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APPLICATION OF GENETIC ALGORITHMS FOR IRRIGATION WATER SCHEDULING†

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ABSTRACT

The development of a genetic algorithm (GA) to solve an irrigation water scheduling problem is described. The objective is to optimize the utilization of water resources in irrigation systems operating on a rotational basis. An objective function for the water scheduling problem is presented along with constraints that relate to in-field soil moisture balances as well as canal capacities.

The approach was applied to a simple and to a more complex test system. Solutions are presented using a GA in different formulations and comparisons made between these. Results demonstrate that GAs are capable of solving water scheduling problems, including those with water stress. In water stress conditions the GA approach can provide uniformity in soil moisture content in schemes within a system if formulated with a 0–1 approach.

An application to the Pugal branch canal in the Indira Gandhi Nahar Pariyojana (IGNP) irrigation system in north-west India has demonstrated that the approach is robust and can produce appropriate schedules under extreme conditions of water stress. The GA approach is a useful tool for water scheduling in complex systems.

KEY WORDS: irrigation; water scheduling; optimization; genetic algorithms; water management

RÉSUMÉ

L’article décrit le développement d’un algorithme génétique (AG) pour résoudre un problème de programmation d’irrigation. L’objectif est d’optimiser l’utilisation des ressources en eau dans les systèmes d’irrigation qui fonctionnent avec un tour d’eau. Pour l’optimisation, une fonction objective est présentée ainsi que les contraintes relatives au bilan hydrique et à la capacité des canaux.

Cette approche a été expérimentée sur un système-test simple et sur un plus complexe. Des solutions utilisant différentes formulations de l’algorithme sont présentées et comparées. Les résultats montrent que les AGs sont capables de résoudre les problèmes de programmation des tours d’eau y compris en présence de stress hydrique. Dans des conditions de stress hydrique, l’outil peut procurer une uniformité de teneur en l’eau du sol à l’intérieur d’un système avec une formulation booléenne.

Une application sur le Pugal Branch Canal dans le système d’irrigation Indira Ghandi Nahar Pariyojana (IGNP) situé dans le nord-ouest de l’Inde a démontré que l’approche est solide et peut produire des résultats appropriés dans des conditions extrêmes de stress hydrique. L’approche de l’AG semble donc être un outil utile pour l’allocation de l’eau dans des systèmes complexes.

MOTS CLÉS: irrigation; allocation de l’eau; optimisation; algorithme génétique; gestion de l’eau

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INTRODUCTION

In a recent paper by Wardlaw and Bhaktikul (2001), a genetic algorithm (GA) was applied to the real-time allocation of water supplies in irrigation systems with complex distribution networks. This work had built upon earlier work by Wardlaw and Barnes (1999), who had solved the water allocation problem using a quadratic programming (QP) approach. The QP approach was applied to the Tukad Ayung irrigation systems in Bali. Wardlaw and Bhaktikul (2001) applied their GA approach to the same system. They found that the GA approach could produce satisfactory results in application to the real-time water allocation problem, but that it offered no advantages over QP. The QP approach was faster and produced more equitable allocations. Wardlaw and Bhaktikul (2001) were of the opinion, however, that a GA approach did hold promise in application to irrigation scheduling problems.

There have been numerous applications of optimization techniques to a variety of irrigation water scheduling problems. Some have been concerned only with scheduling fixed demands within the constraints of canal system capacity, while others have used soil moisture accounting models as a means of determining demands in response to irrigation and hydro-meteorological conditions. A few of these applications are summarized below.

Canal scheduling

Shyam *et al.* (1994) developed an optimal operation scheduling model for the Golawar main canal in Uttar Pradesh, India, using a linear programming technique. Variables included cropped areas, water allocations, and running times of secondary and tertiary canals. They were able to demonstrate the superiority of developed operational strategies over existing policy.

Reddy *et al.* (1999) studied irrigation scheduling between canal outlets with different flow capacities. Running times were formulated in a 0–1 linear programming problem. They developed an interactive computer program called ZERO1 to generate the optimal rotation schedule that ensured that all the secondary canals received the specified water allocation during the given rotation. The objective was to schedule the secondary canals to deliver at full supply as far as possible during the given rotation period. The approach to formulating the problem was to derive a schedule that minimized the differences between the required capacity and actual capacity of the supply canal. It was applied to data for the Haeto irrigation system in China.

Anwar and Clarke (2001) used a mixed integer programming approach for scheduling canal irrigation water among a group of users who request water at varying times in each scheduling period. The objective was to schedule supplies as close as possible to the times requested by farmers. Anwar and Clarke (2001) built upon earlier work by Suryavanshi and Reddy (1986) and Wang *et al.* (1995).

Scheduling field deliveries

The literature cited above has been concerned primarily with canal scheduling to meet predefined irrigation demands. Other authors have considered scheduling water deliveries at the field level to ensure the most efficient use of available resources.

Rao *et al.* (1992) studied the problem of real-time irrigation scheduling under water shortage conditions. They took soil moisture content and available water supplies as state variables characterizing the irrigation scheduling problem. The objective was to develop irrigation schedules that would maximize crop yields. The decisions were made in two stages: (1) a design stage; and (2) a real-time stage. At the design stage, irrigations were planned for weekly intervals using historical data of seasonal supply, probable weekly rainfall, average weekly potential evapotranspiration, and basic data on soils, crops, and the irrigation system. A standard soil moisture deficit model was used to obtain weekly design irrigation requirements for the season. In the real-time stage, the decisions for the subsequent weeks were revised at the end of each week after updating the model with the real-time values of rainfall, evapotranspiration, and availability of water supply.

Singh *et al.* (1995) applied a computer-assisted irrigation scheduling system to optimize water use and enhance crop production for an okra crop in Trinidad and a raspberry field in Quebec. An optimization model called AISSUM (Automatic Irrigation Scheduling System of the University of Montreal), which is based on a water balance approach, was used. AISSUM calculates the water balance and updates the soil moisture storage on a half-hourly basis. The timing of irrigation applications was integrated with rainfall forecasts. The amount of water to be applied, according to the model, was based on the practice of full irrigation. In times of scarcity, deficit strategies could be applied.

Sunantara and Ramirez (1997) studied optimal seasonal multi-crop irrigation water allocation and optimal daily irrigation scheduling using a two-stage decomposition approach based on stochastic dynamic programming. The goals were to:

1. Optimize the seasonal allocation of a limited amount of irrigation water;
2. Optimize the seasonal allocation of limited acreage for two or more crops;
3. Determine the optimal daily irrigation scheduling policy for each crop, taking into account the dynamics of the soil moisture depletion process and the stochasticity of rainfall.

In the first stage (seasonal water allocation) the optimization model was based on seasonal crop production functions using a single-crop stochastic dynamic programming irrigation scheduling model to determine the maximum expected value of benefits as a function of seasonal water availability. This model incorporated the physics of soil moisture depletion and the stochastic properties of precipitation. The optimal seasonal water allocation between several fields was made using deterministic dynamic programming. The objective was to maximize total benefits from all crops. In the second stage (intra-seasonal water allocation) optimal intra-seasonal irrigation scheduling was performed using a single-crop stochastic dynamic programming algorithm, conditioned on the optimal seasonal water allocation of the first stage. The daily optimal irrigation scheduling functions were obtained as a function of root-zone soil moisture content and the currently available irrigation water. The study showed a strong dependence of optimal multi-crop water policies on the stress sensitivity factors, the maximum yields for each crop, and the costs of irrigation and cultivation.

In this paper, a scheduling approach that combines canal delivery scheduling with in-field requirements is presented as a more comprehensive approach to irrigation water scheduling. The approach developed combines a GA with a deterministic soil moisture balance model. The objective was to achieve equity in water delivery throughout the season among the multiple outlets from an irrigation canal system.

