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USE OF THE GENETIC ALGORITHM FOR THE OPTIMAL OPERATION OF MULTI-RESERVOIRS ON DEMAND IRRIGATION SYSTEM

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SUMMARY- This study presents the application of a Genetic Algorithm (GA) model developed for computation of the optimal supply hydrographs in on demand irrigation systems aimed at the optimal regulation of the upstream storage reservoirs.

The model was applied to an Italian irrigation scheme where the optimal inflows to five reservoirs were computed. The obtained result is characterised by two inflow values. In addition, the maximum discharge supplied by the upstream dam was reduced by 10.65 %, and the maximum violation of reservoirs water levels was reduced to acceptable values.

The optimal solution guarantees to satisfy the daily demand requirements, to minimize the maximum discharge delivered by the upstream dam, and to avoid the reservoirs emptiness. In addition, the on-demand delivery schedule according to the actual demand hydrograph recorded downstream the reservoirs may be applied also during the peak period.

Key words: Optimisation, Genetic Algorithm, Reservoir Regulation, On-demand irrigation.

RESUME- *Cette étude présente l'application d'un Algorithme Génétique (AG) développé pour le calcul des hydrogrammes d'approvisionnement optimaux dans les systèmes d'irrigation à la demande visé pour la régulation optimale des réservoirs de stockage.*

Le modèle a été appliqué pour un réseau d'irrigation italien où les apports optimaux à cinq réservoirs ont été calculés. Le résultat obtenu est caractérisé par deux valeurs d'apports. En addition, le débit maximal fourni par le barrage en amont a été réduit par 10.65 %, et les violations maximales des niveaux d'eau de réservoirs ont été réduites à des valeurs acceptables.

La solution optimale garantit de satisfaire les besoins journaliers, de minimiser le débit maximal de barrage en amont et d'éviter la vidange des réservoirs. En outre, la livraison à la demande selon l'hydrogramme de la demande actuelle enregistrée en aval des réservoirs peut-être également appliqués pendant la période de pointe.

Mots-clés *: Optimisation, Algorithme Génétique, Régulation de Réservoir, Irrigation à la demande.*

INTRODUCTION

On demand pressurised irrigation systems played an important role in the distribution scarce water resources to farmers. They offer a considerable potential for efficient water use, reduce disputes among farmers and lessen the environmental problems that may arise from the misuse of irrigation water. Nevertheless, often, change in cropping pattern respect to the design stage, along with change in climatic conditions and farmer's behaviour, makes, during the peak period, the water volume stored into the upstream reservoirs not enough to compensate water withdrawals. As a result, the reservoir risk to be empty and air enters into the pressurised conduits. It causes unsteady flow conditions damaging the pipe network. In order to prevent such a phenomena managers often are obliged to modify the on demand delivery schedule into different types of arranged demand (i.e: closing 50% of the network for 3 days, alternatively) (Lamaddalena *et al*, 1995).

Several techniques have been developed for identifying operational rules able to prevent reservoirs emptiness during the peak period, without penalizing the on-demand delivery schedule, like Non-Linear programming, Dinamic programming, … (Lebdi, 1996).

Nevertheless, solution with deterministic methods for non-linear optimisation problems may be difficulties in relation to the number of variables and the type of parameters (Hrstka and Kucerova, 2004).

Heuristic approach have been recently developed in order to overcome these difficulties.Genetic Algorithms (GA) are categorized as global search heuristics, using techniques inspired by evolutionary biology such as selection, crossover and mutation. Such approaches are appropriate for solving complex non-linear problems (Hrstka and Kucerova, 2004).

Many applications of the GA approach are available in literature for the optimization on hydraulic networks (Liong and Atiquzzaman, 2004; Morley et al.. 2001; Savic and Walters, 1997; Schaetzen and Al, 2000; Van Vuuren, 2002).

Nouiri and Lebdi (2005) used the approach of genetic algorithms for computing the optimal discharge into potable distribution network.

In the present paper, a complex multi-reservoir on demand irrigation system was analysed by using the Genetic Algorithm and possible operational rules were identified in order to prevent reservoirs emptiness during the peak period, without penalizing the on-demand operation. Optimal reservoirs upstream inflows were computed allowing to satisfy the farmers daily needs, to minimise discharge delivery at the upstream dam, and to avoid the reservoirs emptiness for the whole peak period.

