteorological conditions and crop growth and other key information, providing accurate data support for decision makers [3-5]. Through the data acquisition and processing technology, the information obtained by the sensor is analysed and processed, so as to achieve intelligent control and optimal adjustment of the irrigation system, ensure that the irrigation water quantity matches the crop water demand, and avoid the problems caused by water wastage in the traditional irrigation system [6-8]. In addition, the intelligent irrigation system can be combined with modern information technology, such as artificial intelligence and big data analysis, to carry out more accurate water resource management and optimal use, which provides a strong support for the sustainable development of farmland water conservancy projects [9-12]. Therefore, the selection of intelligent irrigation system as a water conservation measure within the farmland water conservancy project can not only effectively reduce the waste of resources and improve the irrigation efficiency, but also achieve the intelligent management of farmland water conservancy information technology and promote the sustainable development of agricultural production [13-15].

Literature [16] designed a water-saving irrigation management system based on a predictive algorithm that combines a three-layer architecture, i.e., multi-layer perceptron neural network, support vector machine, and k-nearest neighbour classifier, to achieve water use management and prevent soil leakage, with better water and energy saving effects. Literature [17] shows that refined water saving irrigation system is one of the effective measures for water management, empowered by a series of modern technologies such as monitoring and control, architecture, data sharing communication, artificial intelligence, etc., which meets the water management needs, improves the water use efficiency and reduces the environmental damage. Literature [18] deployed a series of sensors to measure temperature, humidity, soil moisture, and water use, which can be accessed through web or mobile applications to obtain relevant soil data and automate irrigation using the sensors. Literature [19] integrated the multi-source big data adaptive weighted fusion algorithm into the farmland irrigation system, constructed a multi-objective irrigation water optimisation allocation model, calculated the weighting coefficients of soil moisture using the adaptive weighted average fusion algorithm, and solved the optimal allocation of irrigation water using a multi-objective particle algorithm, which greatly improved the reliability of irrigation decision-making. Literature [20] introduced the calculation method of soil moisture replenishment and crop evapotranspiration under the water balance theory, on the basis of which an intelligent water-saving irrigation control system based on the agricultural Internet of Things was designed, which can effectively solve the problems of uneven soil moisture distribution and system decision-making lag in order to achieve intelligent water-saving irrigation. Literature [21] also designed an intelligent water-saving irrigation system based on agricultural IoT, where the soil and crop data collected by the terminal monitoring device are processed and sent to the web or application via a cloud server, and the control node opens or closes the inlet gate by comparing the upper and lower thresholds of the node's water level set to achieve automatic irrigation. Literature [22] proposes a digital twin smart irrigation system, where the IoT platform calculates the corresponding irrigation method using the collected data as inputs, and simulates this irrigation behaviour in a virtual simulation model, evaluating different irrigation strategies by establishing corresponding application scenarios.

In this paper, in order to alleviate the shortage of water resources in the irrigation area, based on the optimal allocation of water resources transport and multi-objective optimisation theory, after analysing the composition of the water resources system in the irrigation area, two optimisation objectives, namely, economic and ecological, are selected to establish the optimisation model of water-saving in agricultural irrigation. At the same time, the intelligent SVM algorithm was introduced to automatically plan the agricultural water-saving irrigation path. On this basis, the genetic algorithm is improved, and the optimised NSGA-III algorithm is used to solve the constructed model and path. Finally, simulation experiments are set up to verify the feasibility of the model in terms of optimal irrigation paths and agricultural irrigation water-saving effects, respectively, so as to provide a decision-making basis for water resource management in irrigation districts.

2. Multi-objective optimisation of water-saving irrigation resources in agriculture

2.1. Optimal allocation of water resources

2.1.1. Connotation and characteristics of optimal allocation of water resources。 Optimal allocation of water resources is based on the balance of supply and demand, the use of engineering or non-engineering measures within a given area to rationally allocate limited water resources, thus ensuring the coordination of economic, social and environmental development. Optimal allocation of water resources has the characteristics of rational planning, in the case of agricultural irrigation area is not reduced, supply to set demand, priority to meet the production of water for domestic use [23].

Optimal allocation of water resources can effectively improve the distribution efficiency of water resources, rationally allocate the proportion of water use in various sectors, and alleviate the tension between supply and demand of various types of water users. In addition, for the improvement of the water conservation mechanism has a role in promoting the improvement of sectoral water use efficiency, can promote the efficient use of water resources in different sectors of all walks of life. The optimal allocation of water resources is a global strategic plan that takes into account the inherent conditions of water resources in different regions and basins, as well as the coordinated development of different aspects of the region as a whole, in order to maximise the overall benefits.

2.1.2. Methods of water allocation:

1) Dynamic Planning. Dynamic planning belongs to operations research and is a process of solving optimal decisions. Dynamic planning simplifies the problem by transforming a multidimensional decision problem into multiple one-dimensional decision problems. Dynamic planning models are used to deal with multilevel decision making by dividing the problem into different spatial or temporal features and making decisions at each stage successively. At the same time, when using the principles and methods of dynamic planning, the problem must be analysed specifically based on determining the specific problem and finally the solution.

2) Multi-objective planning method. Multi-objective planning, also known as multi-objective optimisation, is mainly used to study the situation of multiple objective functions, so as to achieve the overall objective optimisation. There are two common multi-objective planning methods: the first is the linear weighting method, the ideal point method and other methods to convert complex multi-objective problems into simple single-objective problems; the second is the hierarchical sequence method, which is a method of classifying the objectives according to the degree of importance [24].

2.2. Multi-objective planning theory

2.2.1. Concept of multi-objective planning solutions:

1) Non-inferior solution. In general, there is no absolute optimal solution to the multi-objective planning problem, which requires the introduction of a new 'solution' concept - non-inferior solution. Let $f(x)$ be the objective function of the multi-objective decision-making problem, and its components $f_j(x)$ and $j=1,2,\cdots\cdots,n$ are larger and better. For $x^* \in X$, x^* is said to be a non-inferior

solution to the optimisation problem if there is no x in X such that $f_j(x) \ge f_j(x^*)$, $j = 1, 2, \cdots\cdots, n$, and at least one j strict inequality holds.
2) Pareto Optimality. Pareto optimality refers to an ideal state of resource allocation, i.e., the situation that everyone is in is not getting worse, at least some people are getting better. In the process of finding the optimal solution, multiple sub-objectives cannot achieve the optimal state at the same time, using Pareto optimality can allocate the individual fitness and can obtain a non-inferior solution that satisfies the conditions and is acceptable [25].

