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Deriving Parametric Discrete and Continuous Operating Rules Through Heuristic Optimization for Multiuse Water Supply Systems

V. Nicolosi[1], G. Rossi[2], A. Preti[3] and A. Cancelliere[4]
Department of Civil and Environmental Engineering
University of Catania - 95125, ITALY
E-mail: [1]vmnico@dica.unict.it; [2]grossi@dica.unict.it; [3]angelopreti@yahoo.it; [4]acance@dica.unict.it

ABSTRACT: The role of reservoirs to transfer in time water from wet to dry periods is particularly important for water supply systems located in drought-prone areas. Impacts of natural variability of water availability on different water uses can be heavily modified by thorough definition of operating rules of reservoirs. The identification of hedging rules including monthly rationing factors defined for each use could guide water managers on managing foreseen temporary water shortages both reducing their total amount and distribution throughout the year. The aim of this paper is to explore the effectiveness of several types of discrete and continuous hedging rules defined through heuristic optimization and validated by simulation. In particular genetic algorithms have been used to investigate the complex solution domain of rationing factors and storage volumes in reservoir used to trigger rationing on different water uses. The procedure focuses on the definition of the objective function of the optimization problem that plays a crucial role on the achievement of the desired goal. A multiuse water supply system in southern Italy supplying municipal, irrigation, industrial uses and respecting environmental constraints has been used as case study. Implementation of optimized hedging rules improves the performance of the water supply system leading to the reduction of the peaks of shortages and to a better monthly distribution of shortages among uses characterized by different priorities.

INTRODUCTION

The definition of operating rules of reservoirs has been and continue to be the subject of numerous research works mainly due to the importance of the topic both from an academic and technical standpoint. The main focus leading the procedure for defining operating rules of a single reservoir or a complex system of reservoirs is strictly tied to the purpose of the system itself that can range from flood control to drought management, from hydropower generation to streamflow regulation for ecological purposes. The simplest operating rules consists in the so called Standard Operating Policy (SOP), also addressed to as S-shaped curve of operation (Maass *et al.,* 1962; ReVelle *et al.,* 1969; Loucks *et al.,* 1981).

The effects of the SOP on water system management have been early analyzed in many papers (Klemes, 1977; Hashimoto, 1982; Stedinger, 1984) and operating a system following a SOP is often used as a comparison to test the performance of more complex operating rules.

The use of SOP can result in an high volume reliability for the water system but, on the other hand, it often shows low performance in terms of maximum deficit leading the system to severe water shortages especially where uncertainty of inflows is high and droughts are frequent. As a consequence one of the most common measures implemented in management of water systems in drought-prone areas is water rationing, which reduces demand and conserves more water for future use.

This common way of managing foreseen temporary water shortages is known as hedging (Bower *et al.,* 1962) and is widely diffused among water managers that prefer adopting a sequence of smaller water shortages before an impending drought to avoid one severe abrupt water shortage. Hedging Rule Policies (HRP) are applied by limiting the releases when future shortage conditions are expected, thus saving water to reduce heavier shortages in the future. Effective hedging rules can reduce a very high-percentage single period water shortages even if possible unnecessary hedging could favour more frequent small shortages that deteriorate water supply reliability.

Performance of water supply systems can be strongly affected by some decision variables necessary for hedging such as the onset and termination of hedging and the percentage of water reduction for the

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[1]Conference speaker

different demands. A variety of hedging rules and their effects have been investigated computing the optimal amount of carryover storage for hedging (Neelakantan *et al.,* 1999; Ilich *et al.,* 2000; Tu *et al.,* 2008), assessing and balancing between rationing and corresponding global benefits. Particular hedging rules have been developed with specific purposes such as taking mainly into account for reservoirs in series or in parallel (Lund and Guzman, 1999) including quality issues (Paredes and Lund, 2006) or drought management (Bayazit and Unal, 1990; Cancelliere *et al.,* 1998; Lund, 2006). Broadly speaking, depending on their form, all hedging rules can be divided into two main classes namely discrete and continuous hedging rules. Shih and ReVelle (1994) explored the hedging mechanism during drought conditions minimizing the maximum monthly shortfall to determine the trigger value for a continuous hedging rule whereas, in a further research, maximized the number of months in which no rationing is required with the goal to determine the trigger values for monthly discrete hedging rules (Shih and ReVelle, 1995).