FORMULATION OF THE PROBLEM

For an irrigation system composed by R reservoirs (Fig. 1), the optimal hourly reservoir inflow, Qa(r, t), for each reservoir, r, at all the steps, t, for an operation period, Tmax, has to be identified. The main objective function is the minimization of the total discharge delivered at the upstream dam; the boundary conditions are expressed by the minimum and maximum water levels into each reservoir (Nouiri et al, 2005).

Therefore, the objective function of the problem is expressed by the following equation:

$$\text{Minimise } [\text{Max } Q_T(R, t)] \qquad t = \Delta t, \ldots, T_{max} \tag{1}$$

Where: $Q_T(R, t)$ is the total discharge delivered at the upstream dam for supplying R reservoirs, at time t. Δt is the simulation time step.

The total upstream discharge at time t is given by the equation:

$$Q_T(R,t) = \sum_{r=1}^{R} Q_a(r,t) \qquad r = 1,\ldots, R \tag{2}$$

Where Qa(r, t) is the inflow to the reservoir r at time t.

Knowing the discharge withdrawn by farmers downstream each reservoir r at time t, Qd(r, t), and the inflow discharge, Qa(r, t), to the reservoirs r at time t, the water level, h(r, t) into the reservoir r at time t is:

$$h(r,t) = h(r,t-\Delta t) + \frac{(Q_a(r,t) - Q_d(r,t))}{S(r)} \qquad r = 1,\ldots, R \text{ et } t = \Delta t, \ldots, T_{max} \tag{3}$$

Where "S(r)" is the section of reservoir r (Fig. 2).

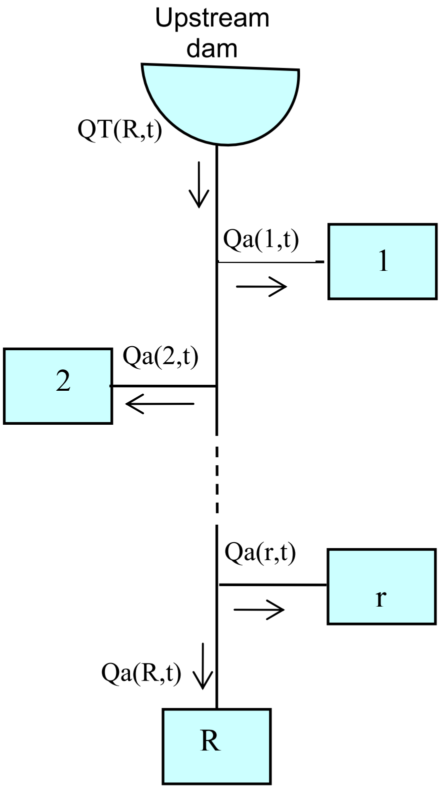


Fig. 1. Scheme of a multi-reservoir irrigation system

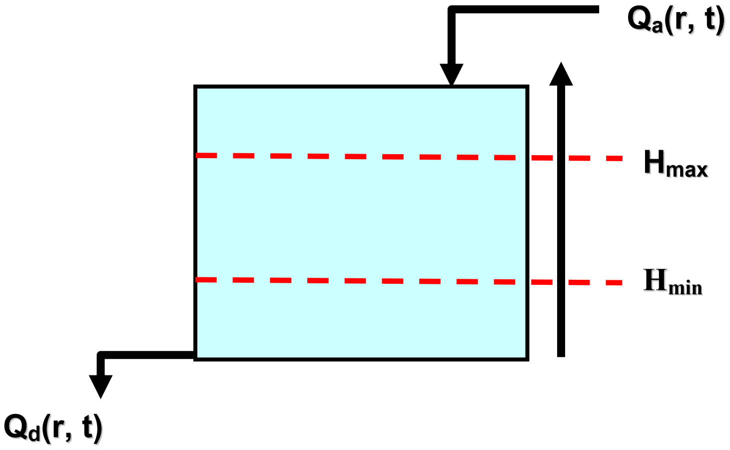


Fig. 2. Scheme of the reservoir

The water level into each reservoir, r, must be maintained between the two limiting values Hmin and Hmax. Moreover, at the beginning of each distribution's cycle, t=0, the initial water level must be known. These constraints are expressed by the equations:

$$H_{min}(r) \leq h(r,t) \leq H_{max}(r) \qquad \text{for} \quad t = \Delta t, \ldots, T_{max} \tag{4}$$

$$h(r,0) = H_o(r) = Hmax \tag{5}$$

Where Ho(r) is the water level in the reservoir r at time t=0,assumed to be $H_o(r)$ =Hmax; Hmax(r) and Hmin(r) are, respectably the maximum and the minimum water levels acceptable for the reservoir r. Reservoirs are considered to be full also at the end of each distribution cycle, for t = Tmax.