AN OBJECTIVE FUNCTION FOR CANAL SCHEDULING

A test irrigation network is shown in Figure 1. The objective in scheduling is considered to be one of optimizing the utilization of water resources by maintaining the soil moisture between field capacity (FC) and wilting point (WP), while minimizing drainage losses. Modelling soil moisture should therefore be a fundamental component of a scheduling system.

The problem may be described as follows:

$$\text{Minimize } Z = \sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{i=1}^{I} X_{ijt} + R_1P_1 + R_2P_2 + R_3P_3 \tag{1}$$

where

X_{ijt} = irrigation supply to tertiary i of secondary j in time period t,
t = time step
T = number of time periods
i = tertiary canal number
I = number of tertiary canals on secondary canal j
j = secondary canal number
J = number of secondary canals

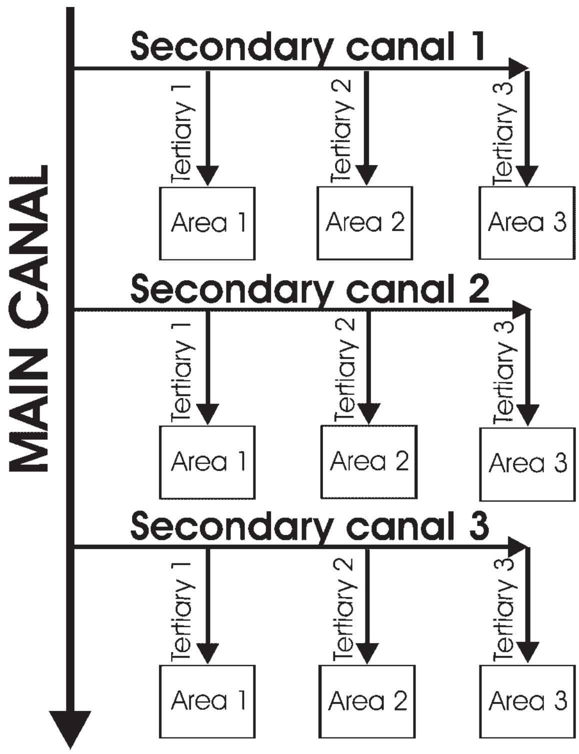

Figure 1. Test network

P_1, P_2 and P_3 are penalties for constraint violation, and R_1, R_2 and R_3 are the penalty weighting factors.

The constraints may be defined as follows:

$$\theta_{ijt} \geq WP_{ijt} \tag{2}$$

and in any time step:

$$\sum_{i=1}^{I} q_{ij} \leq Q_j \tag{3}$$

$$\sum_{j=1}^{J} Q_j \leq Q\mathrm{main}_t \tag{4}$$

where

θ_{ijt} = soil moisture content at time t in scheme i of secondary canal j (mm)
WP_{ijt} = soil moisture at wilting point at time t in scheme i of secondary canal j (mm)
q_{ij} = full supply capacity of tertiary canal i on secondary canal j ($m^3\,s^{-1}$)
Q_j = full supply capacity of secondary canal j ($m^3\,s^{-1}$)
$Q\mathrm{main}_t$ = flow in the main canal at time t ($m^3\,s^{-1}$)

A number of alternative GA formulations are possible. The following were considered:

1. A 0–1 approach;
2. A Warabandi approach (Malhotra *et al.*, 1984; Shrestha, 1999).

The crop stress penalty is defined as P_1 and is used to represent the soil moisture constraint. It is common to both formulations and is written as follows:

$$P_1 = \sum_{t=1}^{T} \sum_{j=1}^{J} \sum_{i=1}^{I} \left(\max\left(\mathrm{WP}_{ijt} - \theta_{ijt}, 0\right)\right)^2 \tag{5}$$

The decision variables and the expressions for the canal capacity constraints vary depending upon the formulation being adopted, and are outlined below.

The 0–1 approach

In the 0–1 approach the irrigation supply to any scheme is defined as follows:

$$X_{ijt} = q_{ij}.\,IFLAG_{ijt} \tag{6}$$

where, $IFLAG_{ijt}$ takes a value of zero or one, indicating whether or not there is irrigation in time step t, and is the decision variable.

For the network shown in Figure 1 and for 100 time steps, the length of a chromosome for the 0–1 approach is 900: 3 schemes per secondary canal, 3 secondary canals and 100 time steps ($3 \times 3 \times 100$). The secondary canal capacity penalty factor is defined as follows:

$$P_2 = \sum_{t=1}^{T} \sum_{j=1}^{J} \left(\max\left(\sum_{i=1}^{I} \left(q_{ij}.\,IFLAG_{ijt}\right) - Q_j, 0\right)\right)^2 \tag{7}$$

The main canal capacity penalty is a little more complex and is defined as:

$$IFLG\_S_{jt} = 0$$

If

$$\begin{aligned} &\sum_{i=1}^{I} IFLAG_{ijt} > 0, \qquad IFLG\_S_{jt} = 1 \\ &P_3 = \sum_{t=1}^{T} \left(\max\left(\sum_{j=1}^{J} \left(Q_j.\,IFLG\_S_{jt}\right) - Q\mathrm{main}_t, 0\right)\right)^2 \end{aligned} \tag{8}$$

The above canal capacity constraints will in effect control the water diversion combinations. The quadratic form of the penalties increases the sensitivity of the GA to their violation. In addition, the penalty factors R_1, R_2 and R_3 can be used to attach different weights to each penalty as the scales of each are different. For this formulation, in which the secondary canals are assumed to run at full capacity, the only decision variables are IFLAG. Schemes either receive irrigation or do not receive irrigation. In a GA, a gene can thus be represented by a single binary bit. It may thus be considered to be a 0–1 approach.

The Warabandi approach

In the Warabandi approach (Malhotra *et al.*, 1984; Shrestha, 1999), the duration for which a scheme receives water is fixed and the interval between irrigations is fixed, although either parameter may vary between schemes as command areas differ or soil moisture and cropping characteristics vary. There are two primary decision variables per scheme—the duration for which the scheme receives water during a turn, and the interval between irrigations. It is also necessary to define the starting time period for the first irrigation in each scheme. The starting time may also be incorporated in the GA as a decision variable. This is desirable since in complex systems the best combination of starting times may be difficult to define without optimization. For the test network shown in Figure 1, the total number of decision variables is 27: 9 starting times, 9 irrigation durations, and 9 intervals between irrigations. Generally one would expect these variables to be expressed in units of days, and it is possible in a GA to represent them as real values. A chromosome thus comprises 27 genes. This is significantly shorter than for the 0–1 approach, but the Warabandi approach will be less efficient in terms of water delivery as the irrigation intervals are fixed. The decision variables have been defined as follows:

SI_{ij} = starting time step for irrigation in tertiary i of secondary j
DI_{ij} = duration of irrigation in tertiary i of secondary j
II_{ij} = interval between irrigations in tertiary i of secondary j

For each candidate solution or chromosome in the GA population defined by the above decision variables, the variables $IFLAG_{ijt}$ can easily be determined. It is thus possible to use the canal capacity constraints as outlined in equations (7) and (8) without modification. The irrigation supply is computed from equation (6).

SOIL MOISTURE MODELLING

Application of the objective function outlined above requires the modelling of soil moisture. For the purposes of this research, a relatively simple soil moisture balance model was used. The approach to the computation of crop evapotranspiration is based on the methods outlined by Allen *et al.* (1998). A dual crop coefficient approach has been adopted to account for water stress periods and resulting reductions in evapotranspiration.

The constraint given in equation (2) is applied to the crop root zone only. Crop root development must therefore be modelled through the growing period. The recommendations of Allen *et al.* (1998) were again followed. Root zone soil moisture is tracked and adjusted as the roots develop. For modelling purposes, the soil column was divided into a series of discrete layers, where soil moisture is tracked. This simple model is adequate to permit evaluation of a GA approach to water scheduling.

