Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (43) No. (4) October . 2021

Optimization for the Conjunctive Use of Surface Water and Groundwater Using Genetic Algorithms in Quesna Irrigation District, Egypt

Kariman Kamal[a,*], Mohamed F. Sobeih[b], Talaat El-Gamal[a], Fahmy Salah Abdelhaleem[c]

[a]Water Management Research Institute (WMRI), National Water Research Centre, Delta Barrages, Cairo, Egypt
[b]Civil Engineering Department, Faculty of Engineering, Menoufia University, Menoufia, Egypt
[c]Civil Engineering Department, Benha Faculty of Engineering, Benha University, Benha, Egypt.

ملخص البحث :

يعتبر الاستخدام المشترك للمياه السطحية والمياه الجوفية مصدر اهتمام عالمي بسبب محدودية الموارد المائية والزيادة المستمرة في الطلب على المياه بسبب النمو السكاني .عرفت هذه الدراسة الاستخدام المشترك الأمثل للمياه السطحية والمياه الجوفية لهندسة الري بقويسنا (المديرية العامة للموارد المائية والري بالمنوفية) عن طريق استخدام نموذج تحسين. قلل نموذج التحسين من إجمالي إمدادات المياه من المياه السطحية مع الحفاظ على كفاية إمدادات المياه ، والسحب المسموح به من المياه الجوفية الضحلة ، والقدرة التصميمية للترع والأحباس ، وإجمالي تدفق المياه السطحية عند مدخل الهندسة. تم حل نموذج التحسين باستخدام تقنية الخوارزميات الجينية .أظهرت النتائج أن تقنية GA هي أداة فعالة لحل نماذج التحسين في مجال إدارة المياه.

Abstract:

The conjunctive use of surface water and groundwater became a worldwide concern due to limited water resources and the continuous increase in water demands due to the population growth. This study defined the optimal conjunctive use of surface water and groundwater for Quesna irrigation district (El-Monofiya irrigation directorate) using an optimization model. The optimization model minimized total water supply from surface water while maintaining water supply sufficiency, the allowable withdrawal from shallow groundwater, the design capacity of canals and reaches and the available surface water flow at the head of the district. The optimization model was solved using Genetic Algorithms (GA) technique. The results showed that the GA technique is an efficient tool for solving optimization models in water management field.

Keywords: Conjunctive Use; Optimization model; Genetic Algorithm; Surface Water; Groundwater

1. Introduction

Water is one of the most important inputs for the sustainable development of economic; the importance of water increases as a result of the increase of water demand, El Bedawy (2014). Burt (1964) introduced conjunctive water use concept and he suggested considering surface water and groundwater as two elements of an integrated water system instead of being separated elements. Singh (2014) reviewed applications combination of simulation and optimization models for the conjunctive use planning and management of surface water and groundwater resources for sustainable irrigated agriculture. Soleimani et al. (2021) reviewed (1) hydrologic models applied for the simulation of GW-SW interaction in the water resources systems, (2) conventional optimization methods, and (3) published works on optimized conjunctive GW-SW use by coupling simulation and optimization methods. Dalla Porata et al. (2019) assessed allocation of economic water and the potential of SW-GW conjunctive use operations using a hydro-economic model for the scarcity and scarcity cost evaluation at an irrigated agricultural region in Southern Brazil. Song et al. (2020) proposed a multi-objective optimization framework for the integrated management of surface water and groundwater and demonstrated its validation through a spatial optimization of water use practices for agricultural irrigation in YB basin in northwest China. K. Jha et al. (2020) combined a groundwater-flow simulation model and two optimization models to develop optimal reconnaissance-level water management strategies. The optimization models were applied to part of the Mahanadi River basin groundwater system in Odisha State, India.

Over the last decades, genetic algorithms (GAs) have been extensively used as search and optimization tools in various problem domains. The concept of a genetic algorithm was first introduced by John Holland of the University of Michigan, Goldberg (1989). GA's population approach causes that GA has been extended to solve search and optimization problems efficiently, including multimodal, multiobjective and scheduling problems, as well as fuzzy-GA and neuro-GA implementations, Deb (1999).