The above conditions allow to face the peak demand with the maximum water stock. This objective is expressed by the following equation:

$$h(r, T_{max}) = h_f (r) \tag{6}$$

Where hf (r) is the water target level into the reservoir r at time t = Tmax,

The violations of the acceptable limits, for each reservoir r, are:

$$\text{If } (h(r, t) < H_{min} (r)) \text{ then Violation } H_{min}(r, t) = H_{min} (r) - h(r, t) \tag{7}$$

$$\text{If } h(r, t) > H_{max} (r)) \text{ then Violation } H_{max}(r, t) = h(r, t) - H_{max} (r) \tag{8}$$

$$\text{If } (t = T_{max}) \text{ then } \Delta H_f(r, T_{max}) = \left| h(r, T_{max}) - h_f (r) \right| \tag{9}$$

Where, for each reservoir r at time t, Violation Hmin(r, t) is the violation of acceptable minimum water level, Violation Hmax(r, t) is the violation of the acceptable maximum water level, and $\Delta H_f (r, T_{max})$ is the variation of the water level at the end of the cycle of distribution, compared to the final target level, Hf(r).

THE OPTIMISATION MODEL

The weighted sum method was selected to build a composite single objective by joining the principal objective function, the violations of the acceptable limits of water level and the variations of the water levels compared to the target values.

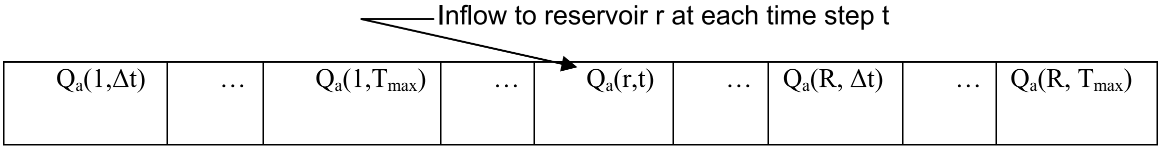
The solution of the above formulated problem is given by using the genetic algorithm (GA) approach. The GA is inspired to the genetic mechanisms (Goldberg, 1991). It starts by randomly generating the solutions. For each one of them, the maximum flow, the violations of the acceptable limits and the variations of the water levels compared to the target level, are computed. Than, the performance of each solution is evaluated. On the basis of such a performance, an iterative process of selection, crossing, mutation and elitism intervenes to generate a new population (Dreo et al, 2003). At each iteration, an evaluation of all the solutions is carried out. The iterative process is stopped when the maximum performance of all solutions is stabilised.

The application of the above approach requires the knowledge of the physical characteristics of the irrigation system (sources, pipes length and diameters, reservoirs dimensions, topography) and of the demand hydrograph (Qd(t)) downstream each reservoir. Moreover, the initial, the boundary conditions and the simulation period have to be imposed.

The optimisation algorithm for the computation of the reservoir's inflows is described as follow:

- Step 1: Creation of the initial population (P = 0) of "Tpop" solutions.

In this application, it was adopted a real coding of the variables. Each solution is a chain of real bits representing the reservoir's inflow per hours. Figure 3 represents the form of a solution to this problem:



$Q_a(1,\Delta t)$	…	$Q_a(1,T_{max})$	…	$Q_a(r,t)$	…	$Q_a(R, \Delta t)$	…	$Q_a(R, T_{max})$

Fig. 3. Structure of the simulated solution

The value of each solution is calculated by the following equation:

$$Qa(r, t) = RND \times Qamax(r) \qquad \text{for } r = 1..., R \text{ ; and } t = \Delta t..., Tmax \qquad (10)$$

Where RND is a generator of random real numbers between 0 and 1; Qamax(r) is the acceptable maximum reservoir’s inflow (usually imposed by the design conditions).

