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Abstract. Operation of a daily compensation reservoir in on-demand irrigation systems depends mainly on the geometric characteristics (depth and reservoir surface area), the downstream demand and the upstream supply. This paper presents a stochastic methodology based on real coded genetic algorithms aiming at generating the optimal supply hydrograph able to satisfy the network demand and taking into account the volume of the storage reservoir. An executable computer program was developed on C++ language. The model was applied and tested on one reservoir of the *Sinistra Ofanto* irrigation scheme (Italy) facing the risk of emptying during peak periods. Results demonstrated that it is possible to find solutions overcoming this risk where two theoretical alternatives were proposed based on the results of the simulations.

Keywords. Reservoir's operation – On-demand irrigation system – Genetic algorithm.

Analyse du fonctionnement d'un réservoir dans les systèmes d'irrigation à la demande

Résumé. *Le fonctionnement d'un réservoir de régulation journalière dans les systèmes d'irrigation à la demande dépend principalement de ses caractéristiques géométriques (profondeur et surface d'occupation), de l'offre et de la demande en eau. Ce papier présente une méthode stochastique basée sur le principe des algorithmes génétiques pour la détermination de l'hydrographe d'alimentation du réservoir afin de satisfaire la demande en eau du réseau. Pour atteindre cet objectif, un fichier exécutable a été développé sur C++. Le modèle a été appliqué et testé sur un réservoir du périmètre irrigué de la Sinistra Ofanto (Italie) qui présente un risque de vidange durant les périodes de pointe. Deux alternatives, qui ont prouvé leur efficacité, on été proposées pour résoudre le problème.*

Mots-clés. *Fonctionnement du réservoir – Système d'irrigation à la demande – Algorithme génétique.*

I – Introduction

The optimal balance between inflow and outflow at a given compensation reservoir in on demand irrigation system is a crucial issue for ensuring good system's operation.

Severe climatic conditions, high crop water requirements (changes in crop pattern and/or growth stage) and farmers' behavior are inter-correlated components and may induce risk of emptying the reservoir especially during peak periods. When such a condition is verified, air entering into the pressurized network may cause unsteady flow and consequently damages the pipes. To prevent such a problem, managers are often induced to modify the on-demand delivery schedule into arranged demand by rotating part of the network alternatively for few days. Such a modification causes all the farmers to irrigate simultaneously when their sector receives water. As a result, this practice does not necessarily provide for water saving but, in certain conditions, it can even increase farmers' withdrawals (Lamaddalena *et al.,* 1995). It is thus important to make diagnostic analysis for the reservoir's operation and review the water balance between inflow and outflow at the reservoir level.

The developed methodology is based on a stochastic approach using the genetic algorithms. In fact, the Genetic Algorithm approach is successfully used for the identification of the optimal solution in many hydraulic problems especially in the design of water distribution systems (Shin and Park, 2000; Tolson *et al.,* 2004; Nouiri *et al.,* 2005; Reca and Martinez, 2006; Elferchichi,

2007). For basic understanding and full description of the genetic algorithms approach, it is possible to refer to Goldberg (1989), Dréo *et al.,* (2003).

To reach the above-said objective, a weighting objective function, including violations of the admissible reservoir water levels (maximum, minimum and target reservoir water level) was proposed and an executable computer program was developed.

The approach was applied to the reservoir (R.1) of the district number 4 in the *Sinistra Ofanto* irrigation scheme (Italy).

II – Modeling approach

This work aims to verify if the supply system {maximum inflow discharge and reservoir storage capacity} is able to satisfy the downstream demand of a given reservoir (R). The hydraulic variables of the model are reported in Figure 1.
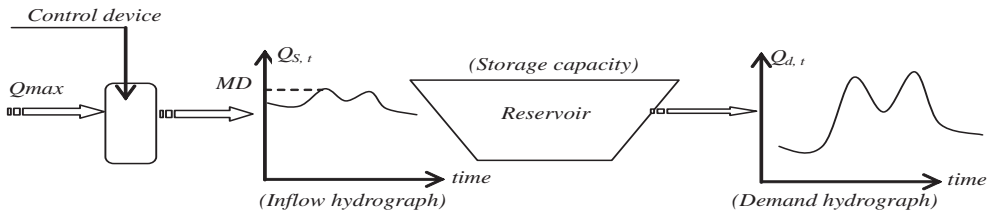

Figure 1. The hydraulic variables of the model.

