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A New Optimization Method for the Layout of Pumping Wells in Oases: Application in the Qira Oasis, Northwest China

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Abstract: Oases are vital habitat areas for both humans and wild plants and animals in desert areas of arid Northwestern China. The efficient management of oasis water resources, especially groundwater resources, is very important for the environmental sustainability and economic development of the region. Pumping wells play a vital role in the oasis groundwater supply; therefore, optimizing the layout of these wells is essential for water resource management. In this study, we present a novel optimization methodology that implements a genetic algorithm and nonlinear programming model for the layout of pumping wells. The methodology was tested and evaluated in the real oasis case study of Qira Oasis located in southern Xinjiang Province, China. The optimization result shows that only 68 pumping wells are required for irrigation purposes of Qira Oasis, and this layout reduces the number of current pumping wells strongly by 59%. Thus, a large number of pumping wells can be closed to save resources. The optimizing method presented in this research is mathematically general and can be applied to other oasis areas without any obstacles. This method can provide decision-makers and managers with key information to ensure the optimal management and safety of valuable groundwater resources in oases.

Keywords: oasis; pumping well; optimization; groundwater

1. Introduction

The management of irrigation water is of critical importance for both agricultural manufacturing and water safety, especially in arid regions with limited water resources [1]. China is the largest consumer of the world's limited water resources, and the proportion of agricultural water in its total water consumption is greater than 70% [2,3]. Groundwater is an essential source for agricultural irrigation, accounting for nearly 10% in China [4,5]. In the vast land of Northwest China, there are numerous large and small oases. The irrigation water of oases mainly derived from surface runoff and groundwater. Compared with other regions in China, agriculture, as the main industry of oases, has a much higher demand for groundwater than that in other regions [6]. Hence, groundwater management, especially oases groundwater management, is an increasingly important issue. To efficiently exploit groundwater, the layout of pumping wells needs to be optimized to achieve the sustainable utilization of groundwater in irrigated areas [7–9]. For the overall planning of irrigation wells, determining suitable locations for wells is very important for helping prevent the construction of redundant wells or identifying existing wells that can be closed. Moreover, it is particularly important to evaluate the spatial distribution of wells in areas where water resources are scarce because the groundwater level in such areas is declining significantly and the ecological environment is deteriorating.

The current optimization research in the context of water supply management focuses on the spatial layout of pumping wells, while considering their number and rates [10,11]. In most of the earlier well layout studies, optimization model was built by using the number of pumping wells as the decision variable and using the economic benefit as the objective function; furthermore, the ecological benefits of irrigation water and groundwater depth are set as constraint conditions for the model [12,13]. Linear programming was first used to solve the optimization problems in previous studies, for example, Gorelick [14] considered many factors, such as the water yield, drawdown, and hydraulic gradient, to establish a model solved by linear and quadratic programming. However, the complexity of groundwater problems leads to complex groundwater management models, hence, nonlinear programing method gained popularity for the problems of the well number optimization [15–17]. Moreover, the results calculated by the traditional solver of nonlinear programming do not satisfy the global optimal conditions, and this approach requires too much effort in the calculation processes [18]. Therefore, the heuristic optimization algorithms, which demonstrated its feasibility and efficiency in the optimization problems, became the preferred methodology. The genetic algorithm is one example of these algorithms [19,20]. Other examples include the simulated annealing algorithm derived from the principle of solid annealing [21], and the particle swarm optimization based on bird predation behavior [22] (Table 1).

Table 1. Chart of different heuristic optimization methods in the field of pumping wells optimization.

Name of Method	Reference	Example of Application
Genetic Algorithm (GA)	Holland, 1975	Huang et al. [23] optimized the total cost and number of pumping wells applying GA method.
Simulated Annealing (SA)	Kirkpatrick et al., 1983	Fragoso et al. [24] regarded the pipe costs, the well installation, and pumping costs as the objective function applying SA method.
Particle Swarm Optimization (PSO)	Kennedy and Eberhart, 1995	Gaur et al. [10] made pumping water amount maximum and the total cost minimum using PSO method.

However, above studies only studied the optimized number of pumping wells, few methods have been developed to study their spatial layout. The choice of well location not only affects the input cost of the well construction, but also influences the economic benefits of agricultural production. For the overall planning of the wells in the irrigation area, especially in areas where water resources are scarce and the groundwater level is seriously degraded, it is necessary to determine the appropriate well locations to adjust the layout of existing wells. In general, researchers have considered a single factor, such as groundwater depth, and have divided the irrigation area into centralized and uniform well areas [25]. To obtain the appropriate layout of pumping wells, researchers have often combined groundwater simulation softwares and optimization algorithms to simulate the pumping-well domain and groundwater-level change [26]. Compared with these methods, a more appropriate evaluation method can be used to comprehensively assess the suitability of various spatial layouts of pumping wells from the perspective of the multiple factors that influence those layouts. The main evaluation methods currently available include the fuzzy comprehensive evaluation method [27], analytic hierarchy process method [28], empirical index method [29], and limit condition method [30], with related research concentrated mainly on soil, cultivated land, forests, city construction, and the benefits of resources on rural residential land [31]. For example, Liu et al. [32] selected land use and groundwater depth as the evaluation indices for spatial layout of pumping wells in irrigation areas, and determined the values of these indices by applying information entropy method. However, most of these methods only focused on the basic mechanisms, there is a lack of research from the perspective of water management in irrigation areas regarding the evaluation of the spatial layout of pumping wells, especially for oases in arid areas.