APPLICATION TO A SIMPLE NETWORK

The GA has been applied to the very simple test system shown in Figure 2. The test system comprises three schemes to which irrigation water is distributed by secondary canals. Each scheme has an area of 100 ha. Flow in the main canal is continuous, but secondary canals are rotated and operated at full capacity. The physical characteristics assumed for the system are given in Table I. For the purposes of this evaluation, a conveyance efficiency of 70% was assumed. Field losses were assumed to be handled implicitly by the soil moisture balance model. The main canal capacity was set to $0.24\,m^3\,s^{-1}$, and secondary canal capacities to $0.12\,m^3\,s^{-1}$ each. Losses resulting from opening and closing secondary canals were taken to be $1500\,m^3$. The inclusion of these losses is important as it is through these that the GA is forced to limit the frequency of canal operation. With the basic set-up given in Table I, there is no water stress induced in the system. A water stress situation in which soil moisture could be expected to fall below wilting point, was introduced by reducing the main canal capacity to $0.14\,m^3\,s^{-1}$, and that of the secondary canals to $0.07\,m^3\,s^{-1}$. The purpose of modelling a water stress case was to test the robustness of the model.

A bean crop with a growing period of 100 days was assumed for all schemes. Planting in schemes 1 and 2 was assumed to occur on the same day (1 June), but planting on scheme 3 lagged 3 days. Potential crop evapotranspiration, ET_c, has been calculated throughout the growing period, on the basis of ET_o values for Chiengrai in Thailand. The minimum and maximum rooting depths were assumed to be 0.15 and 0.80 m respectively. A soil moisture depletion fraction of 0.45 was assumed. Effective rainfall was assumed to be zero.

In this simple test system, only the 0–1 formulation was considered. For the GA, genes in a chromosome represent the decision variables (($IFLAG_{ijt}$), $i = 1$, $j = 1, J$, $t = 1, T$), where J is the number of schemes (3) and T is the number of time steps (100). A time step of 1 day was used and the total chromosome length was 300. A chromosome may represent the decision variables in two ways. One is to group the genes by scheme, and the other is to group genes by time step. The former approach has been used. This results in blocks of ones and zeros

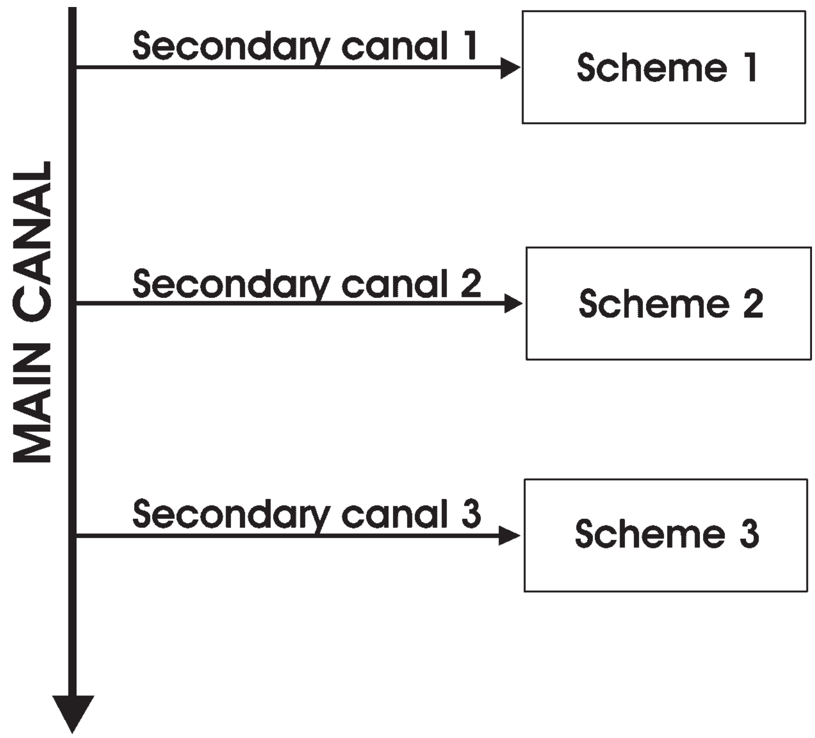

Figure 2. Simple test network

representing periods of water diversion and non-diversion to each scheme and good solutions are less likely to be significantly disturbed by crossover. The representation scheme is real valued in that each gene is represented by a single value. The GA was set up with uniform crossover, tournament selection, and conventional mutation. The population size used was 100 and it was found that good results were achieved with a crossover probability of 0.85 and a mutation probability of 0.05. For this example R_1 was set to 3 and R_3 to 12 500. Very different values are required because of differences in the scales and units of the penalty function components.

Scheduling results, no water stress

With no water stress, canal capacity and wilting point constraints were satisfied in all time periods. The crop water requirements were 302, 302 and 300 mm for schemes 1, 2 and 3 respectively. The lower value for scheme 3 reflects the later planting date thereof. The soil profile was assumed to be at wilting point at the start of the growing

Table I. Simple test network characteristics

Characteristic	Value		
Main canal full supply ($m^3 s^{-1}$)	0.24		
Conveyance efficiency	70%		
Scheme number	1	2	3
Scheme area (ha)	100	100	100
FC ($m^3 m^{-3}$) for sandy soil	0.17	0.17	0.17
PWP ($m^3 m^{-3}$) for sandy soil	0.07	0.07	0.07
Secondary canal full supply ($m^3 s^{-1}$)	0.12	0.12	0.12

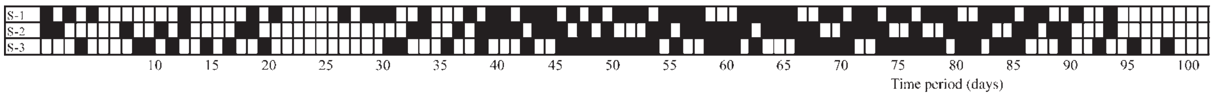

Figure 3. Irrigation schedule for the simple test network with no water stress

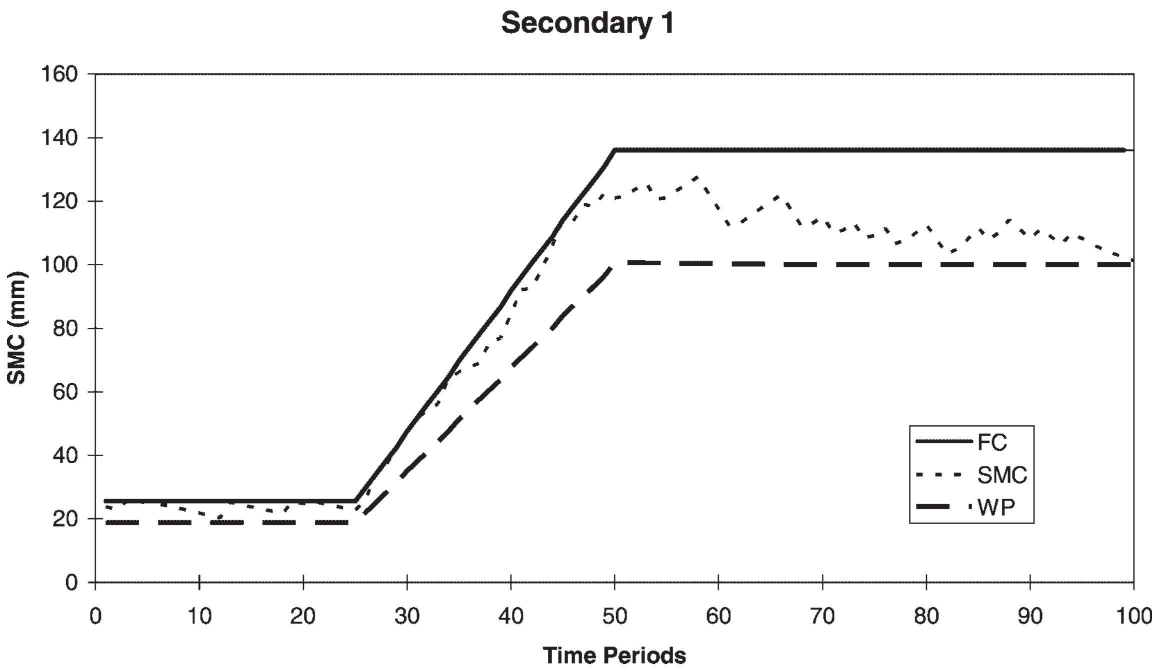

Figure 4. Simulated root zone soil moisture content, simple network, no water stress

period, and as a result, there is a very close match between water supplied and water required. There is no overapplication of irrigation water. The field water supply to each scheme was 303 mm. Conveyance losses of 30% in addition to canal filling and emptying losses were assumed, but no field application losses were considered while moisture content was below field capacity. Figure 3 shows the irrigation schedule produced by the GA. Shading represents irrigation periods. As can be seen from the schedule, irrigation periods generally lengthen as the crop develops. Variations in soil moisture content (SMC) throughout the irrigation period are shown in Figure 4. The GA has successfully maintained SMC between wilting point and field capacity throughout the growing period.