2.2.2. Multi-objective planning solution methods. The following methods are commonly used to solve multi-objective planning problems:
1) Comprehensive Benefit Optimisation Method. Comprehensive benefit optimisation method needs to quantify multiple objectives and construct a utility function through certain rules. And then the sum of multiple objectives is calculated, using the relationship between the objective function and the utility function to coordinate the conflict of the objectives.
2) Penalty function method. Penalty function method can transform the constrained optimisation problem into unconstrained optimisation problem. For multi-objective planning problems, the decision maker will explicitly give the ideal state of each objective value or the desired value, and determine the ideal solution by comparing the degree of deviation between the objective values of the variables in the actual model and the desired value.
3) Constrained Model Method. Considering that the decision maker may not be able to give an accurate ideal value of the target, the constraint model method changes this fixed value into an interval value. At this point, the target value becomes a set of constraint intervals, which can be transformed into model constraints, and when multiple target values can be transformed into constraints, the multi-objective model can be transformed into a single-objective model, which reduces the difficulty of solving.
4) Objective planning method. Goal programming method is to give the expectation value for each objective in advance, and then find the closest solution to the expectation value of the objective under the satisfaction of certain constraints.
5) Intelligent Optimisation Algorithm. Genetic algorithm is a method of searching for optimal solutions by converting the problem solving process into a process similar to the crossover and mutation of chromosome genes in biological evolution [26]. However, the algorithm has two disadvantages: first, the algorithm is greatly influenced by the initial solution, and the final optimisation result depends to a greater extent on the advantages and disadvantages of the initial solution. The second is that the computational efficiency is low, for the feedback information in the network calculation, lack of effective and timely use.

3. Multi-objective optimal allocation of water resources systems in irrigation districts

3.1. Composition of water resources systems in irrigation areas

Irrigation water resources system is a complex system consisting of water supply, water transmission and distribution, water use and drainage and other sub-systems.
1) Water supply system: it is divided into water produced in the region and water from outside the region or water transfer. The water produced in the region includes surface water such as water storage, water diversion, water lifting, deep and shallow groundwater, sewage water reuse, etc.; water or water transfer from outside the region includes water diversion, water transfer from outside the basin, etc.
2) Water transmission and distribution system: including water transmission rivers, trunk and branch channels, water pipelines, etc.

3) Water-use system: composed of domestic, agricultural, industrial, ecological and other water-use sectors.
4) Drainage system: including domestic sewage, industrial sewage, agricultural irrigation backwater, flood drainage and so on. Domestic and industrial sewage is discharged into the receiving water body through the drainage network or sewage treatment plant, while agricultural irrigation backwater and flood drainage are discharged into the receiving water body through drainage canals.

3.2. *Objective function and constraints*

In order to maximise the comprehensive benefits of the water saving system in agricultural irrigation areas, 2 objectives of economic and ecological benefits were selected to be determined as the objective function of this model.

3.2.1. Objective function:
1) Economic objectives (RMB 10,000): directly reflected by maximising the economic benefits of the irrigation area through the optimal allocation of water resources.

$$F_2(x) = \max\left\{\sum_{j=1}^{J}\sum_{k=1}^{K}\left[\sum_{i=1}^{I}\left(b_{ijk}^{\pm} - c_{ijk}^{\pm}\right)x_{ijk}^{\pm}\alpha_{ij}^{\pm} + \sum^{c}\left(b_{cjk}^{\pm} - c_{cjk}^{\pm}\right)x_{cjk}^{\pm}\alpha_{cj}^{\pm}\right]\beta_{jk}^{\pm}w_j^{\pm}\right\} \quad (1)$$

Where $F_2(x)$ - the economic objective function (million yuan), that is, expressed as the maximum value of the difference between the benefits and costs of water supply;

$b_{ijk}^{\pm}$, $b_{cjk}^{\pm}$ - j sub-district independent water source i, public water source c to k user units of water supply produced by the water efficiency coefficient, yuan / m^3;

$c_{ijk}^{\pm}$, $c_{cjk}^{\pm}$ - j Sub-area independent water sources i, public water sources c Coefficient of water supply costs incurred in supplying water to k user units, yuan/m^3;

$\alpha_{ij}^{\pm}$, $\alpha_{cj}^{\pm}$ -- j Subdistrict independent water i sources, and water supply sequencing factors for public water c sources;

$\beta_{jk}^{\pm}$ -- j Equity of water use coefficients for subarea k users;

$\omega_j^{\pm}$ - Weighting factor for sub-area j.

2) Ecological objective (t): The ecological use of water in the region is necessarily accompanied by discharges, indirectly measured by the minimum value of discharges (e.g., COD) that is representative of the region's representative pollutant constituents.

$$F_3(x) = \min\left\{\sum_{j=1}^{J}\sum_{k=1}^{K}\left[0.01 d_{jk}^{\pm} p_{jk}^{\pm}\left(\sum_{i=1}^{I} x_{ijk}^{\pm} + \sum^{c} x_{cjk}^{\pm}\right)\right]\right\} \quad (2)$$

Where $F_3(x)$ - the ecological objective function (t), i.e. indirectly expressed by the minimum value of the discharge that can represent a representative pollution component of the region;

$d_{jk}^{\pm}$ - the content of COD per unit of wastewater discharged by j subarea k users, mg/L;

$p_{jk}^{\pm}$ - the coefficient of effluent discharge for users in subarea k of j.

3) Normalisation of the objective function. Since the two objective functions are not consistent in terms of magnitude, it is necessary to unify the magnitude and normalise the objective functions before solving. First of all, the maximum value of each objective function $F_{i,\max}(x)$, minimum value $F_{i,\min}(x)$, through the following formula to normalise the objective function, that is:

$$\gamma_i = \frac{F_i(x) - F_{i,\min}(x)}{F_{i,\max}(x) - F_{i,\min}(x)} \quad (3)$$

The two objective functions are thus normalised to facilitate the solution of the model.

3.2.2. Constraints:

1) Water availability constraint. The total amount of water supplied to each water user in the different water supply calculation sub-districts should not be more than their water availability, i.e.:

$$Independent\ water\ source: \sum_{k=1}^{K} x_{ijk}^{\pm} \le W_{ij}^{\pm} \tag{4}$$

$$Public\ water\ sources: \sum_{k=1}^{K} x_{cjk}^{\pm} \le D_{cj}^{\pm} \tag{5}$$

$$\sum_{j=1}^{J} D_{cj}^{\pm} \le W_{c}^{\pm} \tag{6}$$

Where $W_{ij}^{\pm}$ - the amount of water available from independent water sources i in sub-area j, 10,000 m^3;

$D_{cj}^{\pm}$ - the amount of water allocated to sub-area j from public water source c, million m^3;

$W_{c}^{\pm}$ - the amount of water that can be supplied by public water source c, million m^3.