The southern margin of the Tarim basin is a preferable area for oases in Xinjiang and even in China as a whole [33]. The source of water for agricultural irrigation—the main industry of the oases in this region—originates mainly from the surface runoff caused by the melting of ice and snow in the nearby mountains. However, because of the limited surface water resources, groundwater resources have become increasingly important for the water supply in these oases. In recent years, newly cultivated oasis land has been planted with high-economic-value crops, such as walnut, red date, pomegranate, and other fruits. In the meantime, traditional crops, such as wheat, corn and cotton, are being gradually replaced by fruit cultivation. This change in planting structure has increased the demand for water, which has increased the utilization of groundwater and directly led to the construction of more pumping wells. However, the locations of these wells are randomly distributed. Optimizing the layout and number of wells has not been considered comprehensively from the perspective of the economy and the sustainable use of groundwater. Therefore, a large portion of water resources has been wasted and has caused issues related to groundwater safety and other problems.

Long-term monitoring data are essential for modeling. Because of the availability of long-term monitoring data (groundwater depth) provided by the Cele National Field Scientific Observation and Research Station (hereafter simply referred to as "Cele Station"), Qira Oasis—in the central part of the southern Tarim basin—was selected as an appropriate study area. A nonlinear programming model that considers economic and environmental factors was established first, and then, the optimal number of pumping wells was obtained using a genetic algorithm to solve the nonlinear programming model. After obtaining the number of wells, we introduced information entropy weighting to obtain a pumping-well spatial-layout assessment model. Finally, a "comprehensive evaluation value" of each pumping well was calculated, and wells were ranked in descending order. The optimal distribution of pumping wells was then presented based on the GIS data.

2. Methods

This section describes the methodologies used to optimize the number and layout of the pumping wells, and the global flowsheet is shown in Figure 1. First, we introduce the optimization method of the well number in Section 2.1, and then the spatial layout optimization method of the well is described in Section 2.2.

2.1. The Number of Wells Optimization

2.1.1. Nonlinear Programming Methodology

This study aims to optimize the number of pumping wells and the pumping rate in the study area to achieve the stated economic and ecological goals. The minimization of total cost is taken as the objective function. The number of wells (N) in the study area and the flow rate of the wells (Q) are considered as the decision variables. The flow rate is set to be equal to the annual average value. The supply and demand of water, drawdown, groundwater depth, number of wells, and flow rate are regarded as the constraining conditions. Hence, the model of nonlinear planning for the number of wells and the flow rate can be expressed as follows:

$$\min R = R_m + R_d + R_g + R_e \tag{1}$$

where R_m is the annual management and maintenance cost (RMB) ($R_m = aCN$, in which a is the coefficient of well management and maintenance cost, C is the well construction fee (RMB), and N is the number of wells in the study area); R_d is the depreciation cost designed to recognize quantify the loss of services values that an asset has suffered in any year ($R_d = CN/k$, in which k is the fixed number of years of depreciation); R_g is the groundwater cost per year (RMB) (R_g= $NQTtr_g$, in which Q is the well flow rate (m^3/h), T is the annual average number of operating days, t is the daily average number of operating hours for each well (h/d), and r_g is the price per cubic meter of groundwater (RMB/m^3); and R_e is the energy cost per year (RMB) (R_e= $6.04yQTthr_e$ [34], in which h is the net pumping lift (m), and r_e is the price per kWh of electricity (RMB/(kw·h))).

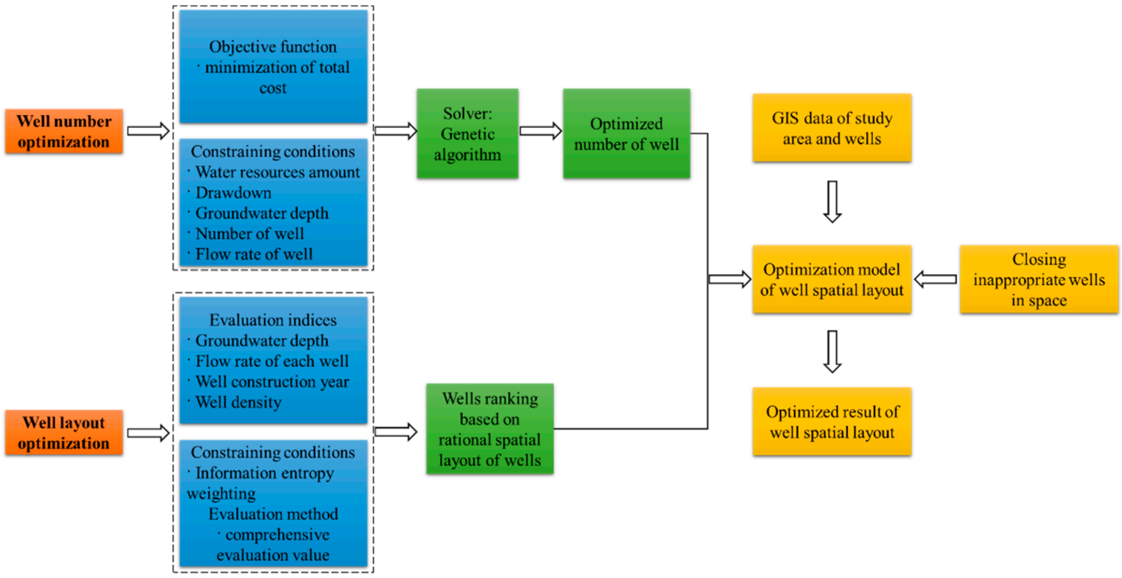

Figure 1. Global flowsheet of well layout optimization.

Subject to:

(1) Constraint of water resources:

$$NQTt \geq P_{ar} - P_{sw} \tag{2}$$

$$NQTt \leq P_{as} \tag{3}$$

where P_{ar} is the irrigation requirement per year in the study area (m^3/a) ($P_{ar} = \sum_{i=1}^{m} I_i A_i$, in which I_i is the irrigation water of crop i throughout the growth period (m^3/ha·a), A_i is the irrigation area of crop i in the study area (ha)), P_{sw} are available surface water resources used for irrigation (m^3/a), which mainly includes river water and rainwater, and P_{as} refers to the water resources for irrigation (m^3/a) ($P_{as} = P_s + P_{rw} - P_{ir} - P_{dr} - P_{er}$, in which P_s is the extractable amount of groundwater (m^3/a), P_{rw} is the return water demand of irrigation and ecology (m^3/a), P_{ir} is the industrial water demand (m^3/a), P_{dr} is the domestic water demand (m^3/a), and P_{er} is the required amount of ecological water, which is the total amount of water to maintain the ecological environment (m^3/a)).