GA is one of a class of algorithms that searches a solution space for the problem optimal solution, through creating a “population” and lets them “evolve” over multiple generations to find better solutions. The fitness of an individual is a measure of how “good” the solution represented by the individual is, Thede (2004).

Optimization models are normally used to enhance the conjunctive use of surface water and groundwater. Genetic Algorithms (GA) are efficient tools to solve such optimization problems.

2. Model Formulation

The object function of the conjunctive use model is to minimize total water supply from surface water while maintaining water supply sufficiency, the allowed withdrawal from shallow groundwater, the design capacity of canals and reaches and available surface water at the head of the district.

The study's Optimization model is as follows:

$$z = \sum_{I \in NI} Q_I - \sum_{O = NO} Q_O \qquad (1)$$

Subject to:

$$WS_{CH} \geq WR_{CH} \qquad \forall_{CH} \qquad (2)$$

$$AWA_{CH} \leq PWA_{CH} \qquad \forall_{CH} \qquad (3)$$

$$QC \leq QDC \qquad \forall_{C} \qquad (4)$$

$$\sum_{CH \in TCH} Qs_{CH} \leq TIF - TOF \qquad (5)$$

Where

Q_I = the inflow from any point to the irrigation district

Q_O = the outflow to any point out of the irrigation district

NI = the total number of inflow points,

NO = the total number of outflow points

WS_{CH} = the water supply to any catchment

WR_{CH} = the water requirements at any catchment,

AWA_{CH} = the actual groundwater abstracted at any catchment

PWA_{CH} = the permissible abstraction from shallow groundwater at any catchment

Q_C = the flow at any reach of the irrigation system,

QD_C = the design flow of any reach of the irrigation system,

QS_{CH} = the surface water supply to any catchment,

TIF = the total inflow to the irrigation district, and

TOF = the total outflow from the irrigation district.

The model has two decision variables: the flow at different reaches of the district and the average operation hours of the groundwater wells at different catchments.

The model was solved using the Genetic Algorithm (GA) technique, which is a suitable tool for this model. In the current study, GA used the real representation to represent different strings. Binary tournament selection, blend crossover and random mutation were used in for different GA steps. Penalty function was used for handling the constraints. Penalty functions has different techniques. In the current study, Additive Static Penalty (ASP) was used. In ASP the amount of constraint violation is multiplied by penalty coefficients and added to the fitness value.

The fitness value is calculated as follows:

$$F = \sum_{I \in NI} Q_I - \sum_{O = NO} Q_O + n_1 * \sum_{CH \in TCH} \max((WR_{CH} - WS_{CH}),0) + n_2 * \sum_{CH \in TCH} \max((AWA_{CH} - PWA_{CH}),0) + n_3 * \sum_{C \in TC} \max((Q_C - QD_C),0) + n_4 * \left(\max\left(\sum_{CH \in TCH} QS_{CH} - TIF \right),0 \right) \quad (6)$$

Where:

F= the fitness value

n_1, n_2, n_3, n_4 = coefficients

3. Model application

Quesna irrigation district (El Monofiya directorate) is selected for the model application. The district area is about 57058 feddan. The district boundaries are the Damietta branch from east and south sides, El-Bajour irrigation district from the west side and Berkt El-Sabee irrigation district from the north side. The dependence on shallow groundwater for irrigation is common in the district, and there are about 1530 authorized groundwater wells. Therefore, Quesna irrigation district is a suitable place to study the conjunctive water use and to optimize the water allocation from surface water and groundwater sources.

Model application was performed during July month as it represents the highest consumption period of irrigation water.

