# AN OPTIMAL FUZZY APPROACH TO AUTOMATED RESERVOIR MANAGEMENT

**Alberto Cavallo** * **Armando Di Nardo** ** **Michele Di Natale** ** **Ciro Natale** *

* *Seconda Università degli Studi di Napoli, Dipartimento di Ing. dell'Informazione, via Roma 29, 81031 Aversa, Italy*
** *Seconda Università degli Studi di Napoli, Dipartimento di Ing. Civile, via Roma 29, 81031 Aversa, Italy*

Abstract: This paper deals with water resource management problems faced from an Automatic Control point of view. The motivation for the study is the need for an automated management policy for an artificial reservoir (dam). Two problems are addressed in the article: the control of the dam gate, that is a typical control problem, and the definition of the water flow to supply to the user, that is a decision problem. In particular, a mathematical model of the reservoir is deduced, and a PID controller with fuzzy (nonlinear) gains is designed to operate the dam gate. Moreover, a hybrid model of the reservoir is considered and implemented in Stateflow/Simulink, and a second fuzzy decision mechanism is implemented in order to produce different water release strategies. A new cost functional is proposed, able to weight user's desiderata (in terms of water demand) with water waste (in terms of water spills). The parameters of the fuzzy system are optimized by employing Genetic Algorithms, which have proved very effective due to the strong nonlinearity of the problem. 

Keywords: Management Systems, Fuzzy System, Hybrid model, Genetic Algorithms, PID Fuzzy Controllers.

## 1. INTRODUCTION

Water resources management is a multiobjective problem where many different disciplines have to be involved. Often management decisions are to be based on very different considerations (political, economical, etc.) rather hard to express in mathematical terms. Generally, water volumes are stored during rainy seasons and released in dry seasons: thus, basically, a reservoir system is a water storage device. Classical approaches to optimization problems in water resources management involve the use of linear, dynamic, nonlinear or stochastic programming (see (Yeh, 1985) and references therein for a good survey on the topic). Moreover, in the last decade, a large number of papers devoted to the solution of reservoir management problems based on fuzzy logic approaches have appeared (e.g. (Russel and Campbell, 1996)), (Panigrahi and Mujumdar, 2000) and references therein). The fuzzy approach has proved to be very effective both for its "native" capability to deal with nonlinear models and for the possibility to take into account heuristic and political rules. However, after an initial "naïve" approach, fuzzy modelling has become more and more formalized: "black box" identification, optimality issues, clustering, stability proofs and other mathematical

[1] Corresponding author. E-mail: albcaval@unina.it Tel. +39 081 5010308 Fax: +39 081 5037042

procedures have conferred a strong mathematical background to the fuzzy approach, allowing the engineer to use a unique design tool for problems described both in terms of heuristic and classical mathematical structures. In this paper a novel decision strategy for reservoir management is proposed, based on a new cost index proposed by the authors. Two control levels are issued based on fuzzy techniques. Indeed, first how much water to release must be decided by the water manager. Next, how to operate the dam gate in order to release the water outflow just defined. To solve the first problem a fuzzy decision controller is used to modulate an "ideal" water demand so that a nominally requested water is released when available, but, if a drought is expected, lower water reference levels are imposed. Moreover, an inner fuzzy PID-like control loop is devoted to operate the dam gate in order to actually release the required water outflow. The inner loop proves to be very effective in regulating the water release also due to the slow dynamics of the reservoirs. However, even in this case, some caution is needed in order to distinguish between physically different situations (namely, water waste and shortage). More critical is the choice of the decision strategy, especially when critical phenomena (e.g. droughts) are to be faced and overcome. It is apparent that too low water levels inside the reservoir prevent any corrective action in the case of droughts, while too high water levels in the reservoir are generally useless and wasteful, since large volume of water are lost for evaporation and/or water overflow. The objective of this paper is to investigate different management strategies based on heuristic and nonlinear mathematical approaches. Moreover, quantitative comparisons are carried out by evaluating standard quality indices for the proposed solutions. The advantage of the fuzzy implementation is the possibility of defining a linguistic meaning for the rules resulting from the mathematical optimization and to add also heuristic rules, thus combining heuristic and rigorous mathematical treatment. As a case study, the management of the Pozzillo (Italy) river basin is considered and simulations are carried on using the MATLAB/SIMULINK integrated environment, using 36-year (1962 to 1998) monthly data. Finally, an hybrid model (Gollu and Varaiya, 1989) is used to describe with a unique model the reservoir also in the presence of water spills.