Scheduling results, with water stress

Water stress was introduced to the system by reducing the main canal capacity to 0.14 $m^3 s^{-1}$, and the secondary canal capacities to 0.07 $m^3 s^{-1}$. Cropping and soil characteristics were not changed. The purpose of the water stress application was to demonstrate the robustness of the approach. Under water stress conditions, the water supply to the system in the 100-day season averaged 241 mm per scheme. Scheme water balances are summarized in Table II. There are minor differences in the actual evapotranspiration (E_a) from the different schemes, but the ratio of ET_a ET_c is similar in all schemes, indicating that equity in water distribution has been preserved.

The irrigation schedule produced by the GA is shown in Figure 5. Figure 6 shows the simulated root zone soil moisture content. With water stress it was not possible to satisfy the wilting point constraint of equation (5). In a stress condition this constraint helps to maintain equity in water allocation between the schemes. The total cumulative water stress was 732 mm days in scheme 1, 616 mm days in scheme 2, and 626 mm days in scheme 3. The higher stress in scheme 1 was reflected in the lower actual evapotranspiration from that scheme. It is possible

Table II. Scheme water balances (water stress case, all values in mm)

Balance component	Scheme 1	Scheme 2	Scheme 3
Net irrigation	231	251	240
ET_c	302	302	300
ET_a	241	245	238
ET_a/ET_c	0.80	0.81	0.79
Change in storage	11.428	1.239	0.258
Drainage	1.458	7.780	2.352

that improved equity in cumulative stress could have been achieved through modification of the penalty factors. This has not been investigated.

Conclusions

A comparison of scheduling results between the soil water stress and non-stress conditions has been made. The total water delivery to each scheme with no water stress was 303 mm, while with water stress it was 241 mm. In the water stress case, irrigation frequency was reduced, thereby reducing the losses associated with water diversions. The total number of irrigations per scheme was reduced from 22 in the non-stress case to 18 in the stress case. The number of irrigation days per scheme was increased from 46 in the non-stress case to 63 in the stress case where secondary canal capacity had been reduced.

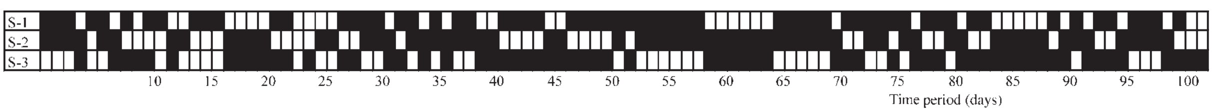

Figure 5. Irrigation schedule for the simple test network with water stress

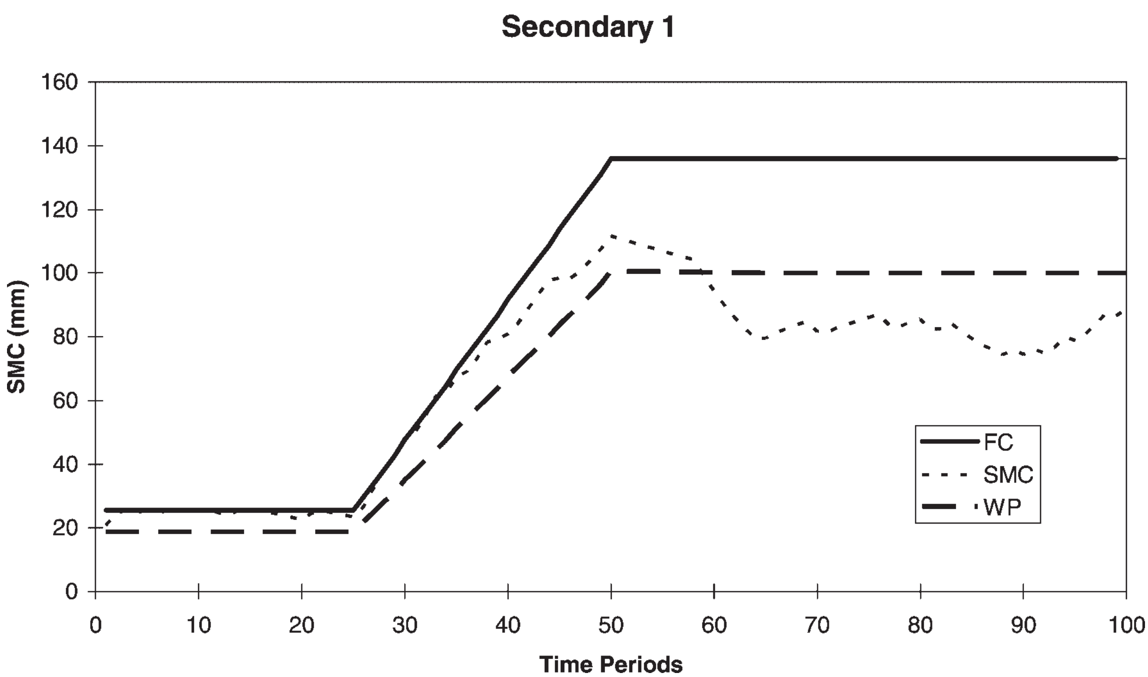

Figure 6. Simulated root zone soil moisture content, simple network, with water stress

These results, although from a very simple system, indicated that the approach had potential and was worthy of further development. More complex applications are outlined in the following section.

APPLICATION TO A MORE COMPLEX NETWORK

Test network characteristics

The system shown in Figure 1 comprises a main canal with three secondary canals. Each secondary canal comprises three tertiaries. Investigations have been carried out with a main canal capacity of 1.4 $m^3 s^{-1}$. Secondary canal capacities were fixed at 0.24 $m^3 s^{-1}$, and tertiary canal capacities at 0.12 $m^3 s^{-1}$. Table III summarizes the assumed system characteristics. Losses in water diversions to tertiary canals were set at 1500 m^3 per canal operation. Losses in water diversions to secondary canals were set at 6000 m^3 per canal operation. The main canal capacity imposes no constraint to water delivery. The crop characteristics, effective rainfall, and potential evapotraspiration used were the same as for the simple network.

The GA was set up with uniform crossover, tournament selection, and conventional mutation. The 0–1 approach was applied with a population size of 100, a crossover probability of 0.9, and 0.05 mutations per chromosome per generation. Convergence was assumed when the improvement in minimum fitness over a minimum generation gap of 300 was less than 0.001%, and canal capacity constraints were satisfied to within a tolerance of $\pm 0.1\%$. The penalty factors R_1, R_2 and R_3 were set at 1, 10 000 and 5000 respectively. On the basis of these criteria, convergence was obtained in 1500 generations. The Warabandi approach was applied to the same problem with a population size of 100, a crossover probability of 0.9, and 0.3 mutations per chromosome per generation. The convergence criteria and penalty factors were the same as with the 0–1 criteria. Convergence was not improved after 900 generations.