(2) Constraint of drawdown:

$$s_0 \leq s_{\max} \tag{4}$$

where S_0 is the drawdown (m), and $S_{\max}$ is the allowed maximum drawdown (m).

(3) Constraint of groundwater depth:

$$h' + \Delta h \geq h_{\min} \tag{5}$$

$$h' + \Delta h \leq h_{\max} \tag{6}$$

where Δh refers to the dynamic change of the groundwater depth from the start moment to the end moment (m); h' refers to the groundwater depth at the initial time (m); $h_{\min}$ refers to the allowed minimum groundwater depth (m); and $h_{\max}$ refers to the allowed maximum groundwater depth (m).

(4) Constraint of the number of wells:

$$0 < N < N_e \tag{7}$$

where N_e is the number of existing wells in the study area.

(5) Constraint of the well flow rate:

$$0 < Q < Q_{\max} \tag{8}$$

where $Q_{\max}$ is the maximum value of the flow rate of individual wells.

2.1.2. Nonlinear Programming Application

In this study, the pumping-well number optimization model of all equations are represented as follows:

Minimum total consumption:

$$\min R = R_m + R_d + R_g + R_e \tag{9}$$

Subject to the following constraints:

(1) Water resources:

$$NQTt \geq P_{ar} - P_{sw} \tag{10}$$

$$NQTt \leq P_{as} \tag{11}$$

(2) Drawdown:

In Northwest China, one of the significant irrigation water sources is the groundwater in the phreatic water zone. The stability of groundwater resources in a short period can be determined based on the balance between groundwater exploitation and recharge.

After a long period of constant pumping rate, a relatively stable con of depression is formed near the well. Based on the Dupuit assumption, which is commonly used in the modeling of groundwater, we assumed that the phreatic water to the well is approximately horizontal and the discharge of groundwater in different cross-sectional area is equal to the flow rate of the well. The equations for the relationship between the flow-rate and drawdown of pumping-wells can be written as follows [5,35–38], and the detailed derivation process of Equation (12) is demonstrated in the Appendix A:

$$Q' = 1.364K(2H - s_0)s_0/(\lg R/r_0) \tag{12}$$

$$Q = Q'(1 - \alpha) \tag{13}$$

Based on Equations (12) and (13), the relationship between s_0 and Q can be denoted as:

$$s_0 = H - \sqrt{H^2 - Q\lg(R/r_0)/(1.364K(1-\alpha))} \tag{14}$$

where Q' is the well flow-rate without interference from other wells (m^3/h); K is the permeability coefficient (m/h); H is the distance from the bottom elevation of the unconfined aquifer to the phreatic free surface (m); R is the radius of influence of the pumping well (m); r_0 is the radius of the pumping well (m); and α is the abatement coefficient of total discharge.

Thus, the drawdown in this study can be demonstrated as:

$$H - \sqrt{H^2 - Q\lg(R/r_0)/(1.364K(1-\alpha))} \leq s_{\max} \tag{15}$$

(3) Groundwater depth:

Because of the overexploitation of groundwater in the most northwestern areas of China, the constraints are too strict for the groundwater depth. In future planning, the quantity of groundwater exploitation should be lower than the value of groundwater recharge to achieve a gradual rise in the groundwater level. Thus, the maximum value of the difference in groundwater depth between the end moment and start moment must be smaller than zero for several decades to meet the constraint. Thus, Equations (5) and (6) can be changed to the constraint

$$\Delta h \leq 0 \tag{16}$$

The balance of groundwater can be presented as

$$P_d - P_r = \mu \Delta h Fa \tag{17}$$

where P_d is the groundwater discharge (m^3) ($P_d = P_{ld} + P_{ed} + NQTt + P_{ir} + P_{dr} + P_{er}$, in which P_{ld} is the lateral discharge (m^3) and P_{ed} is the discharge from evaporation (m^3)); and P_r is the groundwater recharge (m^3) ($P_r = P_{lr} + P_{pr} + P_{rw}$, in which P_{lr} is the lateral recharge (m^3) and P_{pr} is the recharge due to precipitation (m^3)); μ is the extent of groundwater recharge; and Fa is the area of the irrigated district (m^2).

The above equation can be converted to

$$\Delta h = (P_d - P_r)/\mu Fa \tag{18}$$

Thus, the constraining condition of groundwater depth can be expressed as:

$$(P_d - P_r)/\mu Fa \leq 0 \tag{19}$$

(4) Number of wells:

$$0 < N < N_e \tag{20}$$

(5) Well flow-rate:

$$0 < Q < Q_{\max} \tag{21}$$

2.1.3. Genetic Algorithm

This is a nonlinear programming problem with multivariate and multi-constraint conditions, and cannot be solved using the standard mathematical methods. To solve such problems, it can be converted into a linear problem, or dynamic programming, or the application of adaptive search algorithm, such as genetic algorithm, etc. Due to the robustness of genetic algorithm and the speed of computer operations, genetic algorithms are often the preferred algorithms for nonlinear optimization problems. The genetic algorithms take the objective function as the fitness function to carry out the optimization calculation until it satisfies the convergence condition or reaches evolutionary generation.

The conceptual framework of a genetic algorithm was originally developed by Holland [20]. It is a highly parallel, stochastic and adaptive search method that implements natural selection and the natural genetic mechanism of biology for reference. Different from traditional optimization algorithms, which propagate a single solution to the optimum one, the genetic algorithms search for optimum solutions by evaluating and successively improving a set of problem solutions, also denoted as generation. Each individual in the generation of solution is independently evaluated, which allows for the parallelization process.