In this study, based on the discrete and continuous hedging rules proposed by Shih and Revelle for a three months period and a single reservoir, a model for the monthly heuristic optimization of the parameters of discrete and continuous hedging rules has been developed considering a water system supplying several uses characterized by different priorities and enlarging the decision variables domain of the optimization problem both to rationing factors and optimal triggers volumes. Based on results obtained by the simulation of the water supply system operated through the different optimized rules a monthly variable one-phase continuous hedging rule has been chosen. The chosen rule has been further refined analyzing its sensitivity in respect to the different supplied uses always respecting priorities. Due to the high number of decision variables and the mathematical form of the objective function used for optimization the problem has been tackled through genetic algorithms that are often capable of achieving global optimal solutions for problems where traditional methods would fail to converge or get stuck in local optima (Labadie, 2004).

METHODOLOGY

Discrete and Continuous Hedging Rules

Discrete and Continuous hedging rules can be seen as a direct evolution of the simple SOP. Basically the SOP consists in releasing water till it is available in the system as opposite to hedging that curtails releases to retain water in storage to be used in following periods. In particular, in its original form, for each time stage the SOP determines releases as a function of present storage plus predicted inflow in the considered time stage. Neglecting evaporation losses and forecasted inflow for the particular time stage Figure 1(a) shows a simplified version of a SOP. According to this policy demands are always fulfilled unless stored water drops below a given value (V_I) equal to the demand supplied by the reservoir/system of reservoirs. For stored volume below V_I the entire stored volume is released partially fulfilling the demand whereas for stored volume greater than C (maximum capacity) releases include total demand plus the whole input to the system during the given time stage.

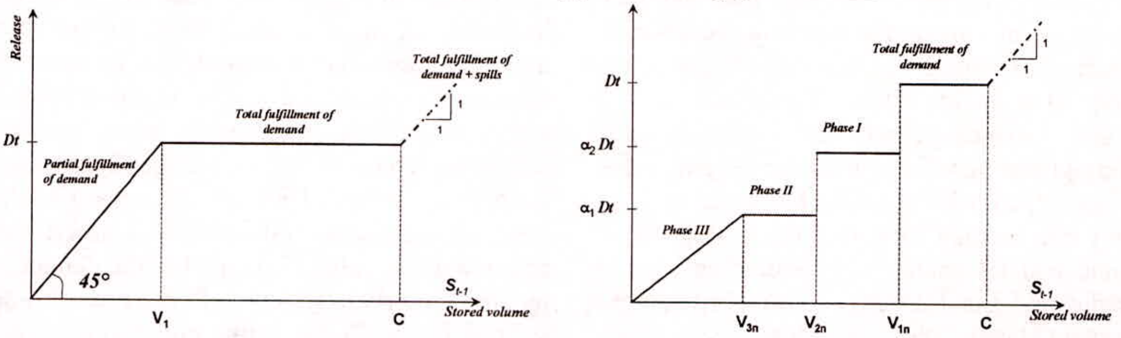
A discrete hedging rule, as the one schematically represented in Figure 1(b), satisfies demands according to phases identified by rationing factors (a_{1n}, a_{2n}) and trigger volumes (V_{1n}, V_{2n}, V_{3n}) variable for each month (n) of the year. According to this rule demand is totally satisfied only if, for the given time stage, the actual stored volume is greater than V_{1n}. This kind of hedging rule is particularly easy to implement during the actual operation of the system and is equivalent to identify zones within the reservoir to which correspond predefined rationing factors of the demands. The main drawback of this type of hedging rule is its lack of flexibility in respect to the rationing factor applied to the demand that, for instance, abruptly switches from a_{1n} to a_{2n} when the stored volume exceeds V_{2n} no matter if its actual value is still very close to V_{2n}.