Scheduling results, no water stress

The irrigation schedules obtained with the 0–1 approach are presented in Figures 7(a) and (b), for tertiary and secondary canals, respectively. Variations in soil moisture for a typical tertiary unit are shown in Figure 8. The schedules produced ensure that there is no water stress in any of the tertiary units. The average field application of water among all tertiary units was 313 mm, compared with a crop demand of 302 mm. Since field capacity was only rarely exceeded there was little percolation from the root zone.

The irrigation schedules obtained with the Warabandi approach are presented in Figures 9(a) and (b), for tertiary and secondary canals, respectively. Variations in soil moisture for a typical tertiary unit are shown in Figure 10. The GA has been successful in creating an irrigation schedule under the Warabandi approach that satisfies the canal

Table III. Characteristics of the more complex network

Characteristic	Value								
Total command area (ha)	900								
Main canal full supply ($m^3 s^{-1}$)	1.4								
Secondary number		S1			S2			S3	
Secondary command area (ha)		300			300			300	
Secondary full supply ($m^3 s^{-1}$)		0.24			0.24			0.24	
Conveyance efficiency (%)		70			70			70	
Tertiary number	T1	T2	T3	T1	T2	T3	T1	T2	T3
Tertiary command area (ha)	100	100	100	100	100	100	100	100	100
FC ($m^3 m^{-3}$)	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
PWP ($m^3 m^{-3}$)	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Tertiary full supply ($m^3 s^{-1}$)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Lag in planting (days)	0	0	3	0	3	0	3	0	0

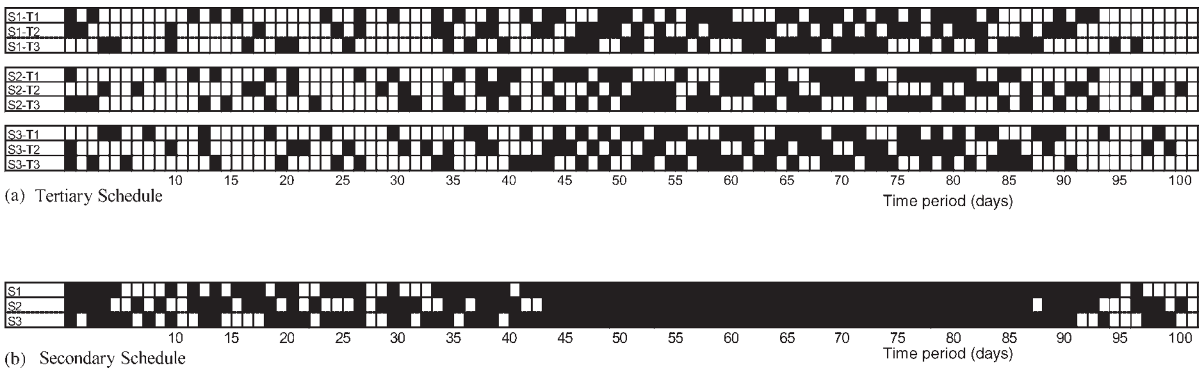

Figure 7. Schedules achieved with the 0–1 approach for the more complex network, no water stress

system constraints, and ensures that no water stress occurs in the system. However, because of the fixed schedule, the Warabandi approach results in much greater water delivery. The average field application of water among all tertiary units was 470 mm. This is 50% higher than under the 0–1 approach.

Scheduling results, with water stress

A water stress situation was created by reducing the main canal capacity from 1.4 to 0.7 $m^3 s^{-1}$. As it was assumed that secondary canals must run at their full capacity, reduction in main canal capacity resulted in the condition that only two secondary canals could run simultaneously. The schedule produced by the 0–1 formulation of the GA is shown in Figures 11(a) and (b) for the tertiary and secondary canals respectively. Variations in soil moisture for a typical tertiary unit are shown in Figure 12. The GA is able to maintain reasonable equity in soil moisture stress among the schemes, as can be seen from Figure 13.

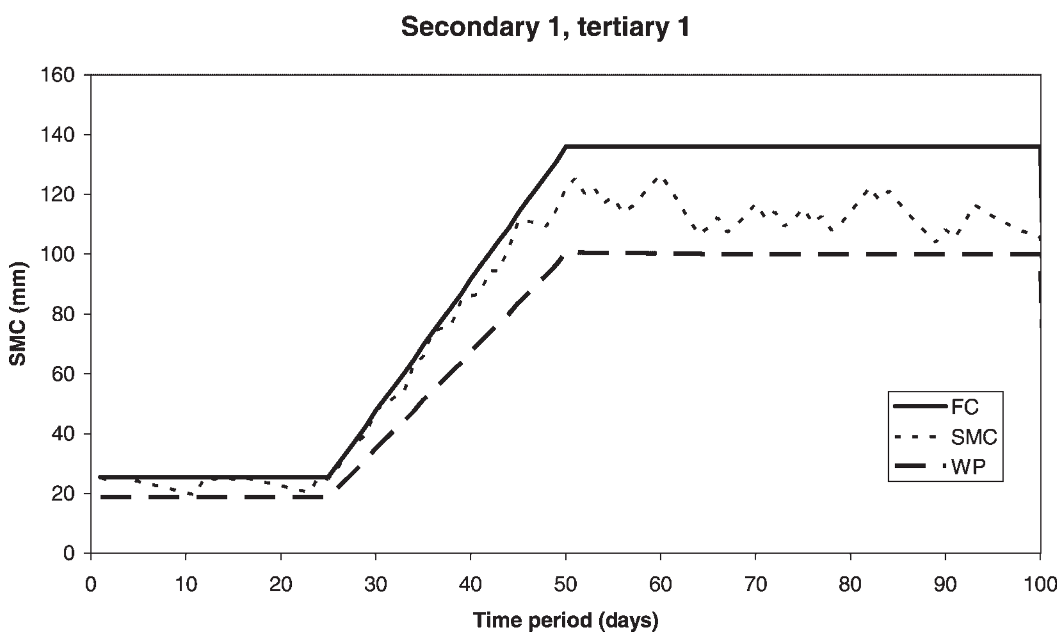

Figure 8. Simulated root zone soil moisture content with 0–1 criteria for a typical tertiary canal in the more complex network, no water stress