Figure 2 displays the flow diagram of a genetic algorithm. The objective function can be $f(y)$; n is the number of decision variables; y_k is one of the decision variables, which contains a vector of y; and the equation of $y = [y_1, y_2, \ldots, y_k, \ldots, y_n]^T$ is generated, in which T represents the transpose operator; the number of constraint conditions about inequality and equality are d_1 and d_2, respectively; $g_i(y)$ and $h_j(y)$ are the inequality and equality constraint conditions ($i = 1, 2, \ldots, d_1$; $j = 1, 2, \ldots, d_2$), respectively; and $y_{k,l}$ and $y_{k,u}$ are the lower and upper bounds of y_k ($k = 1, 2, \ldots, n$), respectively. In this study, $f(y)$ represents minimum total consumption, y_1, y_2 respectively represent the number of wells (N) in the study area and the flow rate of the wells (Q); there is no equality constraints, so $g_i(y)$ respectively represent the constraints water resources, drawdown and groundwater depth for $i = 1, 2, 3$; corresponding, $y_{k,l}$ and $y_{k,u}$ are the lower and upper bounds of N,Q ($k = 1, 2$), respectively. After defining the optimization model, the operation steps of the algorithm are as follows:

(1) Encoding the target problem

The internal expression (genotype) of chromosome is a genes combination, which determines the external expression of individuals. Binary coding, as one of the encoding works to map from phenotype to genotype, is implemented. Based on the upper bounds (200 m^3/h) and lower bounds (0 m^3/h) of the independent variable of the wells flow rate, we determined the code length of the binary code ($L = \log_2((200 - 0)/10^{-2}) \approx 11$, the accuracy level is 10^{-2}). Then, a set of binary codes were randomly generated, such as $b_0, b_1, \ldots, b_{10}$, which were converted to decimal numbers ($(b_0 b_1 \ldots b_{10})_2 = (\sum_{i=0}^{10} b_i \cdot 2^i)_{10} = Q_t$), and the numbers were mapped to real numbers in the interval ($Q = Q_t \cdot \frac{200-0}{2^{11}-1}$).

(2) Population initialization

To ensure the feasibility and diversity of the individuals in the first generation, the initial individuals are randomly produced according to the constraint conditions.

(3) Determination of fitness

The fitness function is transformed by the object function, and the individuals are evaluated in terms of its fitness value. In the search process, on the basis of the fitness function, the genetic algorithm utilizes the fitness value of each individual in the generation; however, it does not use external information.

(4) Genetic manipulation

The evolution of the population depends on the genetic operators acting on the current population and producing a new generation of the population. The common genetic operators encompass selection, crossover and mutation and play a decisive role in the algorithmic performance. Implicit parallelism and effective utilization of global information are two salient features of genetic algorithms.

(5) Optimal saving strategy

The idea behind an optimal preservation strategy is to retain the good traits of individuals in the parent generation in those of the offspring. In other words, the individual with the greatest fitness in the current population is used to replace the individual with the least fitness after crossover, mutation and other genetic manipulations in the population, and it does not carry through the crossover and mutation processes.

Through the above schemes, the optimal solution set can be obtained.

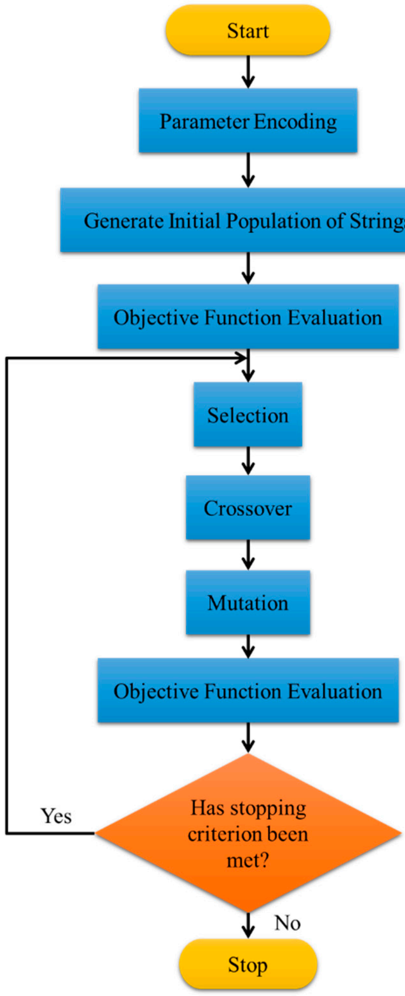

Figure 2. Genetic algorithm flowchart [39].

2.2. Well Layout Optimization

The well spatial layout can be optimized using the information entropy method and comprehensive evaluation index method.

Based on the information entropy weighting method, the spatial-layout evaluation model of pumping wells is established [40]. Groundwater resources must be conserved in woodland and grassland, and thus, these areas are unsuitable for groundwater exploitation. Likewise, it is improper to drill wells for irrigation on unused land or in residential areas. On cultivated land, some factors are selected for use as an evaluation index, including the type of land use, the depth of groundwater, the flow rate of each well, the density of a well (reflective of the productivity of the land) and the exploitation condition of groundwater.