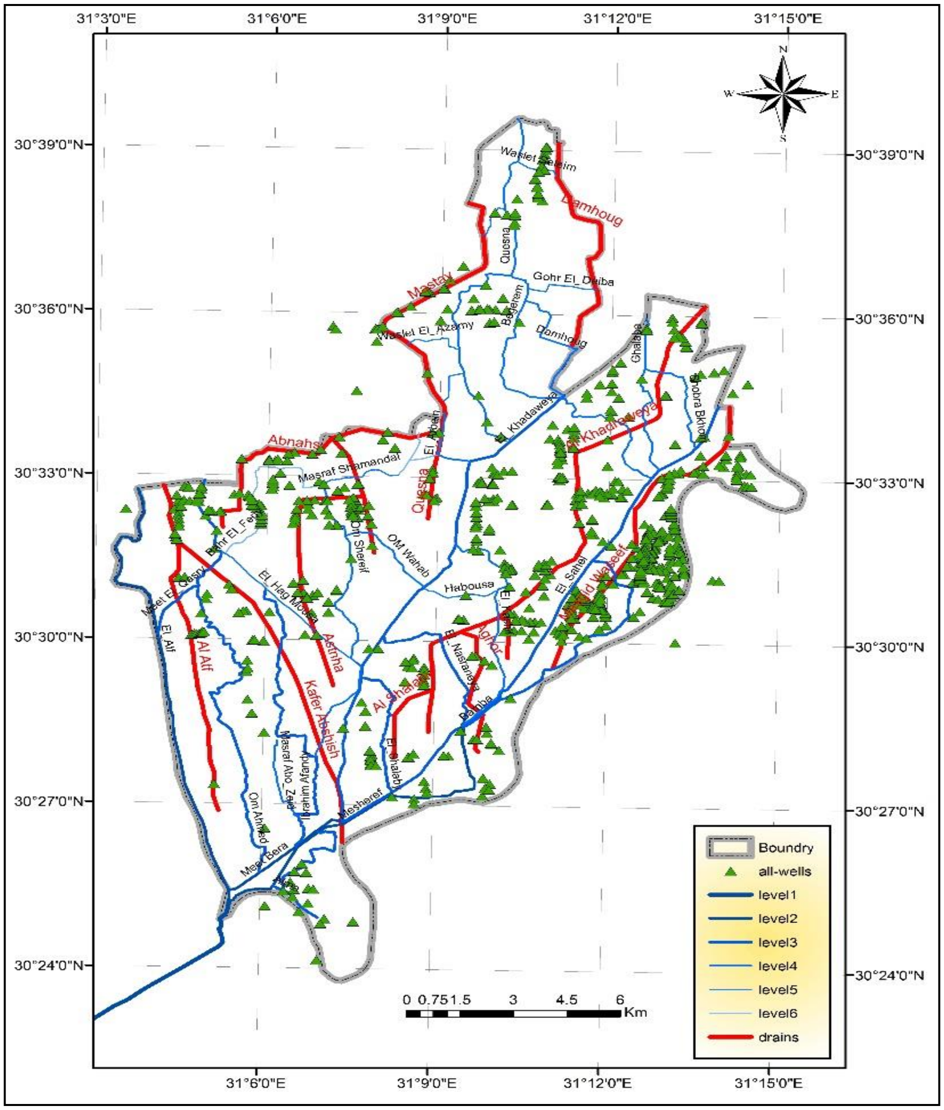

Fig. 1 Irrigation network, drainage network, and private wells in Quesna irrigation district

The following steps were followed to apply the model:

- The canals were divided into 38 reaches,
- The district command area was divided into 29 catchments according to reaches' command areas,
- Water requirements were calculated for every catchment using remote sensing information and MATLAB program.
- Canal capacities were calculated based on Manning equation for each reach
- Groundwater wells' number were collected for each catchment

- The discharge for each groundwater well (25 l/s) and groundwater wells' operation hours (between 0.5 and 13.0 h/day) were determined through a survey and Questionnaire samples.
- The surface water discharge at the head of the district was monitored and its average was 22.5 m^3/s during July month.

4. Results and discussion

The characteristics of GA were as follows:

The population has 100 strings;

The model was run for 100 generations;

Additive Static Penalty (ASP) was used to handle the violation of different constraints;

Values for crossover probability, crossover range and mutation probability were 0.6, 0.7 and 0.01 respectively.

Fortran 90 language was used to develop the model.

Figure (2) presents the evolution during consecutive generations due to GA process. Average fitness decreased gradually from 25.65 in the first generation to 15.21 in the last generation indicating the ability of GA to drive the problem to the optimal or near optimal solution. In the final solution, minimum fitness value was 14.67, while average fitness value for all strings was 15.21. This included water supply from surface water and groundwater, where there are no violations of any constraints for minimum fitness value. In the figure, average fitness was very close to minimum fitness value meaning that most of the strings were close to the minimum (optimal) value with some odd values due to the nature of evolutionary approaches.