## 2. RESERVOIR WATER RELEASE POLICY

In this section the basics of the release policy are presented. The life cycle of the reservoir has been divided into (Cavallo *et al.*, 2003*b*):

(1) ordinary management condition;

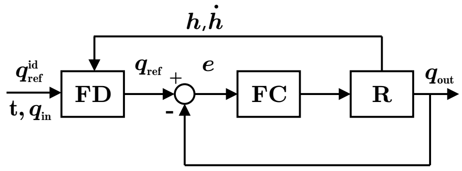


Fig. 1. Automatic Operation System

(2) emergency management condition.

The first refers to the case where, in a given time interval, the total available water volume is not less than the required one. In this case there is enough water to satisfy the user's demand, and the decision strategy must select wether to supply all the water the users ask for or to save some water for possible future needs. Note that, due to evaporation losses, too conservative strategies would result in water waste without fulfilling future users' demand. The second management condition takes place in drought period. In this case the system enters an "emergency operation condition", where reduced water flows are supplied trying to minimize discomforts of the users.

In Fig. 1 the structure of the proposed automatic management system for the reservoir **R** is shown. It is composed by a *fuzzy decision system* **FD** and a *fuzzy controller system* **FC** in which there are two feedback loops. The first is based on the values of $h$, the water level, $\dot{h}$, the height rate, as internal variables and $q_{\text{ref}}^{\text{id}}$, the "ideal" (i.e. in the case of infinite water availability) desired water supply, the current month $t$ and the water inflow $q_{\text{in}}$ as external variables, and produces a possible water supply reference $q_{\text{ref}}$, considering current and foreseen water availability. The inner feedback is needed by the fuzzy control system in order to supply $q_{\text{out}}$ (actual outflow) as close as possible to the reference defined before. Summarizing, **FD** defines $q_{\text{ref}}$, based on the ideal flow reference, $q_{\text{ref}}^{\text{id}}$, and **FC** operates the dam valve to release the required water outflow $q_{\text{out}}$.

In order to design the control laws for the reservoir operations, the mathematical structure of the reservoir must be examined.

## 3. MATHEMATICAL MODEL OF THE RESERVOIR

A typical profile of the water inflow $q_{\text{in}}(t)$ and of required outflow $q_{\text{ref}}^{\text{id}}(t)$ is depicted in Fig. 2. Note that the two curves are, roughly speaking, out of phase by six months, corresponding to the wet and dry seasons. The mathematical model of the dynamics of the reservoir is described by the differential equation:

$$\dot{V} = q_{\text{in}}(t) - q_{\text{ev}}(t) - q_{\text{out}}(t), \qquad (1)$$

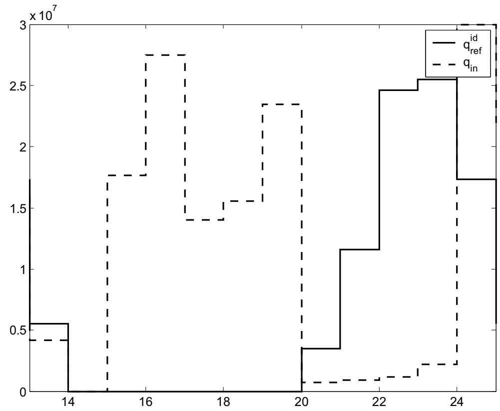


Fig. 2. Typical behavior of natural inflow and required outflow

where $V(t)$ is the reservoir volume at the generic time instant $t$, that depends on the geometry of the reservoir, and $q_{\rm ev}(t)$ is the evaporation. In particular $V = \int_0^h A(\lambda)d\lambda$, where $A(h)$ is the area of the water surface and $h$ is the water height in the reservoir. By applying the chain derivation rule:

$$\dot{V} = \frac{dV}{dh}\dot{h} = A(h)\dot{h}. \qquad (2)$$

The evaporation $q_{\rm ev}(t)$ is usually modelled via an evaporation coefficient $k_{\rm ev}(t)$ deduced from reservoir's losses at time instant $t$:

$$q_{ev}(t) = k_{\rm ev}(t)A(h). \qquad (3)$$

Physically, the volume is lower bounded by the so-called "dead volume", hence $A(h) \neq 0$. Thus, the model of the reservoir can be written

$$\dot{h} = -k_{\rm ev} + \frac{1}{A(h)}(q_{in}(t) - q_{out}(t)). \qquad (4)$$

## 4. CONTROL OF THE DAM GATE

The definition of a control strategy for the dam gate can be formulated as a tracking problem, i.e. a reference outflow $q_{\rm ref}(t)$ is defined, and a control action is sought such that the actual water outflow $q_{\rm out}$ after a transient follows the reference profile with a given maximum error $e(t)$

$$|e(t)| = |q_{\rm ref}(t) - \tilde{q}_{\rm out}(t)| < \epsilon, \forall t > t_1 \qquad (5)$$

where $t_1$ is the transient duration and $\tilde{q}_{\rm out}$ is a filtered version of the water outflow, in order to filter out turbulent motion. A fuzzy PID strategy is imposed as follows

$$u(t) = K_P(e)e(t) + K_I(e)\int^t e(\tau)d\tau + K_D(e)\dot{e}(t) \quad (6)$$

where $K_P(e)$, $K_I(e)$, $K_D(e)$ are proportional, integral and derivative nonlinear control gain, respectively. It is possible to prove, by using sliding manifold control concepts (Cavallo and Natale, 2003), that the closed loop system exhibits strong robustness properties when using high control gains, without loosing stability (Cavallo *et al.*, 2003*a*).

However, from a physical point of view, positive and negative values for the error variable have very different meanings. Indeed, positive errors mean low water supply to the users, while negative errors mean water waste, i.e. supplying the user with more water than required. Thus, larger control gains, i.e. higher control authority, for negative values of the error seem appropriate in order to reduce water waste. This motivates the choice of nonlinear gains, which can be implemented by using fuzzy strategies. In particular, a Sugeno Fuzzy Controller has been designed by using only three membership functions ('negative', 'zero' and 'positive') and three rules for each gain. The results of the closed loop control tested on the model (4) show very good accordance between required and supplied water, at least until there is enough water in the reservoir. Obviously, if this is not the case no tracking control strategy can help, since in this case the problem is not the control strategy, but the excessive water request. Hence an external loop must be taken into account to change in a suitable way the water demand to the reservoir.

## 5. HYBRID DYNAMICAL MODEL OF THE RESERVOIR

Equation (4) describes the hydraulic balance in the reservoir only if the water volume belongs to a given interval at each time instant, i.e.

$$V_{\rm min} \leq V(t) \leq V_{\rm max}, \qquad (7)$$

where $V_{\rm min}$ is the dead volume and $V_{\rm max}$ is the reservoir volume, depending on the dam height. If $V(t)$ tends to increase over $V_{\rm max}$, an overflow $q_{\rm sp}$ (water spill) happens, while if it reduces below $V_{\rm min}$ it will be impossible for the dam to supply any desired flow. The above consideration naturally suggests an hybrid model for the reservoir.

Some additional variables are defined, namely the tentative water volume $V_t$ and the actually released water flow $q_{\rm act}$. The hybrid model of the reservoir encompasses three states (conditions), as follows.