Where: Q_{max} is the maximum discharge allocated to the reservoir (from design and/or current data) and MD is a fraction of Q_{max}, which represents the maximum value of the inflow hydrograph that guarantees the reservoir's regulation. MD is always less than or equal to Q_{max}.

1. Mathematical formulations

A. The objective function

The adequate inflow hydrograph is achieved by minimizing the violation of a fixed minimum level (H_{min}), a fixed maximum level (H_{max}), and a fixed target level (HT) into the reservoir.

Minimizing such a violation corresponds to maximizing the relative functions as written below:

$$F_1 = \frac{1}{1 + MV(H_{max})}$$

$$F_2 = \frac{1}{1 + MV(H_{min})}$$

$$F_3 = \frac{1}{1 + V(HT)}$$

Where $MV(H_{max})$ is the maximum violation of a fixed H_{max}; $MV(H_{min})$ is the maximum violation of a fixed H_{min}, and $V(HT)$ is the maximum violation of a fixed HT. Violations of the admissible water levels in the reservoir are:

$$V(H_{max}) = h(t) - H_{max} \qquad \text{if} \qquad h(t) \geq H_{max}$$

$$V(H_{min}) = H_{min} - h(t) \qquad \text{if} \qquad h(t) \leq H_{min}$$

$$V(HT) = |HT - h(t)| \qquad \text{for} \qquad t = T$$

Where $V(H_{max})$ is the violation of the maximum water level; $V(H_{min})$ is the violation of the minimum water level and $V(HT)$ is the violation of the target water level.

The following objective function "F" was used for solving the problem:

$$\text{Maximize } F = W_1F_1 + W_2F_2 + W_3F_3$$

W_1, W_2 and W_3 being the weighting coefficients, whose sum is equal to 1.

Based on the maximization of this objective function, the output result is a supply hydrograph characterized by a maximum simulated discharge (MD).

B. Boundary conditions

The reservoir water balance is modeled as follow:

$$h(t + \Delta t) = h(t) + \frac{[Q_s(t + \Delta t) - Q_d(t + \Delta t)] * \Delta t}{S}$$

where Δt is the time step; h (t) is the water level at time ; h (t+Δt) water level at time t+Δt; Q_s (t+Δt) is the inflow discharge at time (t+Δt); Q_d (t+Δt) is the demand discharge at time (t+Δt)and S is the average reservoir surface area, assumed as

$$S = \frac{storage \quad capacity}{reservoir \quad depth}$$

Boundary conditions for such an optimization problem are:

$$h(t = 0) = Ho$$
$$h(t = T) = HT$$
$$H_{min} \leq h(t) \leq H_{max}$$

Where H_o is the initial water level; HT is the water level after a certain period of operation T, called target water level; H_{max} is the maximum reservoir water level; H_{min} is the minimum reservoir water level

The main objective is to keep the reservoir water level between the maximum and the minimum value.

2. The Genetic Algorithm approach

The Genetic Algorithm, whose name recalls the strong operational similarity with the biological behavior of living beings (Marseguerra and Zio, 2000), was formally introduced in the United States in 1975 by John Holland at the University of Michigan. It is a stochastic optimization search method that belongs to the soft computing technologies. Genetic algorithm is a particular class of evolutionary algorithms, categorized as global search heuristics. It can be applied to many complex problems that are difficult to solve using traditional techniques such as linear and non-linear programming or methods based on gradient calculations (Goldberg, 1989; Hrstka and Kucerova, 2004; Savic and Walters, 1997).

Given the extensive literature existing on the theory of the Genetic Algorithm, only few basic concepts are reported in this paper.