2) Water conveyance capacity constraints. The water conveyance systems of different water sources should not convey more water than their maximum conveyance capacity, i.e.:

$$x_{ijk}^{\pm} \le Q_{ij\max}^{\pm} \tag{7}$$

$$x_{cjk}^{\pm} \le Q_{cj_{\max}}^{\pm} \tag{8}$$

Where $Q_{ij\max}^{\pm}$ - the maximum capacity of independent water source i to supply water to subarea j, 10,000 m^3;

$Q_{cj\max}^{\pm}$ - public water source c to j sub-area water supply maximum transmission capacity, 10,000 m^3.

3) User water demand constraints. The amount of water provided by each water source to each user in each sub-area should not be less than the minimum water consumption of that user, nor exceed the maximum water consumption of that user, i.e.:

$$D_{jk_{\min}}^{\pm} \le \sum_{i=1}^{I} x_{ijk}^{\pm} + \sum^{C} x_{cjk}^{\pm} \le D_{jk_{\max}}^{\pm} \tag{9}$$

Where $D_{jk_{\min}}^{\pm}$ - Minimum water demand for users in subarea k of j, in 10,000 m^3;

$D_{jk_{\max}}^{\pm}$ - the maximum water demand of the j sub-area k users, 10,000 m^3.

4) drainage system water quality constraints. Pollutants need to be discharged in compliance with the standards, and the total amount of discharge cannot exceed the total discharge.

$$Meets\ s\tan dards: C_{jkr}^{\pm} \le C_{0}^{r} \tag{10}$$

Where $C_{jkr}^{\pm}$ - the concentration of pollutant r in the wastewater discharged by the users of Subarea k of j;

C_{0}^{r} - Concentration of pollutant r in compliance with discharge regulations.

$$Total\ control: \sum_{j=1}^{J} \sum_{k=1}^{K} \left[0.01 d_{jk}^{\pm} p_{jk}^{\pm} \left(\sum_{i=1}^{I} x_{ijk}^{\pm} + \sum^{C} x_{cjk}^{\pm} \right) \right] \le P_0 \tag{11}$$

Where P_0 - total permitted COD emissions, t.

5) Variable non-negative constraint. The amount of water supplied to any water user in each sub-district is not negative and the amount of water that can be supplied meets the needs of each water user, viz:

$$x_{ijk}^{\pm} \geq 0 \tag{12}$$

3.3. *Automatic planning of optimal paths*

The selection of reference values for SVM algorithms is usually an example method, an intelligent optimization method, and a network search, the most commonly used of which is to use a network search to receive data. In this method, the error value A and the kernel function reference value B can be taken as X and Y values respectively, and the combination of $X \times Y$ and (A, B) can be used to analyze them separately, and the group with the highest accuracy can be selected as the optimal reference value.

Assuming that the best error values and kernel function reference values for the classification manager of the above SVM algorithm are A_{SVM} and B_{SVM}, respectively, the values are transformed into the corresponding coordinates on the basis of the network search, i.e:

$$\begin{cases} X_{SMM} = PLA_{SVM} \\ Y_{SVM} = PLB_{SVM} \end{cases} \tag{13}$$

(13) Where: P is the parameter independent variable, and L is the value of the independent variable when the function is updated to take values.

From equation (13), the reference range of data for the manager is $X \in (X_{SVI} - 2, X_{SVI} + 2)$, $Y \in (Y_{SVM} - 2, Y_{SVM} + 2)$. It can be seen that X, Y are the coordinates transformed on the basis of network search, when the data length is 1, the data is within the range of 5 values respectively, so the optimal reference value is obtained from it. Based on the network search within the region, the data is then classified and optimised using the optimal SVM classification manager on the basis of samples of the original data to obtain the most accurate range of data.

When the data has been calculated by the SVM algorithm, there may be certain types of data that are not within the normal specified range, so special calculation steps need to be added after the above calculations. The added algorithmic steps are used with different penalty values for majority and minority classes respectively, which improves the output of the SVM classification manager by adding penalties to the erroneous minority sample data.

4. Modelling water saving optimisation in irrigated agriculture

4.1. *Genetic algorithms*

Genetic algorithm is a global multi-objective optimization algorithm for solving complex problems, which simulates the mechanism of natural selection and genetic variation in the biological world, based on Mendel's theory of genetics and Darwin's "survival of the fittest, the survival of the fittest," the basic idea of the theory of evolution, selection, mating, mutation, and other evolutionary operations on the individual to produce the next generation of population, and keep evolving until a population that meets the conditions is created.

Genetic algorithm uses adaptive global optimization technology and intelligent search technology, good convergence, so it is suitable for solving the traditional search algorithm is difficult to solve, with a large amount of computation of complex discrete or continuous variable problems. Genetic algorithm is suitable for solving complex optimization problems, and in recent years, it has been widely used in the field of industrial engineering and achieved good research results, and it is also widely used in many fields such as pattern recognition, neural network, image processing, industrial optimization control, machine learning, biological science, adaptive control and social science.

4.2. NSGA-III Algorithm

Since NSGA-II mainly relies on the crowding degree for ranking, the solution with larger crowding distance will be preferred, so it works poorly in the high dimensional objective space, Deb further proposed the NSGA-III algorithm with predefined multiple reference points to maintain the diversity of the population, and improved the display of the objective optimisation results, and the solution flowchart of NSGA-III is shown in Fig. 1.

1) Initialisation: the NSGA-III algorithm firstly needs to define a set of reference points, set up an initialisation population with a specified number of N, and the number of genetic generations T to randomly generate the initial parent population $P(0)$.

2) Crossover and mutation: In generation t, the algorithm generates the offspring population $Q(t)$ with the same number of N by random selection operator, two-point crossover operator and polynomial mutation operator on the basis of population $P(t)$5.

3) Calculation of fitness: the objective function values of 2N individuals in population $R(t)$ of generation t are calculated using the specified objective function, which is used to calculate the individual fitness values.

4) Selection: the purpose of selection is to choose the best N solutions from population $R(t)$ into the next generation $P(t+1)$.