(1) A standard condition (*NORMAL*), when the bounds (7) are satisfied and eq. (4) applies.
(2) An overflow condition (*SPILLS*), where the water volume is constrained to its maximum value.
(3) A drought condition (*EMPTY*), where no water can be supplied to the user ($q_{\rm act} = 0$) and no evaporation occurs (at least approximately, actually a small evaporation happens, but can be neglected).

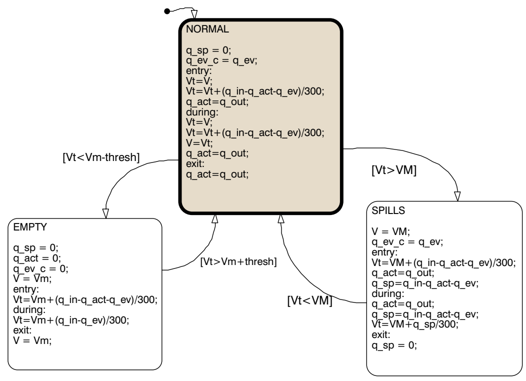


Fig. 3. Steteflow statechart for the reservoir

Finally, a fixed integration step $\Delta T = 1/300$ is considered. The resulting statechart is reported in Fig. 3.

The Stateflow element is integrated into a MATLAB/SIMULINK simulation scheme, to be used to evaluate and compare different operation strategies.

Due to the effectiveness of the dam gate controller, it is reasonable to assume that in NORMAL and SPILLS states the tracking error is 0, i.e. $q_{\text{out}} = q_{\text{ref}}$, in order to reduce the computational burden.

## 6. FUZZY DECISION SYSTEM

The outer loop employs a fuzzy automatic decision system to define, in real-time, the "actual flow reference" in the case of "emergency management conditions". As it's known in the literature (e.g. (Dubois and Prade, 1980) and references therein), fuzzy systems allow to turn numeric input through linguistic knowledge into numeric output.

Thus, the core of fuzzy logic theory is linguistic rules set: in this study, trying to take into account knowledge reservoir management operator, the following Sugeno-type rule system is developed

$\mathrm{R}^{(l)}$: `if` $x_1$ `is` $P_1^{(l)}$ `and` ... `and` $x_n$ `is` $P_n^{(l)}$ `then` $y = \rho^{(l)} y^{\text{id}}$

where

- $x_i \in U_i \subset R$ is the $i$-th input linguistic variable in the universe of discourse $U_i \subset R, i = 1, \ldots, n$;
- $y \in S \subset R$ is the output linguistic variable in the universe of discourse, expressed as product of a coefficient $\rho^{(l)} \in [0, 1]$ by an ideal output $y^{\text{id}} \in S$
- $P_i^{(l)}$ is the fuzzy set referred to the $i$-th input variable and the $l$-th decision rule, $i = 1, \ldots, n$, $l = 1, \ldots, r$;
- $\rho^{(l)} \in C_1 \subset [0, 1]$ is a crisp multiplier for the $l$-th rule, $l = 1, \ldots, r$, assuming values in the set $C_1$, with cardinality $\gamma_1$. This is a "reduction factor" of the output with respect to an "ideal" output.

The range of values of the coefficient $\rho^{(l)}$ is chosen so as to reduce the user's water demand. In particular, a decision rules system consisting of $r = 13$ rules and $\gamma_1 = 6$ levels of output reduction has been selected of the form

$\mathrm{R}^{(l)}$: `if` $h$ `is` LOW `and` $\dot{h}$ `is` ZERO `and` *month* `is` DRY `and` $q_{\text{in}}^{\text{C}}$ `is` DROUGHT `then` $q_{\text{ref}}$ =EMERGENCY $q_{\text{ref}}^{\text{id}}$

with linguistic values and variables:

$$
\begin{aligned}
x_1 &= h \\
x_2 &= \dot{h} \\
x_3 &= month \\
x_4 &= q_{\text{in}}^{\Sigma}(t) = \int_0^{1year} q_{\text{in}}(t - \tau) d\tau \\
P_1 &= \{\text{LOW}, \text{HIGH}\} \\
P_2 &= \{\text{NEGATIVE}, \text{ZERO}, \text{POSITIVE}\} \\
P_3 &= \{\text{DRY}, \text{WET}\} \\
P_4 &= \{\text{DROUGHT}, \text{NOT\_DROUGHT}\} \\
C_1 &= \{\text{NOTHING}, \text{VERY\_LITTLE}, \text{LITTLE}, \\
&\quad \text{MUCH}, \text{VERY\_MUCH}, \text{EMERGENCY}\}
\end{aligned}
$$

where $q_{\text{in}}^{\Sigma}$ is cumulative value of the inflow in the last year. The choice of the variables has the following rationale: $h$ takes into account the water currently at disposal, $\dot{h}$ the presumed future volume trend, *month* the expected future inflow, $q_{\text{in}}^{\Sigma}$ the past inflow history. Based on these variables, the decision strategy tries to foresee the water availability to satisfy current and future customers' requirements, suitably reducing water supply in the case of hypothetical future negative scenarios.

## 7. OPTIMIZING THE DECISION STRATEGY

Three different reservoir management strategies have been designed and analyzed.

(1) SOP: Standard Operation Policy;
(2) FOP: Fuzzy Operation Policy;
(3) OFOP: Optimized Fuzzy Operation Policy;

The SOP (Cancelliere *et al.*, 2002) policy releases all water demand if there is enough available water stored, whether there is a ordinary management condition or an emergency management condition. This policy, although often used by reservoir managers, can be the cause of many users disadvantages. The FOP strategy distinguishes between ordinary and emergency working conditions trying to reduce negative consequences for users in drought situations. It is designed with a heuristic estimation of all parameters. Finally, the OFOP strategy is an optimized version of the FOP. In particular, shape and number of membership function, number of rules, are chosen heuristically, while the six values for the $\rho$'s, have been optimized. An original objective function is proposed, i.e.

$$y = \int w(q_{\rm sp}) \left(q^{\rm id}_{\rm ref}(t) - q_{\rm ref}(t)\right)^2 dt, \qquad (8)$$

in which $q_{\rm ref} = \rho q^{\rm id}_{\rm ref}$, $\rho \in C_1$, so the parameters to optimize are the values of the set

$$C_1 = \{c_1, c_2, c_3, c_4, c_5, c_6\} \qquad (9)$$

with following constraints: $0.95 \le c_3 \le 1$, $0.8 \le c_2 \le 0.95$, $0.6 \le c_3 \le 0.8$, $0.4 \le c_4 \le 0.6$, $0.2 \le c_5 \le 0.4$, $0.05 \le c_6 \le 0.2$. The constraints have been chosen so as to keep the linguistic meaning of the fuzzy variables. Moreover, $w(q_{\rm sp})$ is a fuzzy weighting function which penalizes situations with high spills. Indeed, it is apparent that saving more water can alleviate droughts, but increases water waste due to spills and evaporation. The strongly nonlinear nature of the optimization problem calls for specific algorithms. In particular, a genetic algorithm (Goldberg, 1989) has been employed, using the objective function as fitness function. Specifically, 10 iterations have been considered, starting from a population of 50 individuals each with 6 chromosomes and 20 natural selections have been carried out as follows.

(1) random generation of 50 individuals
(2) crossover of two individuals chosen at random with probability 0.7
(3) mutation of one or more chromosomes with probability 0.8
(4) replacement of the old best individual with one generated at random.

OFOP performs a nonlinear optimization using the FOP solution as a starting guess. In this way, the optimization solver is allowed to start from a "good" starting guess, and trivial local minima are apriori avoided.