The possible solution of the problem is defined as a chromosome. This is subdivided into genes. A genetic algorithm starts with an initial population of random generated chromosomes with respect to the problem constraints. Then, new populations are generated and evaluated through iterative, random and probabilistic mechanisms ruled by the four fundamental operators of parent selection, crossover, replacement and mutation (Marseguerra and Zio, 2000). The iterative procedure is shown in Figure 2.
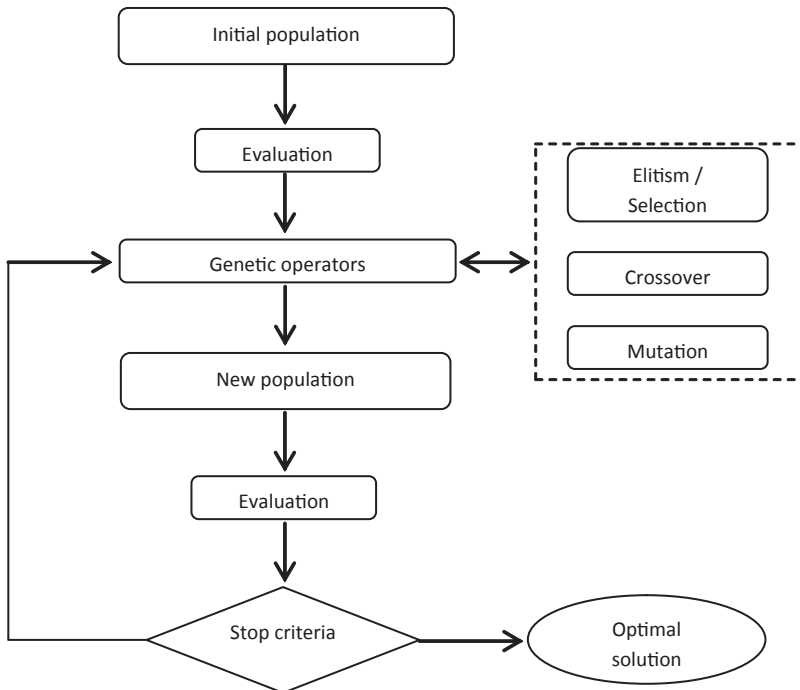
Figure 2. Principle of the Genetic Algorithms.

By using the genetic algorithm approach, the objective function is translated into a positive fitness function that measures the suitability of a chromosome and its performance to satisfy the objective of the problem to be optimized.

In this work, a real coded genetic algorithm was used. The structure of the solution for the investigated hydraulic problem is a sequence of real values of inflow discharges. Therefore, the

solution represents the hourly supply hydrograph that should guarantee the optimal reservoir operation. Each value of the inflow discharge is called gene. Thus:

Chromosome: Qs (1), Qs (2),…, Qs (i),…, Qs (T/∆t): Inflow discharges

Gene: Qs (i)

Each gene is a set of equal flows during the interval ∆t. For example, by considering a simulation for one day with a time step of 6 hours, the solution (supply hydrograph) over 24 hours is:

$$\{ Qs(1), Qs(1), Qs(1), Qs(1), Qs(1), Qs(1), Qs(2), Qs(2), Qs(2), Qs(2), Qs(2), Qs(2),$$
$$Qs(3), Qs(3), Qs(3), Qs(3), Qs(3), Qs(3), Qs(4), Qs(4), Qs(4), Qs(4), Qs(4), Qs(4) \}$$

The initial population of chromosomes (supply hydrographs) was randomly generated under the constraints of non negative values and the maximum simulated inflow discharge (MD). Each chromosome is evaluated on the basis of the value of the fitness function.

III – The case study

The reservoir (R.1) of the Sinistra Ofanto irrigation scheme (Italy) was studied. It has the following characteristics: H_{min} = 0.5 m; H_{max} = 4 m; H_o = 4 m; HF = 4 m; V = 28000 m3. The maximum allocated discharge Q_{max} (from the design) is equal to 790 ls-1.

The reservoir faces the risk of being often empty during peak periods. Consequently, managers are often induced to modify the on-demand delivery schedule into arranged demand by rotating part of the network alternatively for few days. Such a modification causes all the farmers to irrigate simultaneously when their sector receives water. As a result, this practice does not necessarily provide for water saving but, in certain conditions, it can even increase farmers' withdrawals (Lamaddalena *et al.*, 1995).

The objective was to identify an adequate inflow hydrograph that satisfies the farmers' demand and avoids emptying the reservoirs, without changing the on-demand delivery schedule. The model was tested with the 10-day peak period data collected during the year 1999, which can be considered as a typical one.

IV – Results and discussion

1. Actual situation of the reservoir R.1

Results of the above described case study are presented in figures 3 and 4. Figure 3 shows that there is no flexibility in the supply hydrograph. In fact, the reservoir is using its maximum allocated discharge (Q_{max}) starting from the second day. Nevertheless, the reservoir presents violations of the minimum admissible water level (MV(H_{min}) = 0.182 m) by the end of the sixth day, as shown in figure 4.

As a result, the supply system is not able to ensure a good operation of the distribution network starting from Tc and, consequently, managers are induced to modify the on-demand delivery schedule into arranged demand.