- Step 2: Evaluation of the solution performance:

The best solution is the one which presents the maximum performance. In this optimisation problem, the minimization of the maximum flow, the violations of the maximum and minimum water level and the variations compared to the target values are computed. Thus, the initial objective function to minimise the maximum discharge delivered at the upstream dam, is transformed into a new objective function to maximise the performance of the potential solution (i.e: Fitness).

The performance (Fitness) of each potential solution, j, is expressed by:

$$\text{Fitness}(j) = p_1 \times F_{Qa}(j) + p_2 \times F_{1/H}(j) + p_3 \times F_{Hf}(j) \qquad (11)$$

Where "$F_{Qa(j)}$" is related to the minimization of the maximum flow at the level of water source corresponding to the solution "j"; "$F_{1/H(j)}$" is related to the minimization of the acceptable violations water level; "$F_{Hf(j)}$" the function of minimization of the variations compared to the target water level and p1, p2, p3 are their respective weights. The last functions are expressed by the following equations:

$$F_{Qa}(j) = \frac{1}{(a + \frac{Q_{Max}(j)}{QST})} \qquad (12)$$

$$F_{Hf}(j) = \frac{1}{(b + (\sum_{R} \Delta H_f(j))^2)} \qquad (13)$$

$$F_{VH}(j) = \frac{1}{(c + (Max[ViolationH\min(j)] + Max[ViolationH\max(j)])^2)} \qquad (14)$$

Where: a, b and c are positive constants, QMax(j) is the maximum flow of the solution "j" and QST is the maximum flow at the upstream dam.

- Step 3: The evolution: is ensured by four genetic operators (Dréo and Al, 2003):
  - The selection of the solutions, which will take part in the creation of a new solutions: For this model, it was used the technique of tournament selection, between two individuals. It ensures an acceptable pressure and guarantees against the premature convergence of the algorithm.
  - The crossing: Considering the real coding of the variables, it was used the arithmetic technique of crossing between two solutions selected for the reproduction. This technique has the advantage of creating values of the variables that did not exist in the individuals of the initial population. The crossing is generally applied with a probability ranging between 50 and 100 %.
  - The mutation: To support a random research, it operates by the random change of the bit value chosen by chance, at the level of the population solutions in the course of creation, chosen also randomly. This operator is generally applied with a probability from 1 to 10 %.

  - Elitism: To guarantee the convergence of the algorithm, a procedure of elitism ensures the selection of the best solutions of each population and transmits them in the following population without modification. In this model, it was decided to select only one elite solution.

- Step 4: To increment (P = P + 1) and to reiterate since *Step 2* until the stagnation of the maximum performance of the population or when the maximum number of populations is reached.

PRESENTATION OF THE CASE STUDY

The study referred in the present work was carried out on the Sinistra Ofanto irrigation scheme (Fig. 4).

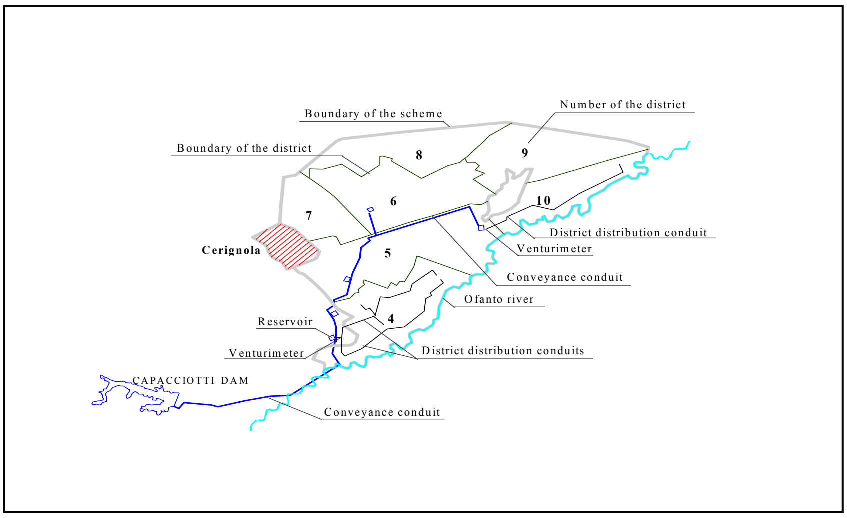


Fig. 4. The Sinistra Ofanto irrigation scheme

It covers an area of around 22 500 ha, in the province of Foggia (Souther Italy). It is divided into 7 districts (numbered from 4 to 10), each one subdivided into sectors having areas ranging between 20 ha and 300 ha. The districts are supplied by upstream storage reservoirs, filled by a conveyance conduit starting from the upstream Capacciotti dam. Each district network is pressurised and designed for on demand operation. It is managed by the Consortium of Capitanata..