5) Selection method: first of all, it is necessary to scalarise the multi-objective function, which will be used to associate the reference points; use the ASF formula to find the intercept on the corresponding coordinate axes of each objective function and carry out the normalisation operation; use the recursive method to get the corresponding division of the reference points to construct the reference vectors.

6) Termination: when the number of iterations reaches T, select the individual with the largest fitness value among the $P(T)$ groups as the optimal individual, i.e., the optimal solution.

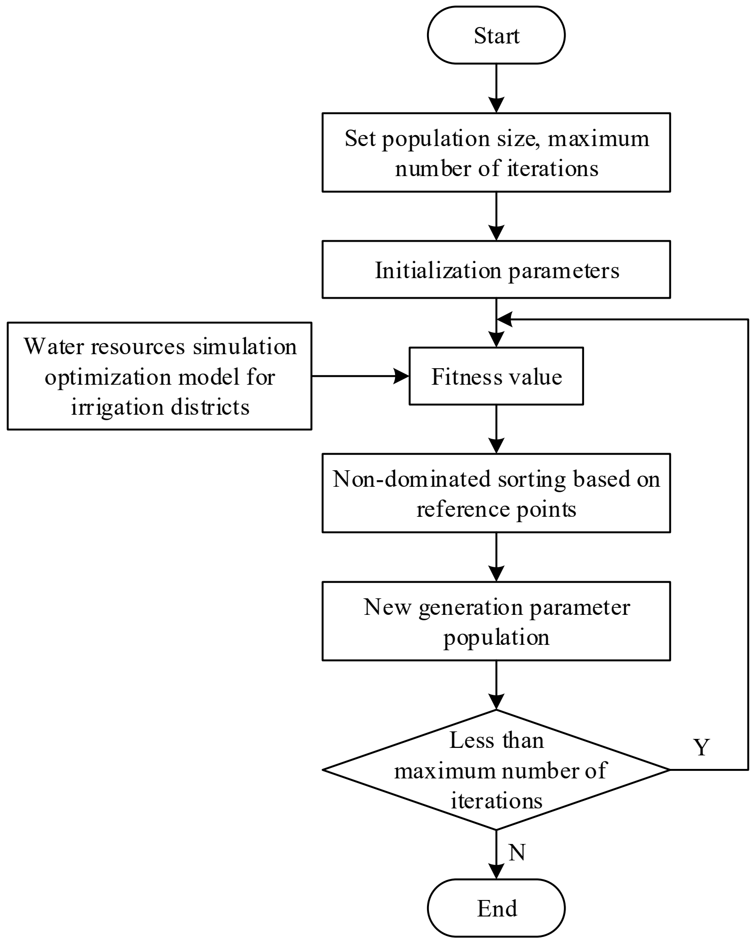


Fig. 1. NSGA-III algorithm solution flowchart

4.3. NSGA-III optimisation steps

1) Initial population generation: based on the set number of 200 individuals as well as 30 decision variables and upper and lower bounds on the decision variables, Pymoo generates a two-dimensional NumPy array of 200 rows and 30 columns as the initial parent population.
2) Crossover and mutation: the parent population P(0) will be randomly selected using binary crossover with crossover probability Pc=0.7 and polynomial mutation with mutation probability Pm=0.05 to generate the offspring population Q(0) with the same number of 200.
3) Adaptation evaluation: the objective function values of 400 individuals in R(0) were calculated using the five objective functions specified in this study, which were used to evaluate the superiority-disadvantage relationship of each individual and to calculate the degree of individual constraint violation.
4) Selection: the purpose of selection is to choose the best 200 individuals from the population R(0) into the next generation P(1).
5) Termination: when the number of iterations reaches 100, the individual with the largest fitness value in the population P(100) is selected as the best individual, i.e., the optimal solution.

5. Model solution for NGSA-III based water saving irrigation pathways

5.1. Experiments with NGSA-III modelling algorithms

5.1.1. Test preparation. In order to test the feasibility of the agricultural water-saving irrigation path optimisation method based on the NGSA-III algorithm designed in this paper, a simulation simulation comparison test was designed. Based on the Windows system, the test platform for the simulation test is built, and the computational parameter settings of the relevant algorithms are shown in Table 1.

Table 1. The calculation parameters of the simulation test are designed

Serial number	Project	Parameter value
1	Initial particle population size	79
2	Particle dimension	5
3	Maximum iteration number	99
4	Learning factor	1
5	Inertia coefficient	0.1~0.7

An agricultural field with balanced growth, quality and yield in a region was used as a test sample for this experiment. In this agricultural field, 10 groups of coordinate nodes were randomly selected for the simulation test.The relative coordinate positions of the 10-group nodes are shown in Table 2.

Table 2. The relative coordinate parameters of 10 group nodes of the simulation test

Serial number	Test node	Relative coordinate value
1	A	(2.14,6.00)
2	B	(7.11,4.99)
3	C	(8.45,6.79)
4	D	(1.68,5.28)
5	E	(2.28,1.95)
6	F	(1.42,2.58)
7	G	(2.91,4.57)
8	H	(3.82,2.57)
9	I	(5.88,1.22)
10	J	(7.59,2.62)

5.1.2. Detection results and analyses. On the basis of the above experimental preparation, the path optimisation method based on NGSA-III algorithm (experimental group), the traditional method (control group 1), and the path optimisation method based on NGSA-II algorithm (control group 2) designed in this paper were applied to carry out the optimisation of agricultural water-saving irrigation paths for 10 groups of nodes, respectively, and the runtimes of the optimisation results obtained by different methods were recorded as shown in Table 3.

As can be seen from the table, for the random 10 groups of node coordinates, the running time of the optimisation path results obtained by the test group methods are lower than those of control group 1 and control group 2, which are lower than 3.93 and 0.97s, respectively, which indicates that the application of the improved particle swarm algorithm can improve the convergence degree of the data information, so as to obtain the optimisation scheme faster, with high efficiency and real-time performance.

Table 3. The path optimization of different approaches is compared

Serial number	Test method	Running time /s

1	Test group	0.31
2	Control group 1	4.24
3	Control group 2	1.28

The results of the optimised paths obtained by the different methods are recorded, as shown in Figures 2-Figures 4.