Two alternatives are discussed hereafter as proposals to solve the problem without modifying the on-demand delivery schedule.
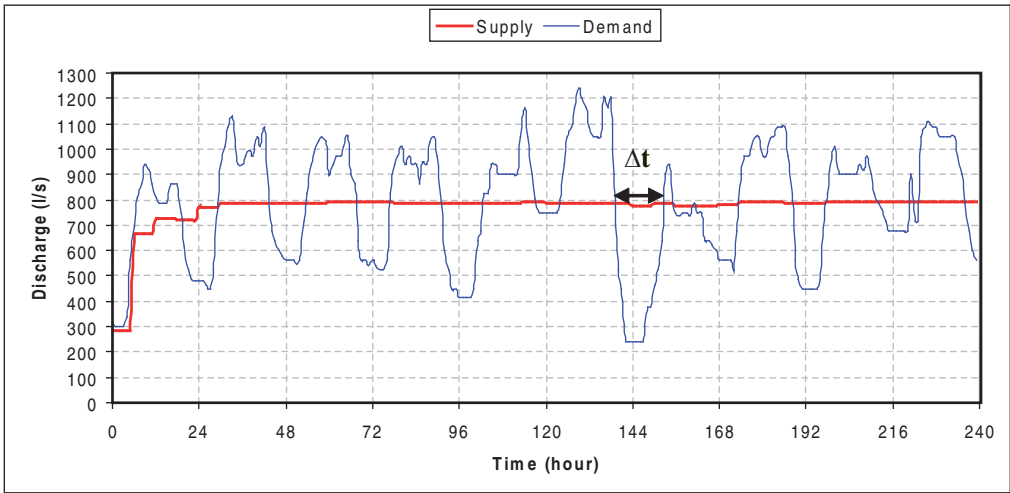
Figure 3. Supply hydrograph with respect to the recorded demand hydrograph for the 10-day peak period (the real case).
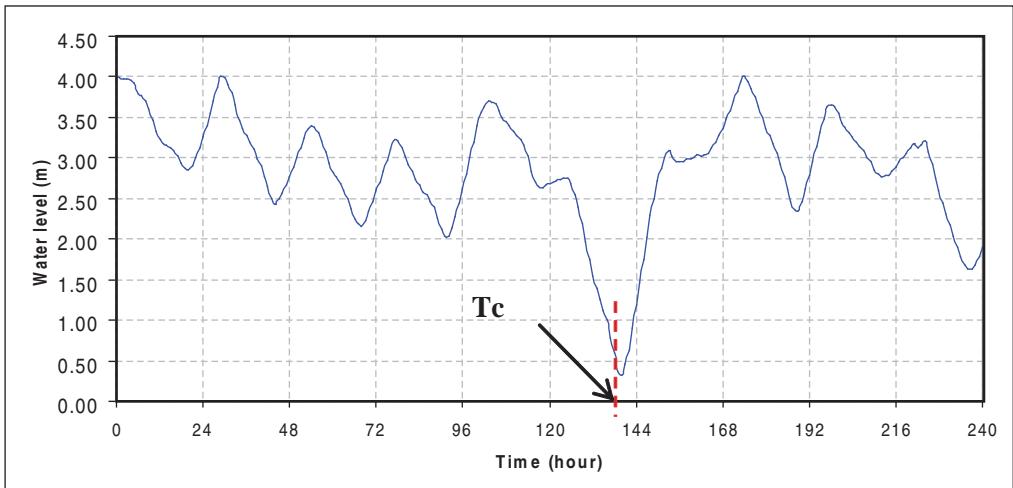

Figure 4. Reservoir water level with respect to the recorded demand hydrograph during the 10-day peak period (the real case).

2. First alternative: changing the maximum inflow discharge

The period where the risk of emptying of the reservoir occurs is represented by Δt = 15 hours in figure 3. Therefore, ΔQ calculated by the following equation should be added to the maximum allocated discharge (Q_{max}) in order to avoid emptying of the reservoir:

ΔQ (ls^{-1}) = MV(H$_{min}$)* S * 1000 / (Δt * 3600)

Then: ΔQ = (0.182 * 7000 * 1000) / (15 * 3600) = 23.6 ls^{-1} $\approx$ 24 ls^{-1}

Therefore, the maximum allocated discharge should be 814 ls^{-1} instead of 790 ls^{-1}.