Very often, during the peak period, because of an increase of the farmers demand respect to the design conditions, the reservoirs become empty and manager, to prevent air entering into the prep networks, modify the on-demand delivery schedule into restricted frequency irrigation, by the closing 50% of the sectors for 3 days alternatively. This new management rule implies more people working in the field for the organization of the rotation and not necessarily produces a reduction in water consumption. Therefore, the above illustrated GA was applied in order to identify alternative operational rules aimed to overcome the problem.

Current State of reservoirs

To control the buffer function of the reservoirs, an analysis was carried out through a deterministic model allowing to calculate the reservoirs water level in the time, by respecting the hydraulic constraints and the physical characteristics of the reservoirs.

The farmers' demand hydrograph and the inflow discharge were recorded respectively upstream and downstream each reservoir, during the 10-day peak period. Such discharges are reported in Figure 5, as observed during the year 1998 for the reservoir R1 serving the District 4.

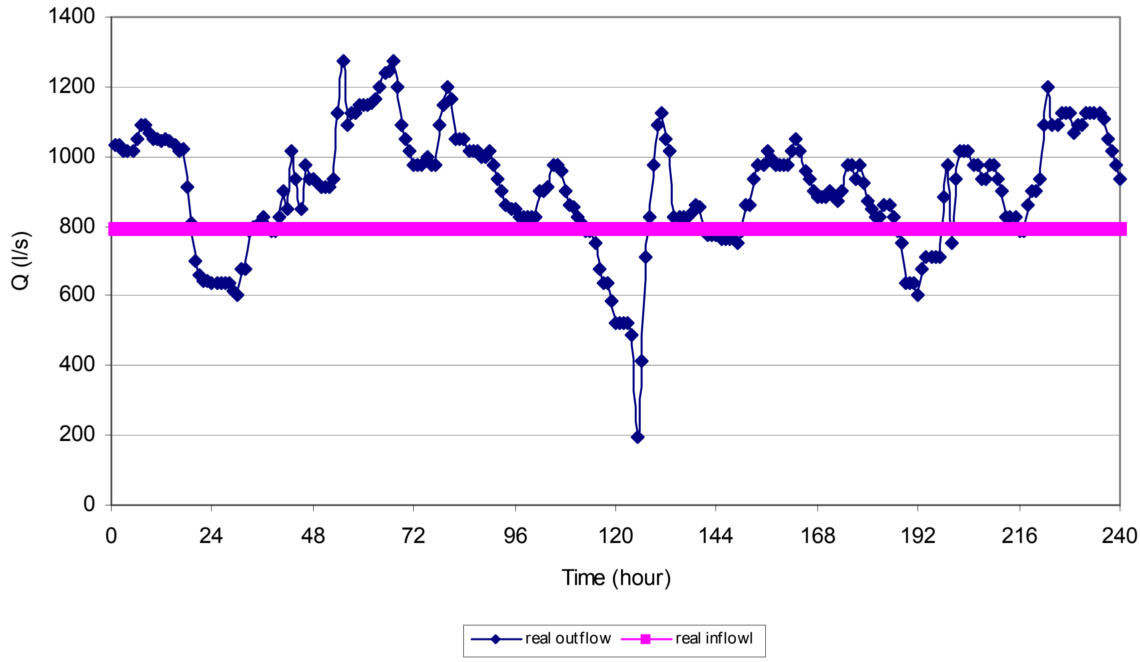


Fig. 5. Reservoir's inflow and outflow, example of the reservoir R1

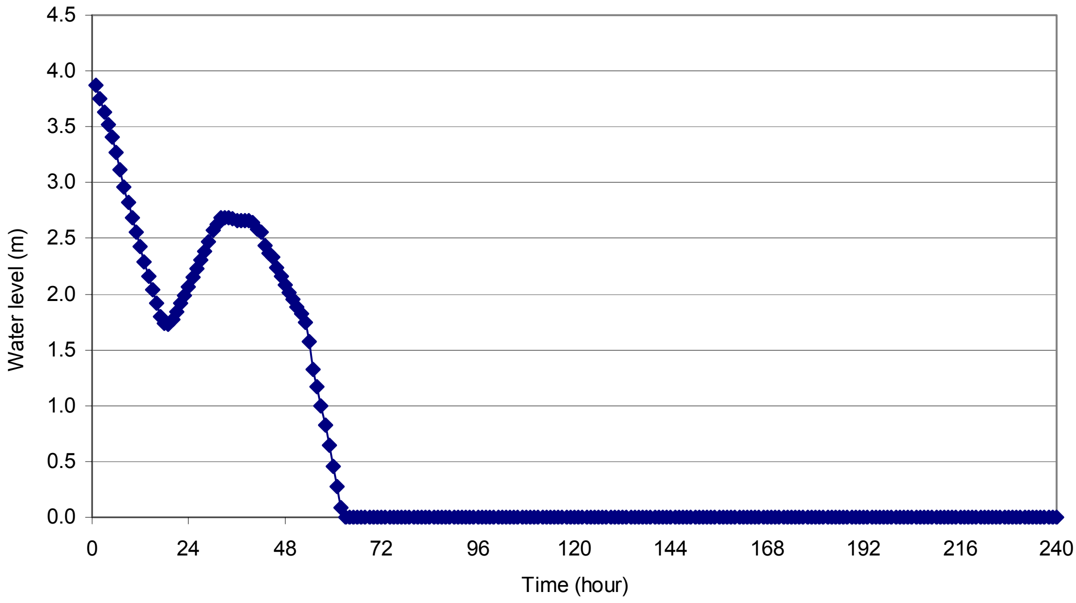


Fig. 6. Simulated water level into the reservoir R1

According to the above hydrographs, from Figure 6, it can be observed that under the actual conditions, during the peak period, the minimum water level in the reservoir R1 attains zero after only two days operation. This is confirmed by field observations.