Assuming W_{ij} is the assessment matrix W of the assessment index j with different i of the pumping well spatial-layout, where $i = 1, 2, \ldots, 166$ represents the number of each pumping well, $j = 1, 2, 3, 4$, respectively represent types of land use, groundwater depth, well density, and flow rate per well. The weights of the evaluation indices can be calculated by information entropy weighting. We can generalize the procedure as follows:

(1) Normalization of the assessment matrix to resolve the multidimensional indices and multiple data units for different indices:

$$\begin{cases} W'_{ij} = \dfrac{W_{ij} - \min\limits_{1 \le i \le 166} W_{ij}}{\max\limits_{1 \le i \le 166} W_{ij} - \min\limits_{1 \le i \le 166} W_{ij}} & \text{Benefit type index} \\ W'_{ij} = \dfrac{\max\limits_{1 \le i \le 166} W_{ij} - W_{ij}}{\max\limits_{1 \le i \le 166} W_{ij} - \min\limits_{1 \le i \le 166} W_{ij}} & \text{Cost type index} \end{cases} \tag{22}$$

where W'_{ij} is the normalized value of the original evaluation matrix, $0 \le W'_{ij} \le 1$; and in the evaluation index j, $\min\limits_{1 \le i \le 166} W_{ij}$ is the minimum value and $\max\limits_{1 \le i \le 166} W_{ij}$ is the maximum value. For $i = 1, 2, \ldots, 166$, y_{i1} represents the value of the land type indicator for each well, as measured by unit area demand for groundwater resources shown in Table 6, which is a benefit type index. The maximum and minimum values of y_{i1} are 1504.71 and 394.46, respectively; y_{i2} represents the value of the groundwater depth indicator for each well, as measured by the mean of the groundwater depth interval in the distribution area of the well shown in Figure 4, which is a cost type index. For example, if the well is distributed in an area where the groundwater depth is in the interval [0, 10], then $y_{i2} = 5$. The maximum and minimum values of y_{i2} are 55 and 10, respectively; y_{i3} represents the value of the well density indicator for each well, as measured by the theoretical well distance, which is a benefit type index. The maximum and minimum values of y_{i3} are 589.38 and 294.69, respectively; y_{i4} represents the value of the well density indicator for each well, which is a cost type index. The maximum and minimum values of y_{i4} are 2000 and 30, respectively. A larger "Benefit type index" value indicates more expensive benefits, while the "Cost type index" indicates the opposite.

(2) Calculation of the entropy value v_j of index j:

$$v_j = -k \sum_{i=1}^{166} q_{ij} \ln q_{ij} \tag{23}$$

where q_{ij} is the proportion of the evaluation index j within different values of i, $q_{ij} > 0$ ($q_{ij} = (W'_{ij} + 1) / \sum\limits_{i=1}^{m} (W'_{ij} + 1)$), $k = 1/\ln 166$, and $0 \le v_j \le 1$ [41].

(3) Calculation of the deviation coefficient c_j of index j:

$$c_j = 1 - v_j \tag{24}$$

(4) Calculation of the weight ω_j of index j:

$$\omega_j = c_j / \sum_{j=1}^{4} c_j \tag{25}$$

Based on Equations (22)–(25), the index weights (types of land use, groundwater depth, well density, and flow rate per well) of the spatially distributed evaluation model of the pumping wells in the study area can be estimated (Table 2).

Table 2. Evaluation model of wells spatial layout.

Target	Evaluation Indexes
Evaluation model of wells spatial layout	1. Type of land use 2. Depth of groundwater 3. Flow rate of each well 4. Density of a well

Together with the weights of the assessment index, the "comprehensive evaluation index" e_i [32,40,42], regarding the rationality of the pumping well spatial distribution, will be estimated via

$$e_i = \sum_{j=1}^{4} \omega_j q_{ij} \tag{26}$$

Then, the rationality of the spatial distribution is sorted based on the descending order of e_i. Ultimately, the optimal number of wells is combined with the assessment results of the pumping well spatial distribution to close the lower e_i of the wells, and according to the GIS data, the optimized distribution of wells can be obtained.

3. Case Study

3.1. Study Area

This research is based on the data collected at the Qira Oasis, Hotan city, southern Xinjiang Province, China (Figure 3). Irrigation plays a crucial role in local agriculture, as the area has high evaporation and low precipitation in the area [33]. In the past few years, the imbalance between the supply and demand of water resources in this area has become increasingly prominent due to rapid population and economic growth. This shortage of the water supply has resulted in a serious overexploitation of groundwater by local residents for their agricultural water usage, which has led to a groundwater recession and a worsening ecological environment. Optimizing the pumping well layout is necessary to protect the groundwater supply and environment in the Qira Oasis.

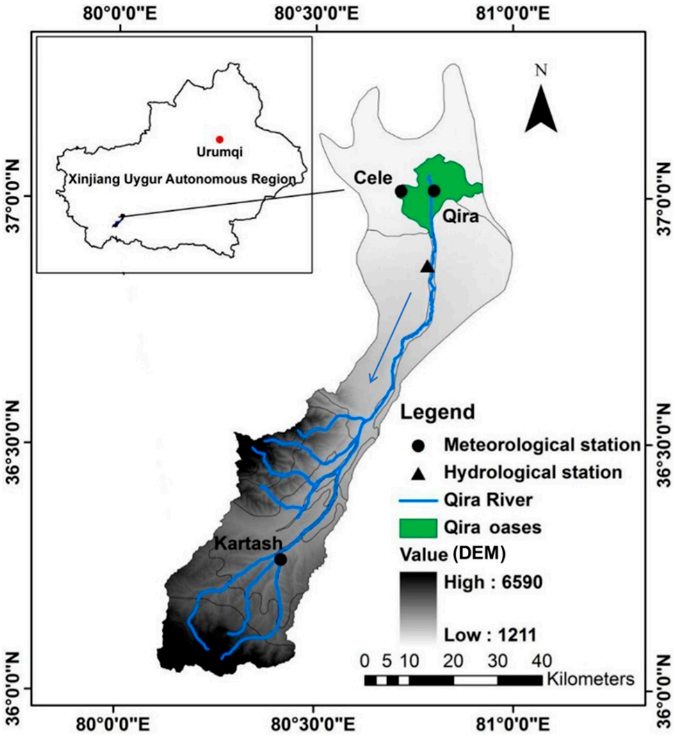

Figure 3. Location of Qira Oasis.