The simulation with the new maximum allocated discharge is presented in figures 5 and 6.
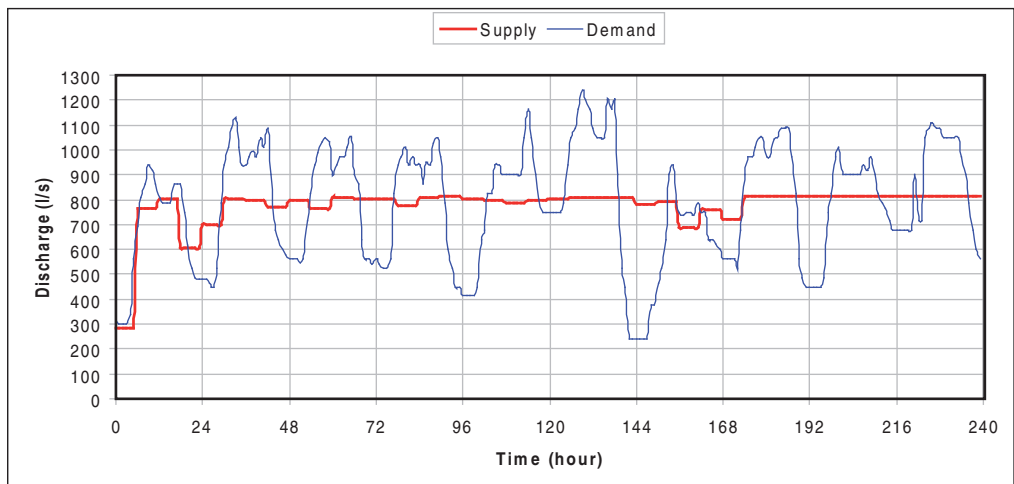
Figure 5. Supply hydrograph with respect to the recorded demand hydrograph for the 10-day peak period (first alternative).
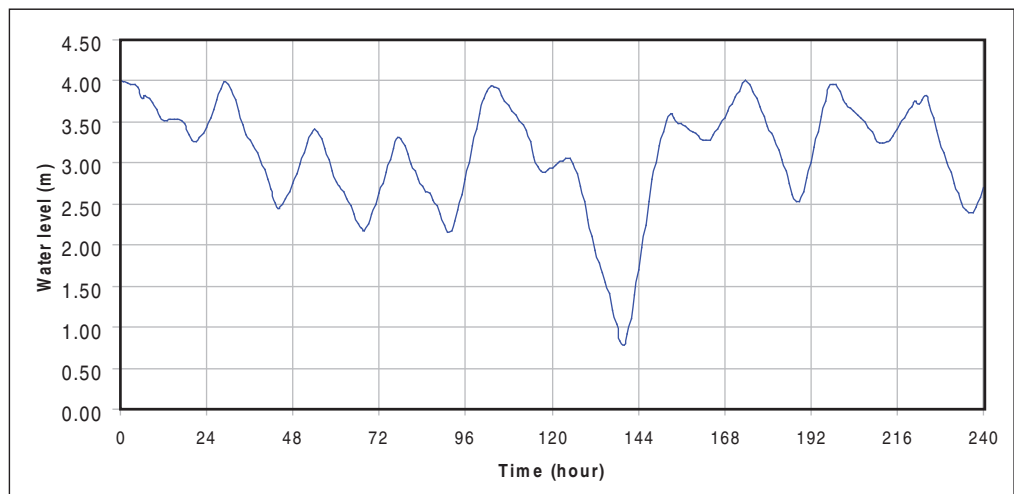

Figure 6. Reservoir water level with respect to the recorded demand hydrograph during the 10-day peak period (first alternative).

From figure 5, it can be observed more flexibility given to the supply hydrograph. No violations of the minimum and maximum admissible water levels are observed (Fig.6).

3. Second alternative: changing the storage capacity of the reservoir by increasing the maximum admissible reservoir water level

In this alternative the maximum admissible reservoir water level is $H'_{max} = 4.182$ m instead of $H_{max} = 4$ m.

Therefore, the new characteristics of the reservoir are:

- a storage capacity (SC) = 29274 m^3
- an initial water level (H$_o$) = 4.182 m
- a maximum admissible water level (H$_{max}$) = 4.182 m
- a target water level HT = 4.182 m