At that time, the managers modify the on-demand delivery schedule to arrange demand by rotating 50% of the sectors alternatively every 3 days.

To overcome this problem, the genetic algorithm was applied in order to identify the optimal inflow discharge able to satisfy the recorded demand hydrograph and to avoid reservoir emptiness.

Application of the model

The application of the present methodology requires the knowledge of the genetic parameters like the size of the population, the number of generations and the probabilities of crossing and mutation.

Four scenarios of constant inflows (6, 8, 12 and 24 hours) were simulated.

The results of optimizations, for each scenario, are presented in *Table 1*.

Table 1 - Performances of the optimised regulation scenarios

Inflow's hours	**Stage Numbers**	**Q_{max} (l/s)**	**Violation Max H_{min}(m)**	**Violation Max H_{max}(m)**	**$\sum\Delta Hf$(m)**	**Fitness max**
6	4	4529.6	0.00	1.75	0.09	0.133
8	3	4845.4	0.00	1.375	2.24	0.129
12	**2**	**5224.7**	**0.79**	**0.57**	**0.09**	**0.163**
24	1	80.3	6.78	0	48.22	0.076

The maximum discharge delivered by the dam is not too different between the stages 2, 3 and 4 but the fitness is higher in the case of stage number 2. In addition, for such a stage the reservoir's inflow minimizes the maximum violations and the maximum variation of the water level at the end of the distribution's cycle.

In Figure 7, the recorded hourly demand hydrograph and the simulated inflow discharge are presented, as obtained in the stage number 2.