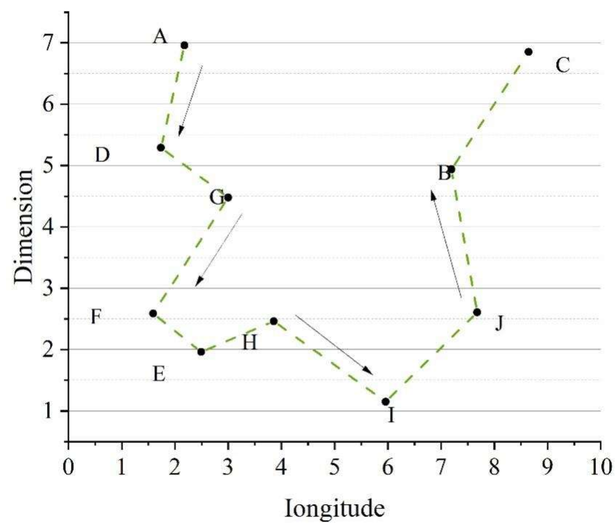


Fig. 2. The path optimization results of the test group method

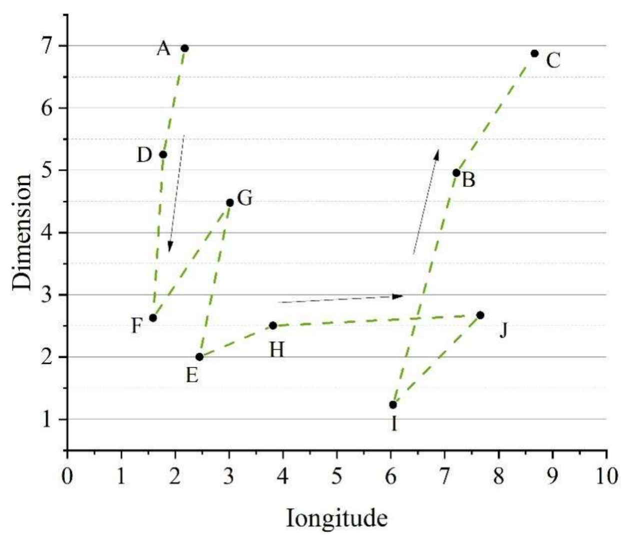


Fig. 3. The path optimization results of the control group 1 method

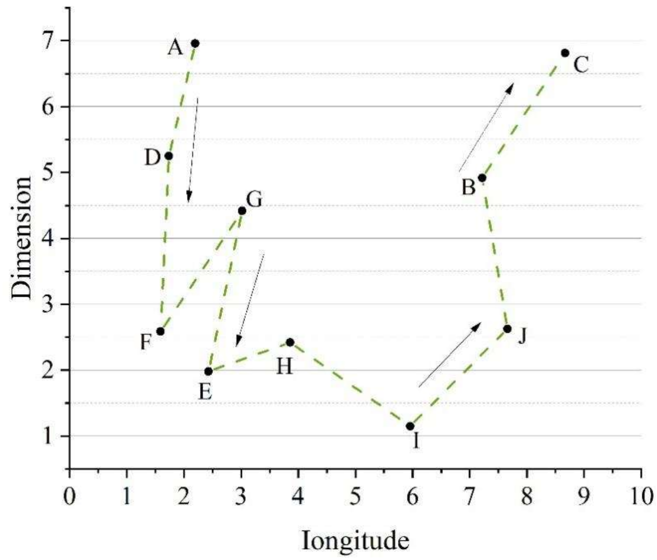


Fig. 4. The path optimization results of the control group 2 method

Setting the same time, the irrigation work was carried out according to the agricultural water-saving irrigation paths of the three methods shown above, respectively. In order to avoid the test results have chance, repeat the irrigation for 5 times, record the water consumption of different methods each time to complete the irrigation, and make a comparative analysis, the results are shown in Table 4.

As can be seen from the table, at the same time, the total water use and average water use were lower than control group 1 and control group 2 when irrigation was carried out according to the path optimisation results obtained from the experimental group method.The total water use was 97.5 and 80.41 $m^3/(h.\ m^{-2})$ lower than control group 1 and control group 2, respectively. The average water consumption was 19.5 and 16.08 $m^3/(h.\ m^{-2})$ lower than control group 1 and control group 2, respectively. It indicates that after applying the method proposed in this paper for irrigation path optimisation, the total water consumption and average water consumption are lower, and the saving effect on water resources is significant and feasible, which can effectively save water for agricultural irrigation, and is conducive to improving the economic and environmental benefits of the agricultural industry.

Table 4. Comparison of irrigation water usage in different methods of the same time

Serial number	Irrigation water use /(m^3/(h·m-2))		
	Test group	Control group 1	Control group 2
1	68.11	87.31	85.26
2	69.33	88.39	84.83
3	67.24	86.25	85.31
4	69.53	89.42	83.88
5	68.19	88.53	83.53
Total	342.4	439.9	422.81
Mean	68.48	87.98	84.56

5.2. Multi-objective Configuration Modelling Application

5.2.1. Data area selection. A city is rich in rice, corn and soybean, and the proportion of agricultural irrigation water consumption in the total water consumption has been increasing year by year.There is a serious phenomenon of over-exploitation of groundwater in A city. According to the statistics in 2015, City A is dominated by electromechanical wells in the water supply of various water conservancy projects, of which electromechanical wells account for 60.08% of the water supply of water conservancy projects in City A. The proportion of water lifting projects is 23.53%, water diversion projects account for 6.88%, and water storage projects account for 9.51%. Due to the lack of water resources controlling projects, compared with groundwater exploitation, the ability to exploit surface water and transit water under the current conditions is poor, and the groundwater level is declining. Therefore, in view of the serious imbalance between surface water supply and underground water supply in City A, this paper evaluates and decides on the trade-offs between the economic and environmental objectives of different scenarios for the optimal allocation of limited agricultural irrigation water among different crops in City A.

5.2.2. Access to data sources. This study reviewed relevant information and field research to obtain data to classify the incoming water situation into three categories: high incoming water scenarios, medium incoming water scenarios, and low incoming water levels, resulting in the available water supply for the planning year 2020, as shown in Table 5.

Table 5. Water supply in 2020

Water source	Water supply	High water scene(108m^3)	Water scene(108m^3)	Low water(108m^3)
Surface water	Max	21.12	18.56	16.87
	Min	14.89	16.52	13.39
Groundwater	Max	58.53	40.39	52.91
	Min	34.15	19.89	18.56

Through field research, it is learnt that the current cost of surface water and groundwater use is 0.3 and 1.1 Yuan· m^{-3} , i.e. Cij , and it is predicted that the cost of surface water and groundwater use will remain unchanged in the planning year 2020. Known from 2010 to 2015, three major crops planting area data, according to the A city area of paddy fields, dry field development plan, planning year 2020 rice, corn and soybean planting ratio of 47%, 30% and 23%. According to the actual research of the crop water requirements as shown in Table 6.