Regarding the reliability of the solution, most of the strings in the last generation satisfied the four constraints. In the last generation, 99%, 91%, 92% and 100% of the strings satisfy the first, second, third and fourth constraint, respectively.

Considering the best (minimum) solution in the last generation, total water supply from both sources (surface water and shallow groundwater) was 27.28 m3/fed/day (14.67 m3/sec). From table (1), total water supply exceeded total water requirements by 1.02 m3/fed/d (3.9% of total water requirements). Water supply values exceeded water requirements values for all catchments. The ratios were between 0.01% and 16.45%. Excluding one low ratio (0.0%), the contribution of shallow groundwater for different catchments was between 1.6% and 67.6% of total water supply. Total water supply from groundwater constituted 32.7% of total water supply to the district.

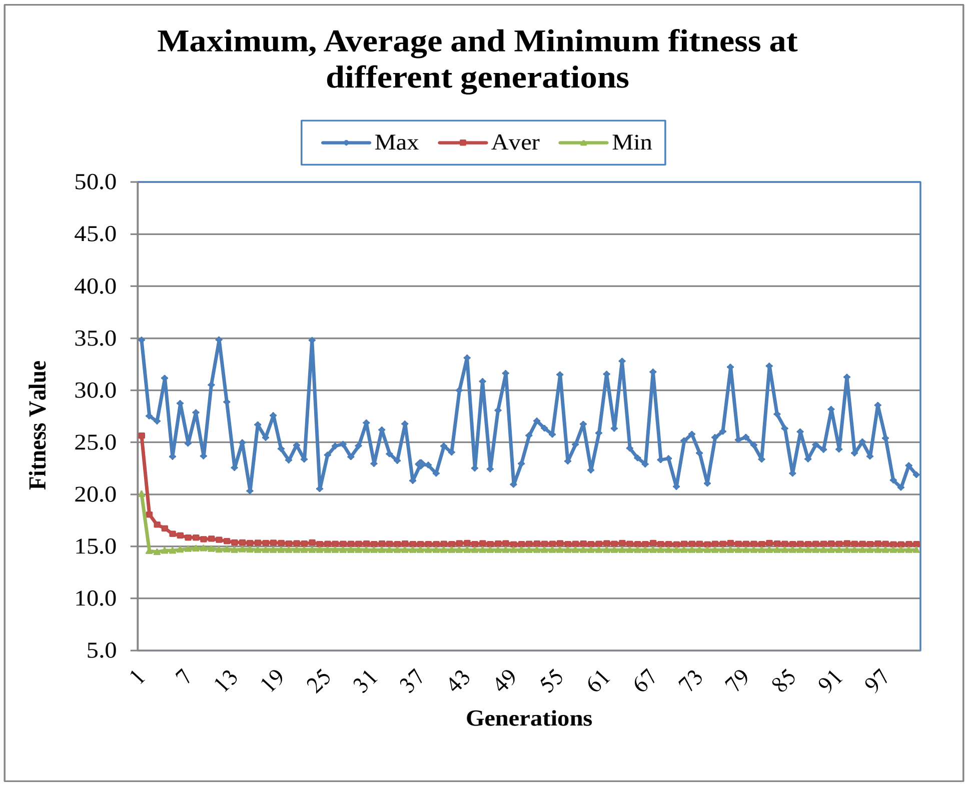

Fig. 2 Maximum, minimum and average fitness values for all generations

Table 1 Water Requirements and Water supply for catchments at the best solution

No	Water requirements (m^3/fed/day)	Water supply (m^3/ fed /day)		No	Water requirements (m^3/ fed /day)	Water supply (m^3/ fed /day)	
		Surface water	Groundwater			Surface water	Groundwater
1	29.97	20.48	14.42	16	27.20	26.94	0.43
2	27.90	29.98	0.00	17	27.37	15.40	13.10
3	26.67	23.34	4.24	18	27.06	16.40	12.57
4	28.09	21.30	8.30	19	27.13	23.30	7.54
5	26.05	8.85	17.58	20	25.76	21.35	5.77
6	26.00	19.66	7.05	21	27.46	13.02	16.28
7	22.44	12.66	11.51	22	27.67	14.17	13.69
8	27.54	21.27	7.16	23	24.50	13.90	12.50
9	26.44	20.47	6.55	24	25.99	15.41	10.99
10	24.52	18.72	5.80	25	25.67	11.96	13.75
11	26.94	18.48	8.47	26	26.99	17.48	9.77
12	26.16	9.83	17.29	27	26.64	8.94	18.23
13	27.92	27.50	1.16	28	25.39	17.85	7.75
14	23.64	25.97	0.00	29	25.52	16.69	11.13
15	25.15	8.39	17.48				