Each policy has its advantages and drawbacks. In order to evaluate the effectiveness of the proposed strategies, the following performances indices are considered

- Volumetric Reliability: $\frac{\int q_{\rm ref} dt}{\int q^{\rm id}_{\rm ref} dt} 100$
- Integral of Squared Deficits: $\int \left(q_{\rm ref} - q^{\rm id}_{\rm ref}\right)^2 dt$
- Deficit Frequency: $100 \int d(t)\, dt$
- Total Spills: $\int q_{\rm sp}(t)\, dt$
- Total Evaporation: $\int q_{\rm ev}(t)\, dt$

where

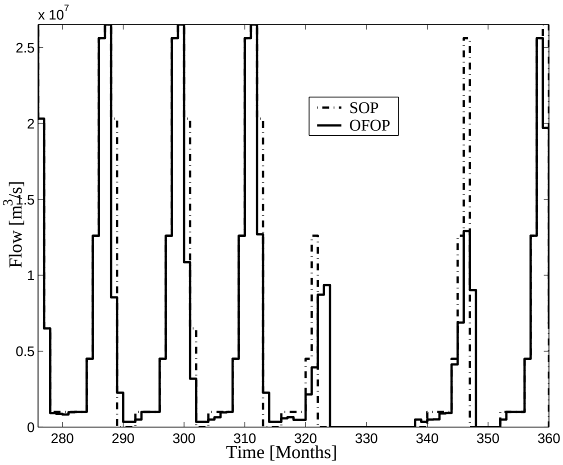


Fig. 4. Simulation results in years 1985-1992.

$$d(t) = \begin{cases} 1 & \text{if } q_{ref}(t) < q^{id}_{ref}(t) \\ 0 & \text{otherwise} \end{cases}$$

A complete 432-months water inflow $q_{\rm in}$ and monthly evaporation rates $k_{\rm ev}$ data set for the years 1962-1998 has been used. All strategies have been designed on an historical 216-months training set, (years 1962-1980), while the performances indices have been tested on a historical 288-months validation data set (years 1974-1998), with 6-years overlap between the data sets.

## 8. CASE STUDY

The methodology developed in this paper has been applied to the case of the management of Pozzillo reservoir, on the Salso River in Sicily (Italy). Pozzillo reservoir is a multipurpose system (hydroelectric, irrigation, and municipal), the basin area is about 577 $\rm km^2$ and net storage is $123 \times 10^6$ $\rm m^3$.

Referring to hydrologic year (October to September) it is possible to see a recent drought events, that struck South Italy in the years 1988-1990. During these years the SOP strategy suffers from a sudden complete drought, while FOP and OFOP are able to face the severe drought for some months (Fig. 4, where only SOP and OFOP strategies are considered). Note moreover that the drought event is not included in the training set, hence the OFOP decision strategy had no way to learn such a catastrophic event.

Simulation results are summarized in Tab. 1, in which the different indices are evaluated. All these indices have been discretized in simulation, sampling the variables with a 1 month time step.

Some comments about Table 1 are in order. First, note that the integral of the square deficits is drastically reduced as the strategy changes from SOP to OFOP. However this happens at expenses

Table 1.

Performance indices of Pozzillo reservoir operation during 1992-1998

| Oper. Policy | Cost Fcn ($10^7 m^3$) | Int. of Sq. Def. ($10^{12} m^3$) | Def. Freq. % | Tot. Spill ($10^6 m^3$) | Tot. Evap. ($10^7 m^3$) | Vol. Rel. % |
|---|---|---|---|---|---|---|
| SOP | 6.56 | 1090 | 26.7 | 81.7 | 11.7 | 75.9 |
| FOP | 5.96 | 909 | 52.4 | 84.2 | 14.7 | 72.9 |
| OFOP | 5.49 | 821 | 52.4 | 86.1 | 14.5 | 73.1 |