Table 6. Crops acreage,irrigation quota and water requirement in 2021

Crops	Planting area(108m^2)	Irrigation quota(m^3·hm^{-2})			Water requirement(108m^3)		
		Low water	Water scene	Water supply	Low water	Water scene	Water supply
Rice	50.2	4210	4866	5320	33.68	38.34	42.32
Corn	32.0	530	1230	1590	2.15	4.8	5.86
Soybean	24.8	530	1230	1485	1.58	3.55	3.88

5.3. *Model solution and result analysis*

In this study, three scenarios were solved and analysed for high, medium and low water inflow. The solution results contain N sets of feasible scenarios (N is the population size), and the objective values of each scenario have a wide range of distribution. The results of all the Pareto solutions of this model under high, medium and low water scenarios are shown in Figs. 5~7. The spatial distribution of the Pareto solution set is that the whole Pareto front is convex, smooth, with good distribution and strong continuity, reflecting that the NSGA-III genetic algorithm has a good capability of searching for Pareto solutions.

The objective functions are $f_1(x)$ maximisation and $f_2(x)$ minimisation, and the best scenario is selected according to certain rules in the Pareto solution set. Determine the best option under three incoming water scenarios, taking the high incoming water scenario option selection as an example.

The Pareto frontier solution for the high water scenario is shown in Figure 5, as the economic and environmental objectives increase, contradicting the integrated objective.There is an inflection point value 911 in the Pareto curve (at scenario 2 in the figure), if the same economic objective value is increased, the increase in the environmental objective value on the left side of the inflection point will be lower than the increase in the value on the right side. On the right side of the inflection point, the increase of economic target value becomes faster while the increase of fertiliser emission becomes slower. Taking this into consideration, it can be seen that if the decision maker focuses on economic development, it is recommended to choose the inflection point of the curve or the point on the right side of the inflection point as the best option. If the decision maker focuses on the sustainable development of the irrigation system, it is recommended to choose the point on the left side of the inflection point.

In order to further study the allocation of water-saving resources for irrigated agriculture in City A, three scenarios are selected for analysis under different water supply scenarios. Scenario 1 (right side of the inflection point) indicates that at this time, $f_1(x)$ and $f_2(x)$ are the largest; Scenario 3 (left side of the inflection point) indicates that at this time, $f_1(x)$ and $f_2(x)$ are the smallest; and Scenario 2 (at the inflection point) is the compromise solution of $f_1(x)$ and $f_2(x)$, and the values are in between, which indicate that they are larger than $f_1(x)$ and smaller than $f_2(x)$.