Flow values in different reaches in Quesna district were between 0.025& 13.44 m^3/s. considering total served areas of these reaches, relative water supply values were between 8.39 m^3/fed/day and 31.81 m^3/fed/day. In the catchment served by the canal with minimum relative water supply, the contribution of groundwater was 67.6%.

Table 2 Total served areas and total discharge at different reaches in Quesna district

Canal name	Total served area (fed)	TQ_c (m^3/s)	Canal name	Total served area (fed)	TQ_c (m^3/s)
Mesharf	8222.96	1.523	El-Khadraweia 1	24700.00	5.146
Alma	67.47	0.025	El-Khadraweia 2	23385.84	4.872
El-Eshren	755.30	0.170	Om Wahab	494.05	0.073
Bambah	1939.76	0.188	El-Arbeen	487.91	0.127
El-Shalaby	1240.00	0.192	Quesna	4296.50	0.742
El-Nasraniya	3061.21	0.546	Waslet Shamandel	239.77	0.040
El-Kashef	1814.23	0.253	Waslet El-Azamy	317.92	0.071
Habosa	316.17	0.046	Waslet El-Khaderat	148.49	0.028
Mit Bera	64500.00	13.437	Waslet Saleim	627.46	0.061
Om Ahmed1	3366.00	0.505	Begerem	1928.31	0.407
Om Ahmed2	2140.88	0.243	Gohr El-Diba	798.97	0.085
Ibrahim Afandy2	8431.22	1.770	Damhoug	800.01	0.131
Ibrahim Afandy1	1423.39	0.385	EL-Sahel 1	25450.00	5.302
Masraf Abo-Zeid	483.76	0.090	EL-Sahel 2	24432.76	5.090
Om Shereif	5776.18	1.073	El-Laimoneya	1577.50	0.319
El-Hag Mosa	2981.58	0.535	Ghalaba	1155.76	0.174
Bahr El-Feqy	1258.09	0.202	Shobra Bkhoum	1284.97	0.229
Masraf Shamandel	654.53	0.095	El-Atf	33300.00	6.937
Taymour	419.66	0.065	Mit El-Qasry	1558.12	0.420