The climate of Qira Oasis is temperate and arid, with an average annual precipitation of 35.1 mm and an average annual evaporation of 2595.3 mm [43]. The Qira River, which originates from the Kunlun Mountains, is the only exogenous supply of water to the Qira Oasis, and the river has an annual mean runoff of 1.27×10^8 m^3. The main crops grown in the Qira Oasis are wheat and maize, but there are also many plantations of fruit crops, such as pomegranate, red date and walnut. The surface runoff of the Qira River is the main irrigation source for the agriculture of the oasis; however, since the water demands have increased due to agricultural expansion, the groundwater has become an important irrigation supplement in the oasis. The Qira Oasis covers an area of 274.63 km^2, within which there are 166 wells (Figure 4) with an average flow rate of 135 m^3/h.

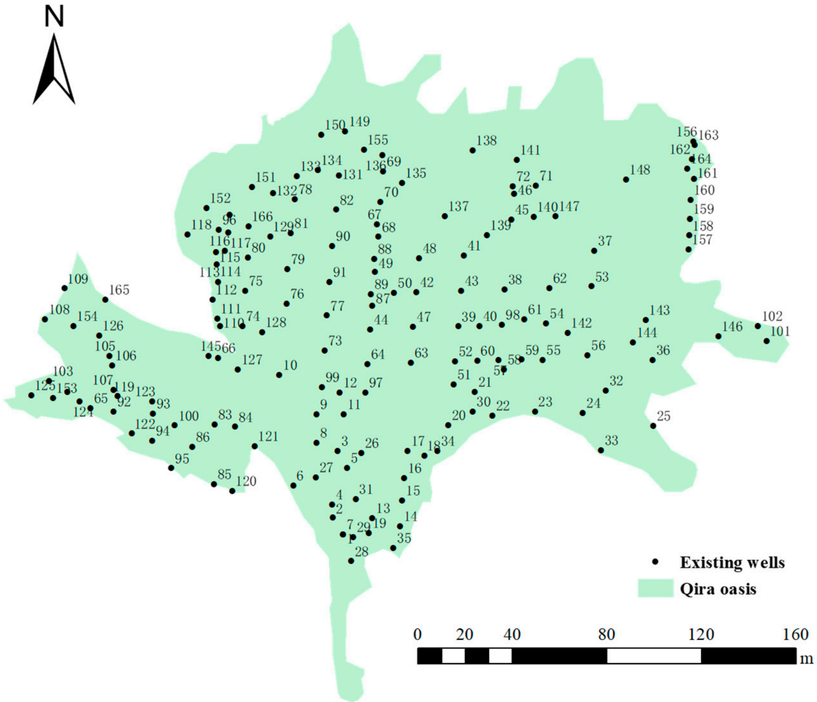

Figure 4. Distribution of existing wells in Qira Oasis.

3.2. Data Description

The data required for this research were obtained from the Xinjiang Statistical Yearbook, Qira National Field Scientific Observation and Research Station, Hotan Hydrology Bureau, and Qira Hydrological Station (initial data not displayed due to their size). Table 3 shows the irrigated area and net irrigation water demand of the main crops.

Table 3. The amount of irrigated area and the required quantity of net irrigation water in the entire crop growing season in the Qira Oasis Irrigated District.

Crop	Irrigated Area (ha)	Net Irrigation Water Demand (m^3/ha·a)	Water Demand (m^3/a)
Wheat	1336	5587	7.46×10^6
Maize	1345	4680	6.29×10^6
Pomegranate	669.5	13,550	9.07×10^6
Red date	1987	10,650	2.12×10^7
Walnut	1371	10,600	1.45×10^7
Sum of values	6708.5	45,067	5.85×10^7

Table 4 displays the amount of water, including the supply and demand of all water resources and the specific quantities of groundwater resources' recharge and discharge. The data in Table 4 was estimated according to crop water demand and crop planting ratio, the relevant industrial data on the Internet, and the water demand of humans and animals. The hydrogeological parameters are shown in Table 5, and these parameters were obtained from the reference of Liu et al. (2015). These data are regionally independent.

Table 4. Values of the water resources.

Parameter	Symbol	Unit	Value
Extractable amount of groundwater	P_s		1500.4×10^4
Return water of irrigation and ecology	P_{rw}		213.5×10^4
Industrial water demand	P_{ir}		104.3×10^4
Domestic water demand	P_{dr}		172.84×10^4
Required amount of ecological water	P_{er}	m^3/a	438.6×10^4
Difference of lateral discharge and recharge	P_{lr}-P_{ld}		1500.4×10^4
Discharge from evaporation	P_{ed}		0
Recharge due to precipitation	P_{pr}		0
Surface water resources for irrigation	P_{sw}		5815.5×10^4

Note: The groundwater depth in the irrigation district is usually below 5 m. Compared with other recharge and discharge processes, infiltration of precipitation and groundwater evaporation will be ignored.

Table 5. Observed hydrogeological parametric values.

Parameter	Symbol	Unit	Value
The well management and maintenance cost coefficient	a	RMB	23.72×10^4
The number of wells	n		20
The annual average operating days	T	d	70
The daily average operating hours	t	h/d	12
Groundwater price per cubic meter	r_g	RMB/m^3	0.20
Net pumping lift	h	m	22.5
Cost of electricity per KW·h	r_e	RMB/(KW·h)	0.15
Allowed maximum drawdown	S_{max}	m	5.00
Permeability coefficient	K	m/h	0.72
Distance from the bottom elevation of the unconfined aquifer to the phreatic free surface	H	m	55.00
Radius of influence of the pumping well	R	m	400
Radius of the pumping well	r_0	m	0.175
abatement coefficient of total discharge	α		0.03
Maximum value of the well flow rate	Q_{max}	m^3/h	200
Existing number of wells	Ne		166
Degree of groundwater recharge	μ		0.25

4. Results

4.1. Well-Number Optimization

In the Qira Oasis, 166 pumping wells operate normally. With economic growth, the maintenance cost of pumping wells is increasing. To solve these problems, we use Equations (9)–(11), (15) and (19)–(21) as the final computational model, select the data in Tables 3–5 as input values, and then perform the calculations using the genetic algorithm. Due to the randomness of the genetic algorithm, it is necessary to run the model multiple times (in this study, 100 times) and take the average value. The optimal well flow rate is 146 m^3/h. Although this value is higher than the original flow rate (135 m^3/h), there is no threat to groundwater safety. The most appropriate number of wells is calculated to be 68, representing a reduction of 59.04%, which is significantly less than the number of existing wells (166). The cost after optimization is 1.77×10^8 RMB, which is a reduction of 54.38% compared with the original cost (3.88×10^8 RMB). The optimization process results can lead to a large decrease in the economic cost.