The simulation with these new input data shows that the flexibility of the supply hydrograph (Fig. 7) is similar to the one of figure 3. The risk of emptying of the reservoir is not observed (Fig.8).
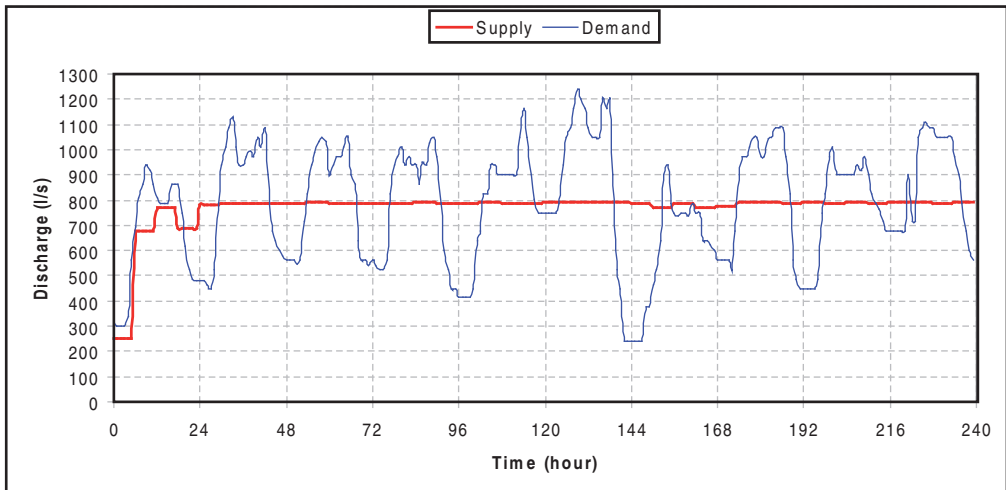

Figure 7. Supply hydrograph with respect to the recorded demand hydrograph for the 10-day peak period (second alternative).
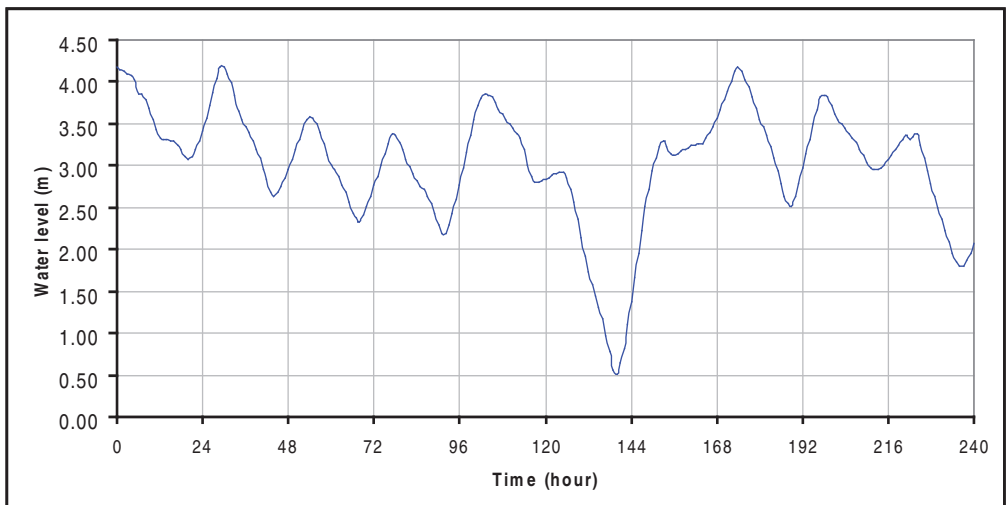

Figure 8. Reservoir water level with respect to the recorded demand hydrograph during the 10-day peak period (third alternative).

The solutions presented by the two alternatives are based on the actual recorded demand hydrograph and the maximum allocated discharge.

The results show that with some minor improvement of the upstream, the on-demand delivery schedule may be maintained without risk of emptying of the reservoir even during the peak period.

V – Conclusion

In on-demand irrigation systems, when the supply {Maximum allocated discharge, reservoir storage capacity} doesn't match the demand, emptying of the upstream reservoir is verified. Therefore it is recommended to verify and ensure the water balance between the supply system and the water demand and propose adequate solutions to reach this objective.

In this paper, the analysis of the reservoir water balance was performed using a stochastic approach based on the genetic algorithms where the output is the optimal supply hydrograph.

The case of the reservoir R.1 in the Sinistra Ofanto irrigation scheme (Italy) was studied. The result given by the model is in line with the field observations. In fact, it was demonstrated that the reservoir faces the risk of emptying during the peak period despite the use of the maximum allocated supply discharge during the whole period.

To overcome this problem, two theoretical alternatives were proposed based on the result of the simulations. No-emptying was verified by the model for the above said alternatives.

The economic feasibility of the technical proposals are not discussed in this paper and deserve an in-deep separate analysis.

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