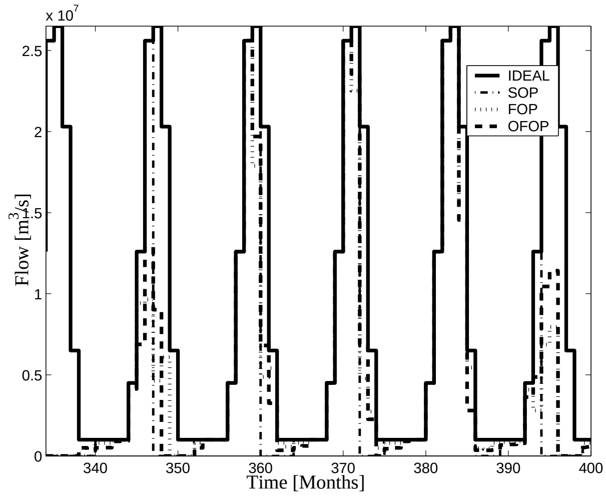


Fig. 5. Simulation results in the period 1986-1998.

of deficit frequency: the user is given generally less water then required, because the fuzzy strategies save some resource for possible future shortage. As a consequence, spills and evaporation losses increase. Nevertheless, the important factor to consider is not only the deficit frequency, but also how much water the user receives with respect to his demand. This is taken into account by the volumetric reliability, i.e. the percentage of water received divided by the required one. The last row of Tab. 1, evidences that the volumetric reliability increases passing from FOP to OFOP. This shows that the proposed index does not reduces directly the spills, but reduces water waste, also affecting evaporation, so as to guarantee higher reliability.

In Fig. 5 the behavior of all the strategies is shown on a larger time span, namely years 1986-1998.

## 9. CONCLUSIONS

In this paper different decision strategies for the problem of handling the water management of an artificial reservoir in a fully automatic way have been analyzed and compared. In particular, a Standard Operation Policy (SOP), a Fuzzy Operation Policy (FOP) and an Optimized Fuzzy Operation Policy (OFOP) have been considered. The SOP releases water whenever possible, regardless of foreseen water demand. The FOP supplies water based on reservoir and external variables state, thus exhibiting forecasting properties and reducing the water release, even if there is currently some available water, if it seems that saving water can alleviate foreseen future droughts. OFOP is an optimized version of FOP obtained with Genetic Algorithms Techniques. To test the proposed strategies, a dynamic hybrid model of the reservoir is deduced, simulating different operative situation. Moreover, a PID controller operates the reservoir gate. The work yields a unique mathematical and software environment for dealing with decision and control problem for reservoir management. Work in progress concerns further development of the hybrid modelling of networks of reservoirs and hierarchical control strategies for optimal distribution of water resources.

## REFERENCES

Cancelliere, A., A. Ancarini and G. Rossi (2002). A neural networks approach for deriving irrigation reservoir operating rules. *Water Res. Management* **16**, 71–88.

Cavallo, A., A. Di Nardo and M. Di Natale (2003*a*). Fuzzy control of artificial reservoirs. *WSEAS Trans. on Systems* **4**(2), 1118–1124.

Cavallo, A., A. Di Nardo and M. Di Natale (2003*b*). A fuzzy control strategy for the regulation of an artificial reservoir. In: *Sustainable Planning and Development* (E. Beriatos, C.A. Brebbia, H. Coccossis and A. Kungolos, Eds.). pp. 629–639. WIT Press.

Cavallo, A. and C. Natale (2003). Output feedback control based on a high order sliding manifold approach. *IEEE Trans. Automatic Control* **48**, 469–472.

Dubois, D. and Prade, H., Eds.) (1980). *Fuzzy Sets and Systems: Theory and Applications.* Academic Press. New York.

Goldberg, D.E. (1989). *Genetic Algorithms in Search, Optimization, and Machine Learning.* Addison-Wesley.

Gollu, A. and P.P. Varaiya (1989). Hybrid dynamical systems. In: *Proc. of IEEE Conference on Decision and Control.* Tampa, FL.

Panigrahi, D.P. and P. P. Mujumdar (2000). Reservoir operation modeling with fuzzy logic. *Water Res. Management* **14**, 89–109.

Russel, S.O. and P.E. Campbell (1996). Reservoir operating rules with fuzzy logic programming. *Journal Water Resources Planning Management* **122**(3), 165–170.

Yeh, W. (1985). Reservoir management and operation models: a state of the art review. *Water Resources Research* **21**(12), 1797–1818.