4.2. Well Spatial-Layout Optimization

The demand for groundwater resources in the unit area changes with different types of land usages, and decision-makers can make different plans for different wells according to variant groundwater demands in different regions. The demand for groundwater resources in town and village areas is equal to the total water requirement for domestic water and industrial water. In woodlands, such as those established to farm red date, walnut, pomegranate and other fruits, as well as the surrounding ecological woodland, the demand for groundwater resources is the water demand of the fruit trees and the surrounding ecological woodland minus the amount of surface water resources. On the dryland plain areas in the study region, land use is mainly a variety of crops and the surrounding protective forests, and the demand for groundwater resources here is equal to the amount of water needed for crops and the surrounding forests minus the amount of surface water resources. After dividing the demand for groundwater resources by the corresponding area for each type of land, the unit area demand for groundwater resources (Table 6) in the town and village areas, woodland and dryland plains is 394.46, 1504.71, and 654.22 mm, respectively.

Table 6. The different types of land area and unit area demand for groundwater resources in the Qira Oasis.

Type of Land Use	Area (ha)	Unit Area Demand for Groundwater Resources (mm)
Towns and villages	176.5	394.46
Woodland	4027.5	1504.71
Dryland plain	2681.0	654.22

Groundwater depth is an important factor used to measure the carrying capacity of groundwater resources in an irrigated area. The decline in the groundwater level caused by extraction in the research area has caused serious ecological and environmental problems, such as desertification and shrub/forest loss. Therefore, when selecting locations for pumping wells, we should choose an area where the groundwater depth is very shallow and easily extracted, and the area should be far from areas where groundwater is deep and water resources are exploited excessively.

Due to the kriging interpolation method is more suitable for geoscience, we select the ordinary kriging method to interpolate the groundwater depth in the Qira Oasis. As shown in Figure 5, the groundwater depth of the Qira Oasis shows an increasing trend from the North to the South.

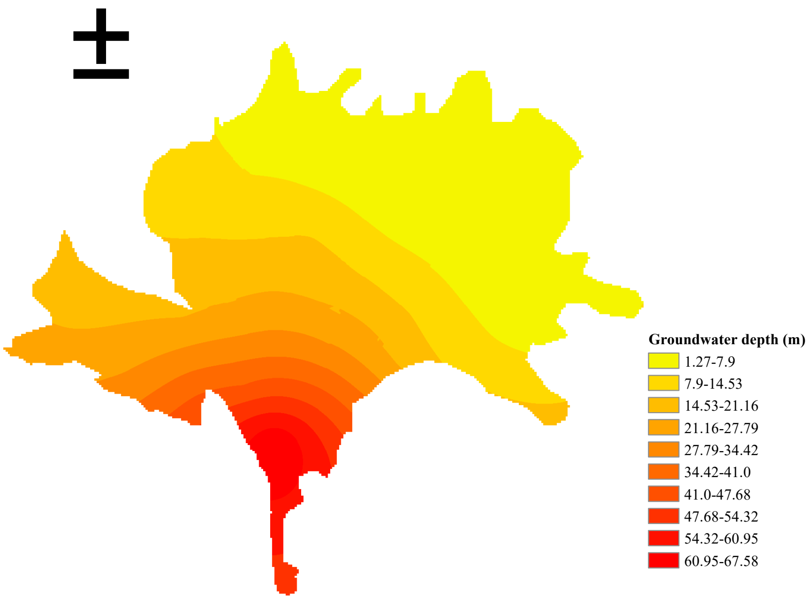

Figure 5. Groundwater depth in the Qira Oasis.

Due to a lack of numerical data on well density, the well density is determined based on a comparison of the length of theoretical and practical well distance. Thus, the calculation of the number of wells by identifying the theoretical distance within alternative wells can be applied to identify which index best assesses the well density. If the number of wells is large, the wells in the study area are densely distributed. According to the distribution shape of the well, it can be divided into plum-shaped layout and square layout. For example, the wells numbered 8, 9, 11, and 12 are a plum-shaped layout, the wells numbered 41, 42, 43, and 48 are a square layout as shown in Figure 4. On the basis of the GB/T 50625-2010 [34], the theoretical well distance can be framed as follows:

$$L = \begin{cases} 99.9\sqrt{fa} & \text{square layout} \\ 107.7\sqrt{fa} & \text{plum-shaped layout} \end{cases} \tag{27}$$

The theoretical irrigation area of each well is expressed as

$$fa = \frac{QTt}{b} \tag{28}$$

where b is the net irrigation quota (m^3/ha).

The weights of the evaluation indices, which have an effect on the pumping well spatial layout in the Qira Oasis Irrigation District, can be calculated using the entropy weighting information. The well density had the highest weight (0.5854), while the weights of the type of land-use and flow rate were relatively lower, with values of 0.1086 and 0.0746, respectively. The 12 wells distributed in the shelter forest belt are retained. In the Qira Oasis, the values of e_i ranged from 0.000252 to 0.196688. The alternative wells with sequence numbers prior to 57 are retained combined with the optimal number of wells.