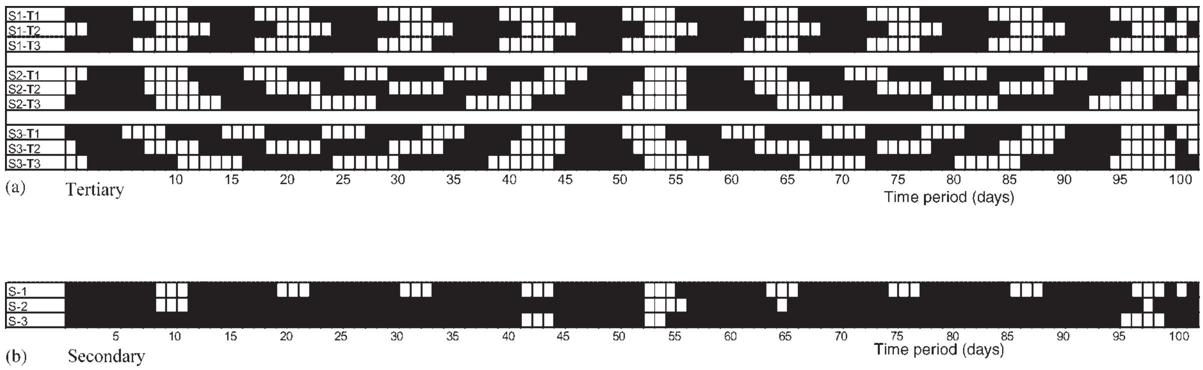

Figure 9. Schedules for the Warabandi approach for the more complex example

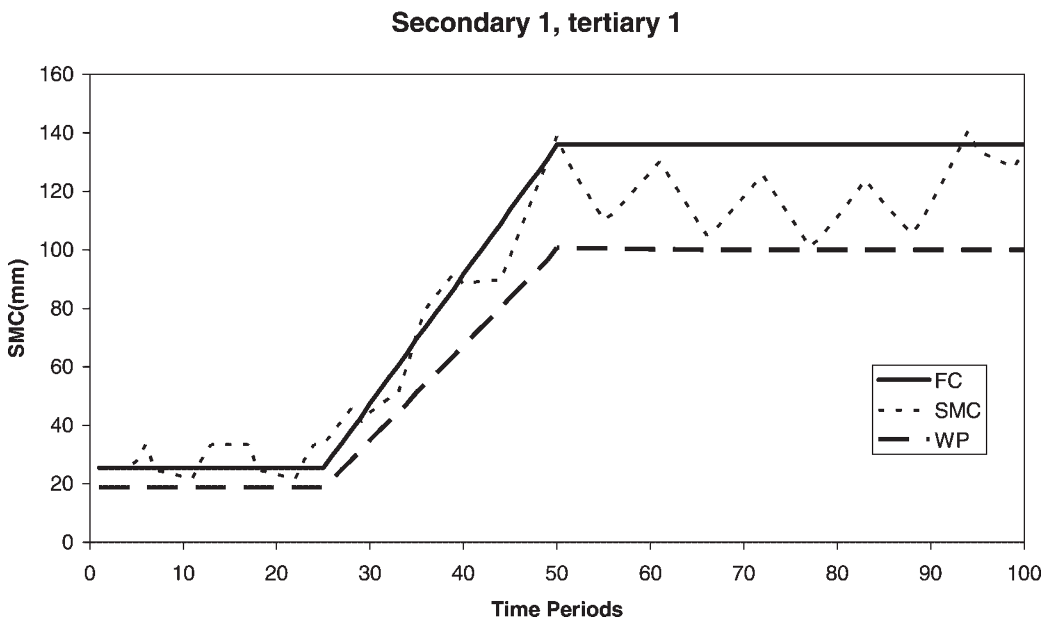

Figure 10. Simulated root zone soil moisture content with Warabandi approach for a typical tertiary canal in the more complex network, no water stress

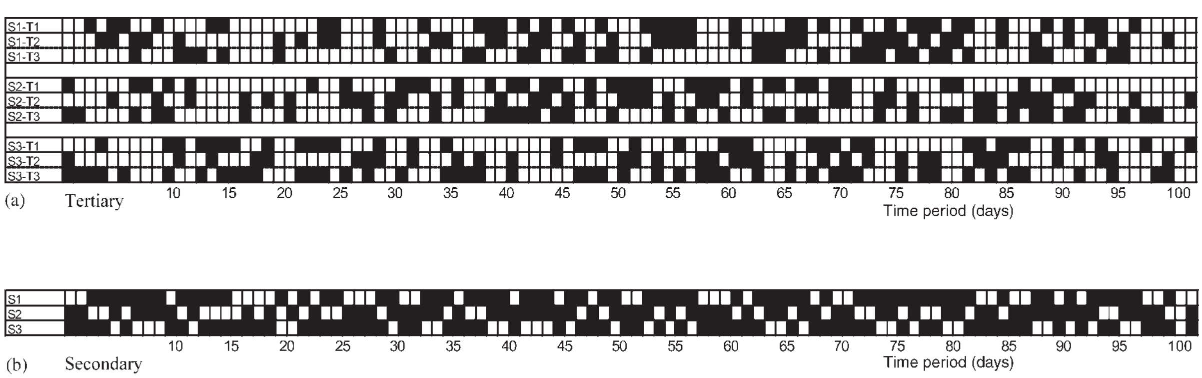

Figure 11. Schedules achieved with the 0–1 approach for the more complex network, with water stress

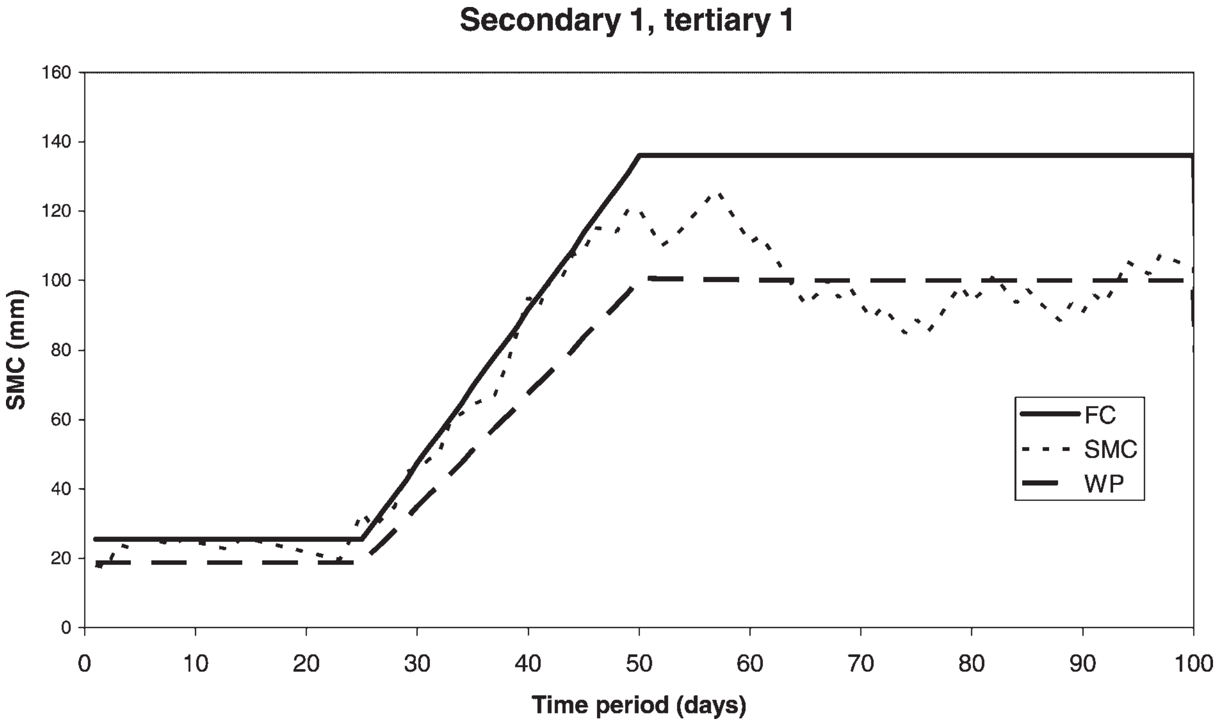

Figure 12. Simulated root zone soil moisture content with 0–1 criteria for a typical tertiary canal in the more complex network, with water stress