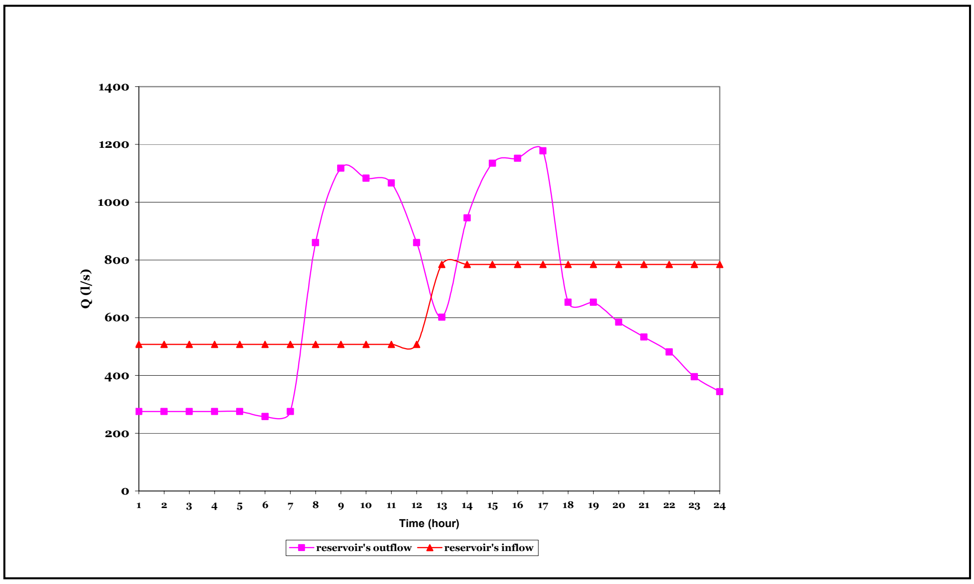


Fig. 7. Hydrograph of simulated hourly inflow and recorded outflow (case of R1)

With the above-obtained optimal solution, the water level in the reservoir never attains zero, as shown in Figure 8 where the simulation of one month operation is presented for the reservoir R1.

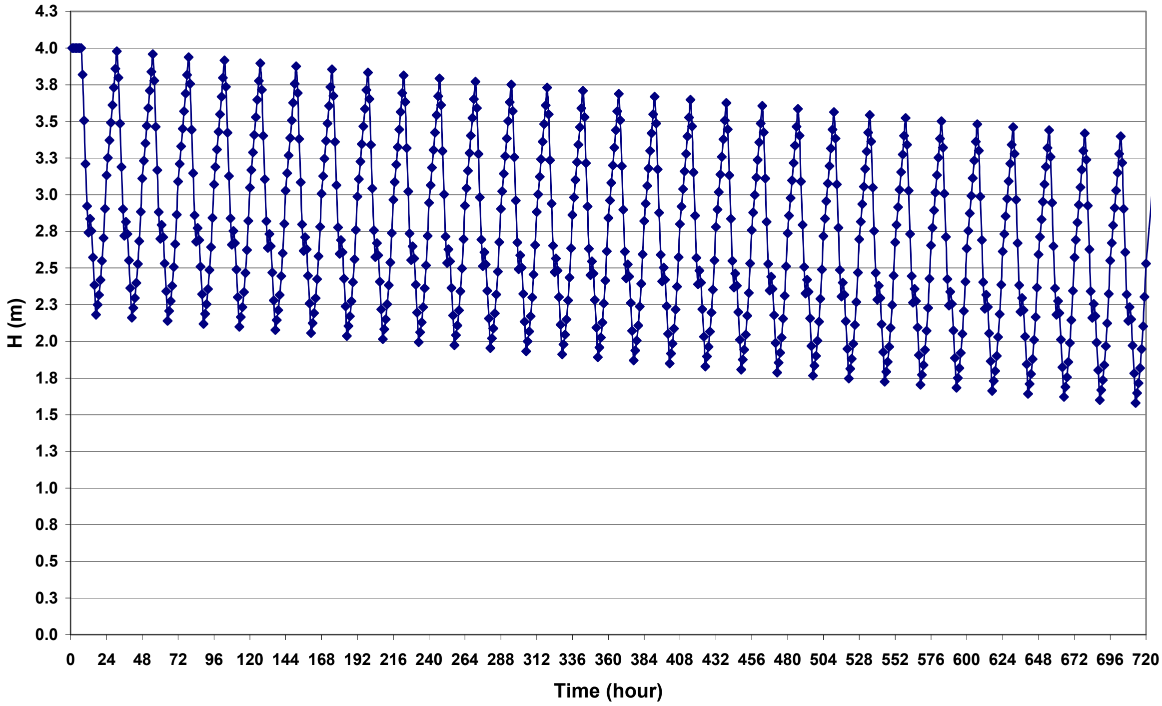


Fig. 8. Variation of the water level into the reservoir R1 during one-month peak period.