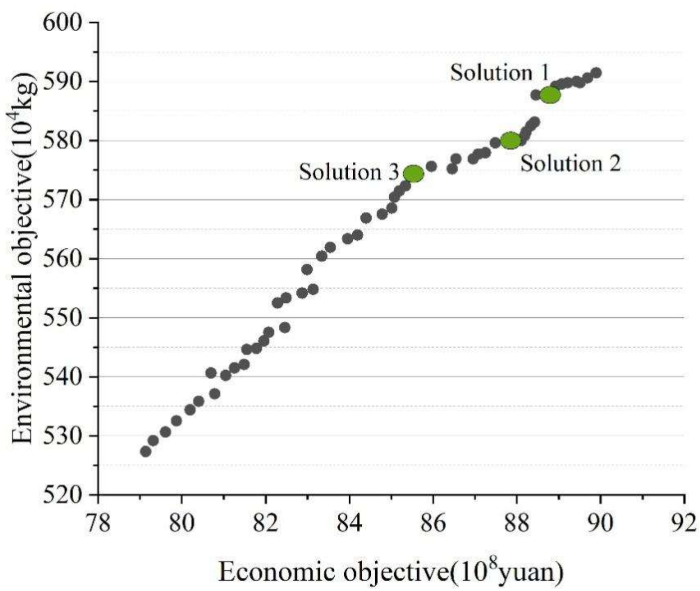


Fig. 5. The high water scenario is iterated 600 times after the pareto front

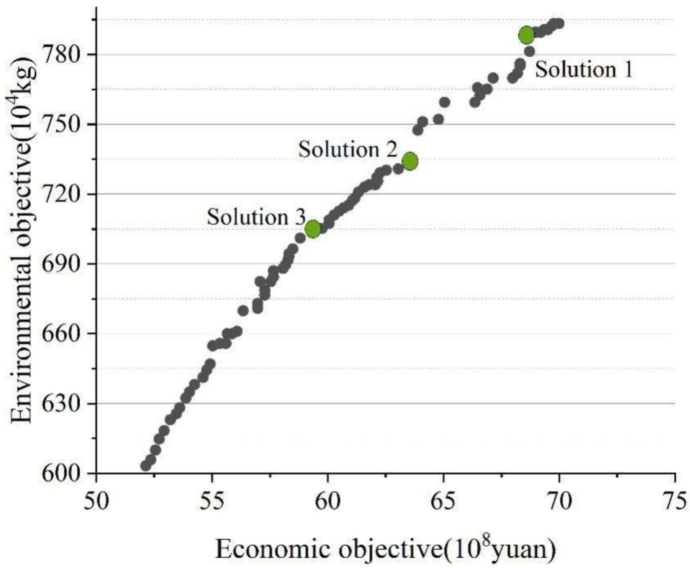


Fig. 6. The front end of the pareto is 600 times in the water

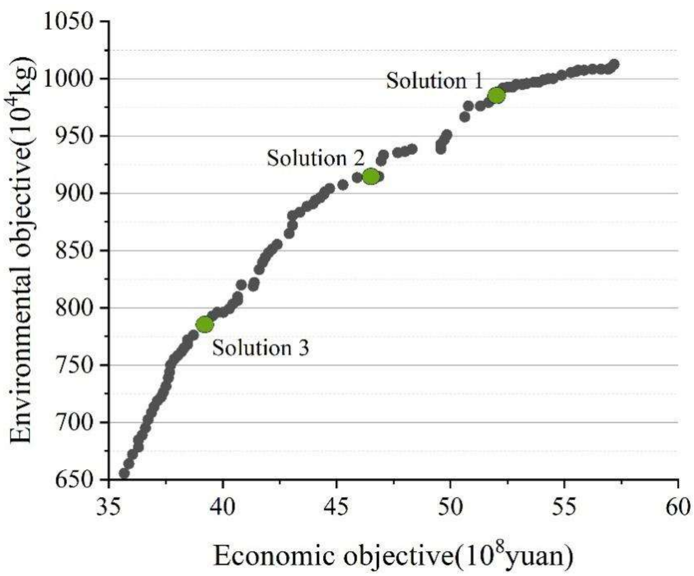


Fig. 7. After 600 times the pareto front is iterative

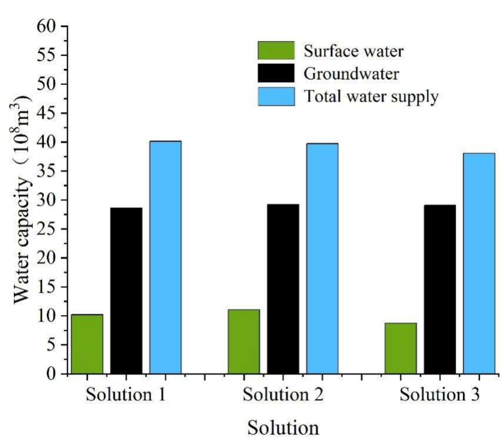
5.3.1. Target value analysis. The economic objectives, environmental objectives and water deficit of different scenarios are shown in Table 7. From the table, it is clear that the economic objective of Option 1 under the high water inflow scenario is the largest, i.e., high volume of irrigation water and high economic returns. However, the maximum environmental objective will harm the soil, surface water and groundwater, etc. Scenario II has both economic and environmental objectives between scenarios I and III and is a compromise. In scenario three, the environmental objective is the smallest and the environmental requirements are fully considered, but the economic objective is the smallest at this time, which is not conducive to the local economic development.

Taken together, Scenario 1 has the largest economic objectives under the high water scenario, but also the largest environmental objectives. Scenario 2 is only 0.55×108 yuan less than the economic objective of Scenario 1, but the fertiliser emissions are reduced by 7.87×104kg, and with the gradual reduction of the total amount of fertiliser applied and the improvement of fertiliser utilisation rate, the zero growth of emissions can be achieved; Scenario 3 has a small amount of water scarcity and the smallest economic objective, and therefore is not considered as an alternative scenario. In the long run, Option 2 is preferable in the high water availability scenario. Similarly, in the medium water scenario and the low water scenario, Option 2 is the decision-making option.

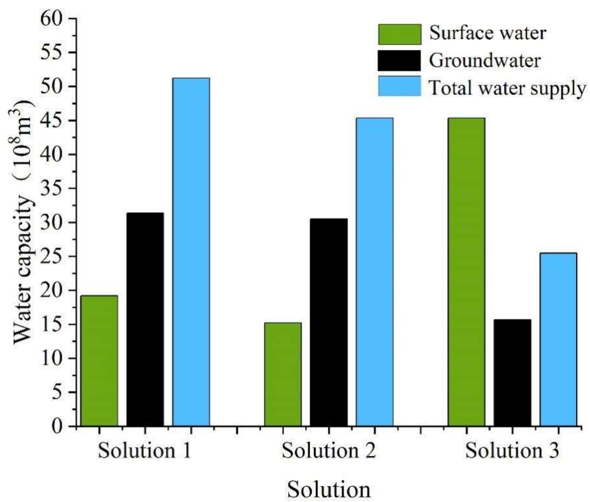
Table 7. Different economic targets, environmental targets and water scarcity

Scene	Scheme	Economic objective (108yuan)	Environmental objective (104kg)	Water shortage (108m^3)
High water scene	Solution 1	87.55	586.11	1.55
	Solution 2	87.00	578.24	1.54
	Solution 3	84.23	569.33	-0.04
Water scene	Solution 1	67.74	789.62	5.22
	Solution 2	62.51	735.24	0.01
	Solution 3	58.24	702.65	-3.98
Low water	Solution 1	50.76	988.51	4.11
	Solution 2	45.28	911.52	-2.99
	Solution 3	38.02	781.22	-7.54

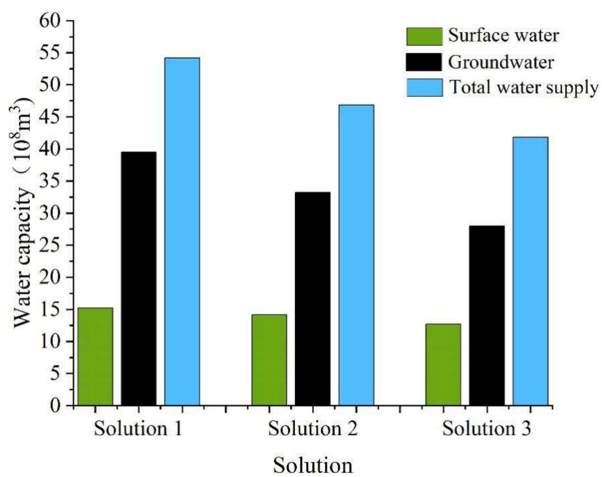
5.3.2. Proportion of water supplied from multiple sources analysed. The total water supply of surface water and groundwater to the three crops in different scenarios under the three water supply scenarios is shown in Fig. 8, with Figs. (a) to (c) showing the high water supply scenario, the medium water supply scenario and the low water supply scenario, respectively. From the calculation results, the overall water supply structure for irrigated agriculture in the A city area is estimated: under the high, medium and low incoming water scenarios in the planning year, the average proportion of groundwater use is 74.2%, 63.4% and 70.1%, respectively, which is a decrease compared with the 69.4%~78.5% in 2010~2016. At this time, the average proportion of surface water use is 25.3%, 36.2% and 29.5%, which is an increase compared to 21.1%~30.2% in 2010~2016. It can be seen that after the multi-objective optimisation of NSGA-III algorithm, the proportion of surface water use in City A is increased, which can alleviate the over-exploitation of groundwater.



(a) High water scene



(b) Water scene



(c) Low water

Fig. 8. Water supply condition of water supply in different water sources

6. Conclusion

In this paper, the NSGA-III algorithm is applied to the multi-objective optimal allocation of agricultural water saving water resources to achieve the global optimal planning by taking the actual water use situation of agricultural irrigation in city A as a case study. The Pareto solution is obtained by studying the water allocation schemes of different water sources for multiple crops, and the results of the study are as follows:

1) The running time of the resource optimisation path for agricultural water-saving irrigation is 0.31 s, which is highly efficient and real-time. The average value of water consumption for five irrigations is 68.48 m^3/(h·m-2), which is water-saving and feasible, and improves the economic and environmental benefits of the agricultural irrigation industry.