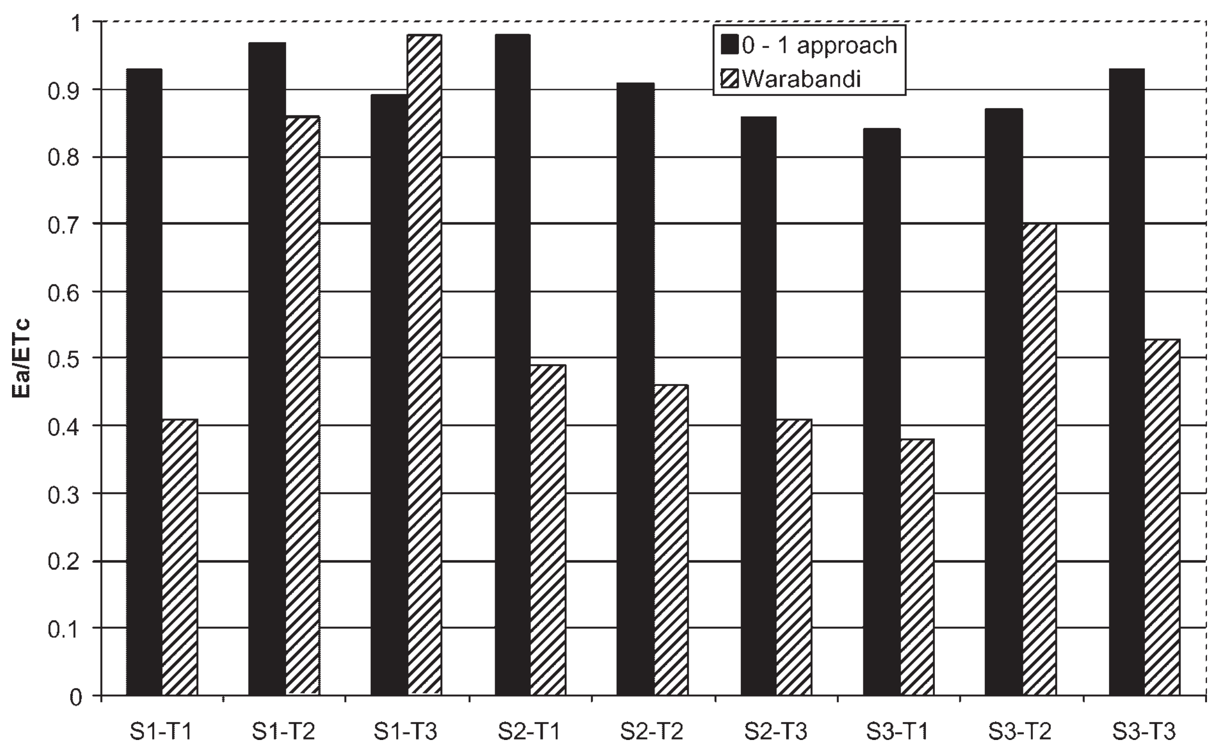

Figure 13. Distribution of evapotranspiration deficits with schedules for a water stress condition

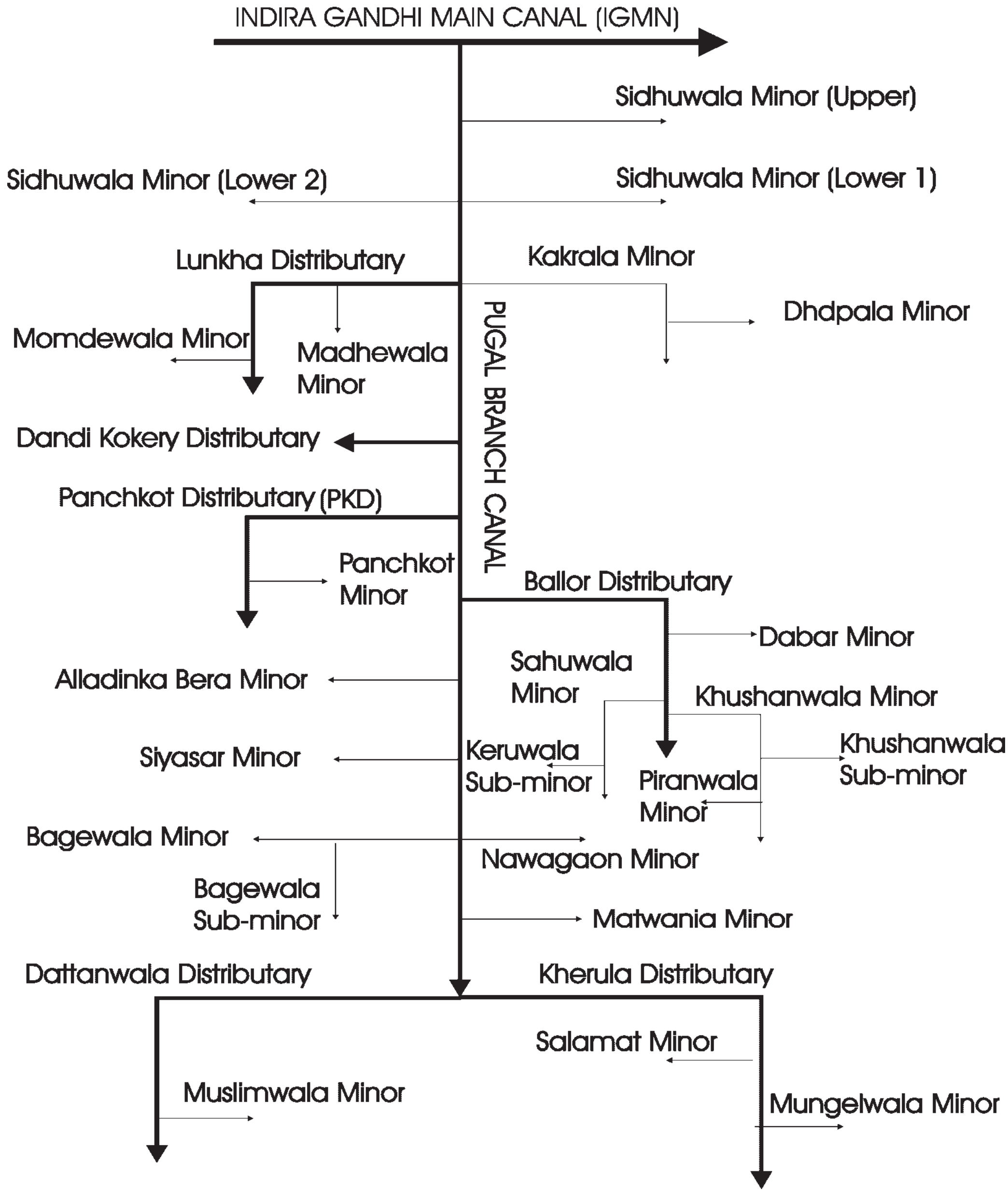

Figure 14. Pugal branch canal

The Warabandi approach was also tested for the water stress situation. The GA was able to produce a feasible schedule, but with the Warabandi approach it was not possible to derive a schedule that provided equity in water stress distribution (Figure 13) or provided efficient utilization of available resources.

Conclusions

The GA was able to produce feasible schedules under both the 0–1 and Warabandi approaches. The 0–1 approach is more flexible and resulted in more efficient water use. The Warabandi approach had a chromosome length of 48, compared to a chromosome length of 1600 for the 0–1 approach. It therefore executed more efficiently, but this did not improve its ability to meet demands during water shortage. The Warabandi approach resulted in more water being supplied than is required in the early part of the schedule. In water stress conditions, the 0–1 approach produced a schedule that resulted in a reasonably equitable distribution of evapotranspiration deficits. Under water stress a feasible schedule was produced with the Warabandi approach, but this was neither equitable nor efficient.

APPLICATION TO THE PUGAL SYSTEM

The 0–1 approach to water scheduling has been applied to part of the Indira Gandhi Nahar Pariyojana (IGNP) irrigation system in north-west India. Currently the Warabandi approach to scheduling is used at minor and sub-minor canal level. In scenarios considered in this paper, scheduling has been investigated at distributary canal level. The intention is to demonstrate application, rather than define an operational strategy. Distributary canals would normally be running continuously.

The Pugal branch canal has a length of 66 km and irrigates an area of 49 394 ha. It has a capacity of 20.4 $m^3 s^{-1}$. A schematic of the branch canal system is shown in Figure 14. Only the branch and distributary canals have been modelled. Characteristics of the distributary canals are presented in Table IV. Physical characteristics for the system have been obtained from reports prepared by Mott MacDonald (1998, 1999).

Modelling has been carried out on the distributary canals fed directly from the Pugal branch canal. Each of these is in effect treated as a scheme. The objective has been to determine an appropriate rotational schedule for operation of these canals. There are 15 canals fed directly from the Pugal branch canal. The canals would normally be operated in groups such that the capacity of the groups closely matched the (capacity) discharge of the branch canal. The GA can optimize the starting time for each canal and form its own groups. In the Pugal branch canal, the sum of the capacities of the distributaries is almost equal to the capacity of the branch canal. If the branch canal were running full, grouping and rotation between distributaries would not be required. However, the condition investigated for this paper is one of water stress in which the Pugal branch canal is not running full.