Thus, as shown in Figure 6, wells located in areas where groundwater is overexploited will be closed due to a variety of problems, such as low flow rate or inefficient operation. The optimal distributed pattern of wells is relatively concentrated; few of the wells are located in the area of the groundwater depth lower than 14.53 m. Additionally, the spatial distribution of wells is more conducive to the sustainable utilization of groundwater than was the original distribution.

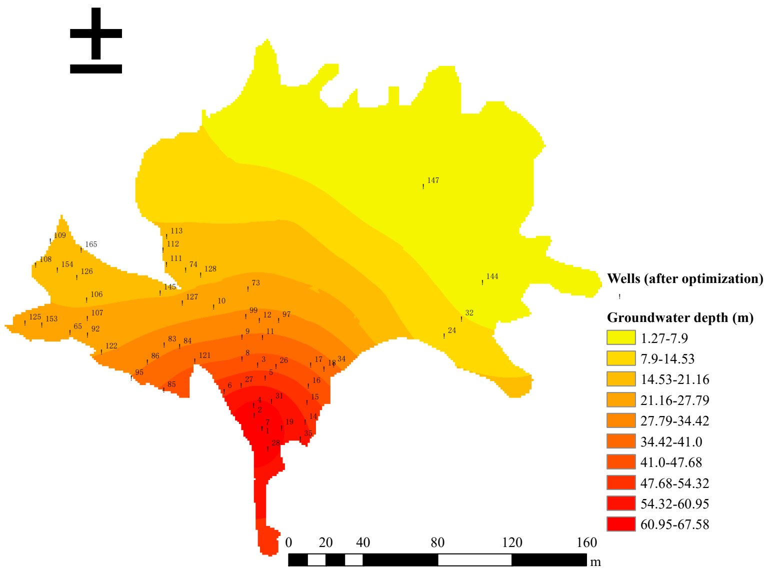

Figure 6. Distribution of wells after optimization.

5. Discussion and Conclusions

In this study, nonlinear programming model solved by genetic algorithm and comprehensive index methods, combined with information entropy weighting, are utilized to optimize the wells spatial layout in the Qira oasis, northwest China. The application of this new optimization method in the Qira Oasis demonstrates the significant reduction in the number of pumping wells and the optimization of the spatial layout considering the water demands and pumping rates.

In general, our study provides an approach to optimize the spatial layout of pumping wells. This method is mathematically general and can be further applied to other oasis regions where groundwater is overexploited and the well density is high. Through this method, the number of excess wells can be greatly reduced, and a substantial reduction in the expense of well construction and operational management can be achieved. Furthermore, this study can provide instruction for residents living in oases to utilize groundwater more rationally, which is of great significance to the sustainable utilization of groundwater and helps improve the ecological environments of these areas.

There are some shortcomings of this work. One weakness is that a simplification (Dupuit assumption) and analytical solution were used in this research for the groundwater flow calculation. A more accurate simulation of groundwater flow can be achieved by establishing a numerical groundwater model, such as MODFLOW, GMS. However, the numerical modeling of groundwater movement in this type of large-scale oasis requires excessive computational power and the accurate simulation of groundwater flow is not the focus of this research. More methods, such as particle swarm optimization, simulated annealing algorithm, can also be applied to solve the nonlinear programming model to ensure the optimization results. Additionally, the comprehensive index method is a traditional ranking approach, thus, new and more advanced methods can be adopted to solve our problem, for example, neural network method. However, the comparison of different methods and algorithms is not the focus of this research. In the future work, we will implement multiple optimization algorithms and quantify the uncertainties further to search for the best optimization model and algorithm for the well layout problems.

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Appendix A

The Calculation of Well Flow Rate Based on Dupuit Assumption

The wells in this study are located in unconfined aquifer area. After a long period of constant pumping rate, a relatively stable drawdown funnel is formed near the well. For practical purpose, the Dupuit Assumption has been applied into the phreatic water wells [35–38].

The assumptions are presented as follows:

The groundwater movement can be considered stable in a short period due to the balance of groundwater exploitation and recharge.

(1) The aquifer is homogeneous and isotropic.
(2) The groundwater obeys Darcy Law.
(3) The phreatic water to wells can be considered as horizontal.
(4) The flow rate of the wells equals to the discharge of groundwater.

According to the assumptions, the steady groundwater governing equation can be denoted by the following partial differential equations:

$$\frac{d}{dr}\left(r\frac{dh^2}{dr}\right) = 0 \tag{A1}$$

With boundary conditions

$$\begin{aligned} h|_{r=R} &= H \\ h|_{r=r_w} &= H_w \end{aligned} \tag{A2}$$

The Equation (A1) can be integrated as:

$$r\frac{d\left(h^2\right)}{dr} = C \tag{A3}$$

Given the Darcy Law,

$$Q' = KAJ = K \cdot 2\pi r \cdot h \cdot \frac{dh}{dr} = \pi r K \frac{d\left(h^2\right)}{dr} \tag{A4}$$

Based on Equations (A3) and (A4),

$$r\frac{d\left(h^2\right)}{dr} = \frac{Q'}{\pi K} \tag{A5}$$

Based on the boundary conditions (Equation (A2)), Equation (A5) can be integrated as,

$$\begin{aligned} \int_{H_w}^{H} d\left(h^2\right) &= \tfrac{Q'}{\pi K} \int_{r_w}^{R} \tfrac{dr}{r} \\ H^2 - H_w{}^2 &= \tfrac{Q'}{\pi K} \ln \tfrac{R}{r_w} \end{aligned} \tag{A6}$$

Because of $s_w = H - H_w$, Equation (A6) can be represented as,

$$\begin{aligned} (2H - s_w)s_w &= \tfrac{Q'}{\pi K} \ln \tfrac{R}{r_w} \\ Q' &= 1.364K \tfrac{(2H - s_w)s_w}{\lg \frac{R}{r_w}} \end{aligned} \tag{A7}$$

which is Equation (12) in the text.

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