2) From the optimised water supply, the groundwater extraction is reduced, and under the medium incoming water scenario, from Scenario 1 to Scenario 3, the water consumption for groundwater irrigation of rice, corn and soybean is reduced. It can be seen that the degree of dependence on groundwater for crop irrigation water use decreases, indicating that improving the use of surface

water and transit water can alleviate the problem of serious over-exploitation of groundwater in the A city area to a certain extent.

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References

[1] Touil, S., Richa, A., Fizir, M., Argente García, J. E., & Skarmeta Gomez, A. F. (2022). A review on smart irrigation management strategies and their effect on water savings and crop yield. Irrigation and Drainage, 71(5), 1396-1416.

[2] Ahmed, Z., Gui, D., Murtaza, G., Yunfei, L., & Ali, S. (2023). An overview of smart irrigation management for improving water productivity under climate change in drylands. Agronomy, 13(8), 2113.

[3] Yang, Y. (2022, May). Research and Implementation of Agricultural Water-Saving Irrigation Prediction Algorithm Based on GA-BP Neural Network. In 2022 13th Asian Control Conference (ASCC) (pp. 2454-2459). IEEE.

[4] Wu, D. (2024). Research and application of neural network - based intelligent water - saving systems. Water and Environment Journal, 38(2), 329-340.

[5] Mestre, G., Matos-Carvalho, J. P., & Tavares, R. M. (2022, July). Irrigation management system using artificial intelligence algorithms. In 2022 International Young Engineers Forum (YEF-ECE) (pp. 69-74). IEEE.

[6] Ray, S., & Majumder, S. (2024). Water management in agriculture: Innovations for efficient irrigation. Modern Agronomy; Sil, P., Chhetri, P., Majumder, S., Santosh, DT, Eds, 169-185.

[7] Akshay, S., & Ramesh, T. K. (2020, July). Efficient machine learning algorithm for smart irrigation. In 2020 International conference on communication and signal processing (ICCSP) (pp. 867-870). IEEE.

[8] Qiong, D., & Hao, P. (2021, March). Design and implementation of irrigation water saving control system based on WSN. In 2021 International Conference on Intelligent Transportation, Big Data & Smart City (ICITBS) (pp. 75-78). IEEE.

[9] Bwambale, E., Abagale, F. K., & Anornu, G. K. (2022). Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: A review. Agricultural Water Management, 260, 107324.

[10] Goap, A., Sharma, D., Shukla, A. K., & Krishna, C. R. (2018). An IoT based smart irrigation management system using Machine learning and open source technologies. Computers and electronics in agriculture, 155, 41-49.

[11] Abioye, A. E., Abidin, M. S. Z., Mahmud, M. S. A., Buyamin, S., Mohammed, O. O., Otuoze, A. O., ... & Mayowa, A. (2023). Model based predictive control strategy for water saving drip irrigation. Smart Agricultural Technology, 4, 100179.

[12] Ma, G. (2022, December). Intelligent Water-saving Control System under Artificial Intelligence Technology. In 2022 IEEE 2nd International Conference on Mobile Networks and Wireless Communications (ICMNWC) (pp. 1-5). IEEE.

[13] Shitu, A., Tadda, M. A., & Danhassan, A. U. (2018). Irrigation water management using smart control systems: a review. Bayero Journal of Engineering and Technology, 13(2), 1-12.

[14] Hassan, E. S., Alharbi, A. A., Oshaba, A. S., & El-Emary, A. (2024). Enhancing Smart Irrigation Efficiency: A

New WSN-Based Localization Method for Water Conservation. Water, 16(5), 672.

[15] Oussama, G., Rami, A., Tarek, F., Alanazi, A. S., & Abid, M. (2022). Fast and intelligent irrigation system based on WSN. Computational Intelligence and Neuroscience, 2022(1), 5086290.

[16] Preite, L., & Vignali, G. (2024). Artificial intelligence to optimize water consumption in agriculture: A predictive algorithm-based irrigation management system. Computers and Electronics in Agriculture, 223, 109126.

[17] Lakhiar, I. A., Yan, H., Zhang, C., Wang, G., He, B., Hao, B., ... & Rakibuzzaman, M. (2024). A Review of Precision Irrigation Water-Saving Technology under Changing Climate for Enhancing Water Use Efficiency, Crop Yield, and Environmental Footprints. Agriculture, 14(7), 1141.

[18] Biswas, S., Sharma, L. K., Ranjan, R., Saha, S., Chakraborty, A., & Banerjee, J. S. (2021). Smart farming and water saving-based intelligent irrigation system implementation using the internet of things. In Recent trends in computational intelligence enabled research (pp. 339-354). Academic Press.

[19] Zhang, X., Zhang, F., Zhang, Y., & Ai, X. (2019). Water saving irrigation decision-making method based on big data fusion. International Journal of Performability Engineering, 15(11), 2916.

[20] Zhang, S., Wang, M., Shi, W., & Zheng, W. (2018). Construction of intelligent water saving irrigation control system based on water balance. IFAC-PapersOnLine, 51(17), 466-471.

[21] Li, J., & He, H. (2019, March). Design of rice intelligent water-saving irrigation system based on agricultural internet of things. In Journal of Physics: Conference Series (Vol. 1176, No. 5, p. 052068). IOP Publishing.

[22] Alves, R. G., Maia, R. F., & Lima, F. (2023). Development of a Digital Twin for smart farming: Irrigation management system for water saving. Journal of Cleaner Production, 388, 135920.

[23] Min Zhou,Dongyuan Sun,Xingfan Wang,Yali Ma,Yanqiang Cui & Lanzhen Wu. (2024). Multi-objective optimal allocation of water resources in Shule River Basin of Northwest China based on climate change scenarios. Agricultural Water Management109015-109015.

[24] K.B.J. Anuradha,José Iria & Chathurika P. Mediwaththe. (2024). Multi-objective planning of community energy storage systems under uncertainty. Electric Power Systems Research110286-.

[25] ZhemingZhang,SikanLi,YuZhang,YifengZhou & JianJi. (2024). Multi - objective reliability - based robust design for a rock tunnel support system using Pareto optimality. International Journal for Numerical and Analytical Methods in Geomechanics(13),3350-3368.

[26] Yifu Sun,Qi Shen,Xiaohua Liu,Lei Zhang,Xin Li,Tao Zhang & Meishun Lin. (2024). Optimal control strategy for building HVAC systems: Satisfying flexible demand response with different value-based selection. Energy & Buildings114823-114823.