For the purposes of this application, it has been assumed that cotton is grown in all scheme areas. Soil characteristics, crop characteristics and potential evapotranspiration data have been taken from Mott MacDonald (1999). The model was set up to operate with the branch canal running at full capacity, and at 75 and 50% of full capacity. Under each of these conditions, it was assumed that the distributaries had always to run at their full capacity when in operation.

The GA was set up with a daily time step, resulting in a total chromosome length of 2925 for 15 schemes and 195 time steps. This chromosome length is significantly longer than in any of the test networks considered.

Table IV. Canals characteristics in the Pugal system

Canal no.	Canal name	CCA (ha)	Design discharge ($m^3 s^{-1}$)	Losses per irrigation (mm)
1	Sidhuwala Minor (Upper)	892	0.344	1.160
2	Sidhuwala Minor (Lower 1)	126	0.049	0.401
3	Sidhuwala Minor (Lower 2)	184	0.072	0.219
4	Kakrala Minor	1684	0.676	3.778
5	Lunkha distributary	5050	2.014	8.429
6	Dandikokery distributary	3270	1.272	4.850
7	Panchkot distributary	5584	2.265	6.621
8	Ballar distributary	12 720	5.249	14.737
9	Alladin ka bera Minor	685	0.328	1.373
10	Siyasar Minor	2286	0.897	3.597
11	Nawagoan Minor	378	0.148	1.714
12	Matwania Minor	565	0.224	2.025
13	Bagewala Minor	967	0.395	1.282
14	Kherulla distributary	5390	2.236	11.739
15	Dattanwala distributary	5123	2.018	6.546

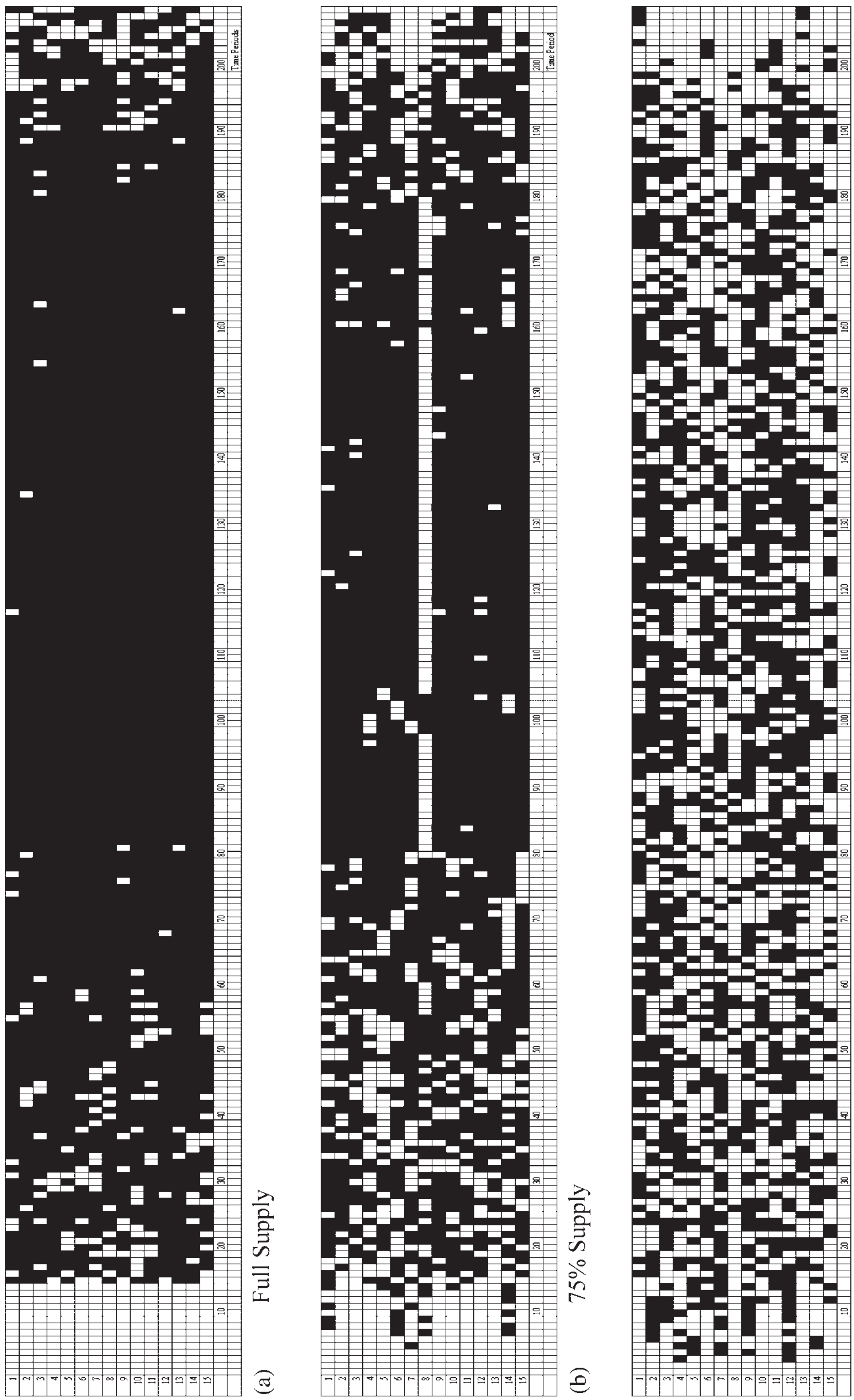

Figure 15. Schedules for disbributaries from the Pugal branch

A population size of 100 was chosen for all runs, and a crossover probability of 0.9 used. The number of mutations per chromosome was set to 0.09. The irrigation schedules produced by the 0–1 approach are presented in Figure 15. It should be noted that water stress exists in the system even under full supply. At full supply, all distributary canals can run simultaneously, and rotation is only required at minor and sub-minor canal level. When branch canal discharges are reduced, the GA then has to schedule distributaries, generally trying to minimize the number of diversion operations. Of particular note from Figure 15 is the fact that distributary number 8 suffers particularly badly in water stress conditions. The reason for this is that significant losses are associated with opening and closing this canal, as can be seen from Table IV. These high losses force the GA to supply where losses are smaller. This is the largest distributary in the system and it will be noted from Table IV that losses amount to 14.7 mm per irrigation. The next worst distributary is number 14.

The schedules produced by the GA and presented in Figures 15(b) and (c) are for extreme water stress conditions. Under these conditions a number of factors other than those incorporated in the GA would be taken into account in developing schedules (e.g. reducing the irrigated areas). The results do, however, demonstrate that the GA approach with a coupled canal and soil moisture optimization is capable of producing irrigation schedules in a robust manner, and would be a useful decision support tool.

CONCLUSIONS

It has been demonstrated that a GA can provide a robust approach to irrigation scheduling problems, and suitable formulations have been presented. The objective function and constraints can be expressed in very simple terms. The GA approach can be coupled with a deterministic simulation of field water balances to permit soil moisture to be a major influence on the schedules produced. A binary representation of canal water diversion periods has been found to provide the most appropriate decision variables for the problem. This has been termed the 0–1 approach and is in some respects similar to a ZERO–1 approach used with LP by Reddy *et al.* (1999). Other formulations are possible, including a Warabandi approach and a running time approach in which water diversion and non-diversion periods for particular canals can vary during the growing season. The 0–1 approach provides more efficient and equitable water use than the Warabandi approach. A running time approach is an improvement on the Warabandi approach in which the lengths of diversion and non-diversion periods are defined for each irrigation. An upper bound can be put on the number of irrigations permitted in a season and there would be two decision variables per irrigation per scheme—a non-diversion time before each irrigation, followed by the length of each irrigation. This approach should be the subject of further research and is expected to result in shorter chromosome lengths and more rapid execution.

It has been demonstrated that scheduling to a level below secondary canals can be achieved, although water allocation becomes less equitable as the number of schemes is increased and chromosomes become longer.

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