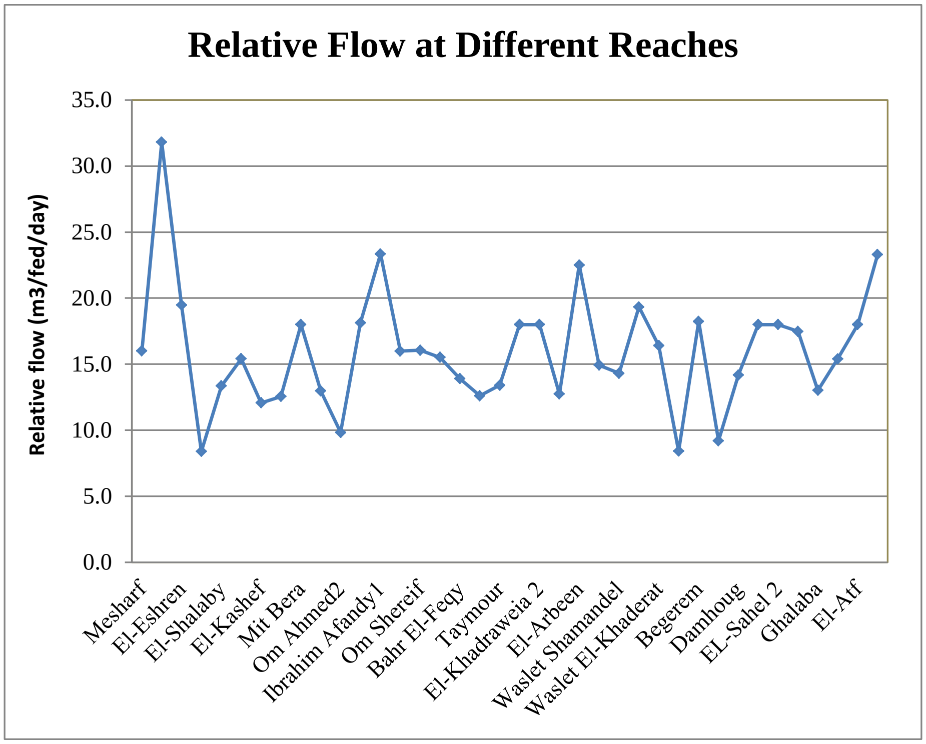

Fig. 3 Relative water supply for different reaches in Quesna irrigation district

5. Conclusions

This study investigated a model to optimize the conjunctive use of surface water and groundwater at irrigation district level. The optimization model minimizes total water supply from surface water while maintaining water supply sufficiency, the allowed withdrawal from shallow groundwater, the design capacity of canals and reaches and the available surface water flow at the district head. The decision variables for the model were the flow at different reaches of the district and the average operation hours of the groundwater wells at different catchments. The model was solved using Genetic Algorithm (GA) technique. Additive Static Penalty (ASP) is the study's constraint handling technique. The study was applied for Quesna irrigation district in Menofiya irrigation directorate, Egypt.

The results of the current study illustrated the ability of Genetic Algorithm to solve the optimization problems for the conjunctive use of surface water and groundwater, where the contribution of Groundwater discharge during July month was 32.7% of total water supply, which was close to the average estimation in the district.

The study recommends continuing the effort in such field while combining the optimization models with the simulation models to enhance water management strategy in different irrigation districts / directorates.

6. References

1. Burt, O.R. (1964) "The economics of conjunctive use of ground and surface water" Hilgardia 36, 31–111.
2. Dalla Porta, C. M., Fernandes, G. M., Medellin, J. A. (2019) "Reassigning Water Allocation Strategies and Conjunctive Use to Reduce Water Scarcity and Scarcity Costs for Irrigated Agriculture in Southern Brazil" Water 2019, 11, 1140; doi:10.3390/w11061140.
3. Deb, K. (1999) "An introduction to genetic algorithms" Sadhana, Vol. 24, Parts 4,5.
4. El Bedawy, R. (2014) "Water Resources Management: Alarming Crisis for Egypt" Journal of Management and Sustainability; Vol. 4, No. 3; 2014, ISSN 1925-4725 E, ISSN 1925-4733, Published by Canadian Center of Science and Education, August 29.
5. Goldberg, D., E. (1989) "Genetic algorithms in search, optimization, and machine learning" New York: Addison-Wesley.
6. K. Jha, M., C. Peralta, R., Sahoo, S. (2020) "Simulation-Optimization for Conjunctive Water Resources Management and Optimal Crop Planning in Kushabhadra-Bhargavi River Delta of Eastern India" International Journal of Environmental Research and Public Health ,2020, 17, 3521; doi:10.3390/ijerph1710352.
7. Singh, A. (2014) "Simulation–optimization modeling for conjunctive water use management" Agricultural Water Management 141 (2014) 23–29.
8. Soleimani, S., Bozorg-Haddad, O., Boroomandnia, A., A. Loáiciga, H. (2021) " A Review of Conjunctive GW-SW Management by Simulation-Optimization Tools" AQUA — Water Infrastructure, Ecosystems and Society, 70.3, 2021, Downloaded from http://iwaponline.com/aqua/article-pdf/70/3/239/890249/jws0700239.pdf
9. Song, J., Yang, Y., Sun, X., Lin, J., Wu, M., Wu, J., Wu, J. (2020) "Basin-scale multi-objective simulation-optimization modeling for conjunctive use of surface water and groundwater in northwest China" Hydrology and Earth System Scince, 24, 2323–2341, https://doi.org/10.5194/hess-24-2323-2020
10. Thede, S. (2004) "An Introduction to Genetic Algorithms" https://www.researchgate.net/publication/228609251.