CONCLUSIONS

In this work the Genetic Algorithm (GA) approach was applied to compute the optimal reservoir's regulation in an on-demand irrigation system. The Sinistra Ofanto irrigation scheme was analyzed. The objective to minimize the peak discharge delivered at the upstream dam was imposed, while satisfying the farmers demand and respecting the boundary conditions of the storage reservoirs.

After the simulation, it is observed that, during the peak period, the Capacciotti dam delivers an actual daily discharge of 21053 m3/h. In fact, the optimal solution gives a constant discharge of 18809 m3/h. Therefore, a reduction of 2244 m3/h, corresponding to 10.65 %, was obtained.

It was observed that the inflow discharge and the water volume stored into the upstream reservoirs did not satisfy the recorded demand hydrograph. As a direct consequence, the reservoirs become empty after 2-days operation, air enters into the pipes network and dangerous transitory regimes occur into the conduits. The managers try to solve this situation, by changing the delivery schedule from on-demand to restricted frequency demand by closing 50% of the sectors for 3 days, alternatively.

As observed by Lamaddalena (1995), during the on demand operation, farmers tend to irrigate when they need and according to their practices (Fig. 9). Whereas, when a restricted frequency demand is imposed, the daily withdrawal indicates abnormal use of water by farmer mainly due to uncertainty in water availability.

Thus operation under restricted frequency demand does not necessarily induce water savings but rather an increase in the water demand. Over irrigation is likely to occur during those periods (Fig. 10) as all farmers tend to irrigate simultaneously when their sector is in charge.

Discharge (l /s)

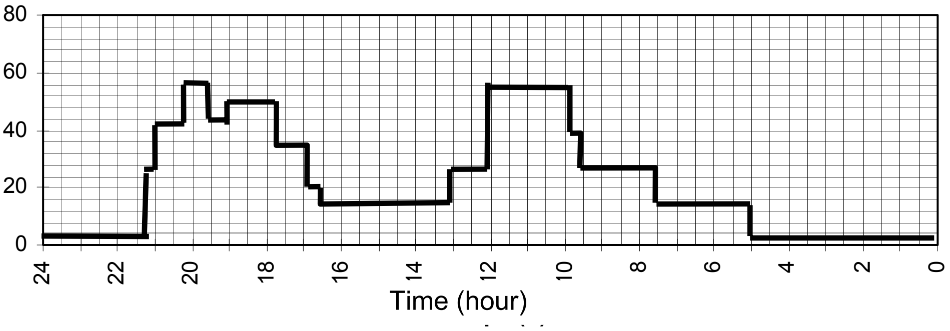


Fig. 9. Example of the discharge hydrograph at the upstream end of an irrigation sector during on-demand operation

Discharge (l /s)

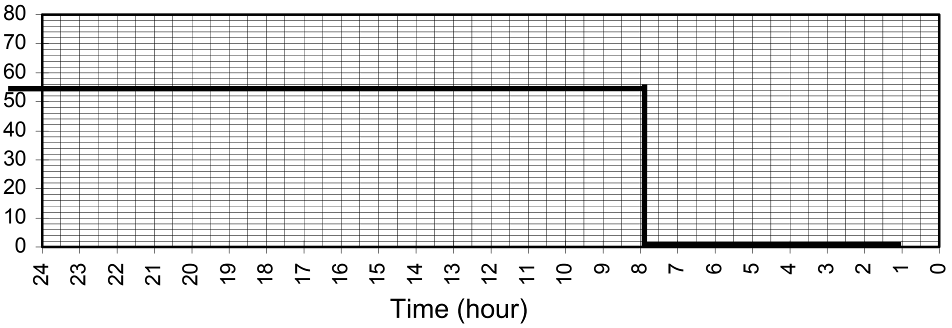


Fig. 10. Example of the discharge hydrograph at the upstream end of an irrigation sector during restricted frequency operation

The genetic algorithm applied in the present paper generated the optimal reservoir's inflow. Indeed, the reservoirs are never emptied, and the farmers demand and boundary conditions of the reservoirs are always respected. Therefore, this methodology indicates to managers alternative solutions able to satisfy farmers needs and avoid changing the on-demand delivery schedule.

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