In this study two different kind of discrete hedging rules have been explored, namely $D1$ and $D2$. $D1$ presents a_1 and a_2 set respectively to .4 and .6 constant throughout the year according to Shih and ReVelle (1995) whereas V_{1n}, V_{2n}, V_{3n} has been considered as the decision variables of the optimization. $D2$ is a more complex version of $D1$ where both rationing factors (a_{1n}, a_{2n}) and trigger volumes (V_{1n}, V_{2n}, V_{3n}) have been optimized and considered variable month by month.

Continuous hedging rules try to overcome the lack of flexibility charactering discrete hedging rules by applying a rationing factor to the demand that continuously varies as a function of the volume stored in the system during a given time stage. In particular for a one-phase hedging rule ($C1$), as depicted in Figure 1(c), the volume V_{1n} has to be defined so that the slope characterized by the angle b_n<45° enables the hedging so that demand can be rationed avoiding the total emptying of the reservoir. A piecewise continuous hedging rule ($C2$) in Figure 1(d) can be seen as

(a) SOP

(b) Discrete hedging rules *D*1–*D*2



(c) One-phase continuous hedging rule *C*1

(d) Multi-phase continuous hedging rule *C*2

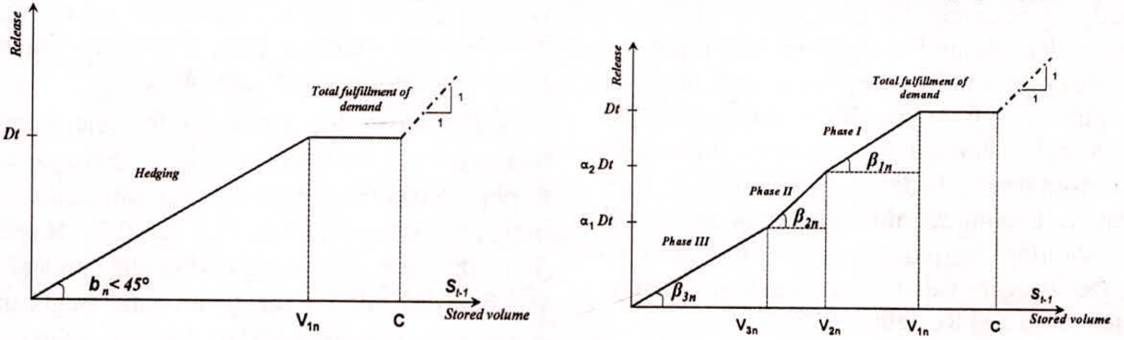


Fig. 1: Standard Operating Policy (SOP), discrete, one and multi-phase continuous hedging rules

a discrete hedging rule where the rationing factor varies among the different phases according to different slopes identified by the angles b_{1n}, b_{2n} and b_{3n}.

Continuous hedging rules, being characterized by more degrees of freedom in respect to discrete hedging rules, should give to the system a greater adaptability to the variability and uncertainty typical of the streamflows to the reservoir resulting in a reduction of shortages. At the same time this greater complexity requires a more accurate tuning and refining process in order to actually improve the performance of a system beside being more computationally demanding in respect to rules defined through less parameters.

The developed methodology includes the combined use of optimization and simulation models. In particular the parameters of the several operating rules investigated have been defined for each month of the year through heuristic optimization and using a dataset drawn from the historic time series of inflows to the system. Once the parameters of the operating rules have been optimized considering an adequate objective function the obtained rules have been tested through the simulation of the system considering as input data not included in the dataset used for optimization. Based on performance indices evaluated as results of simulation, a particular operating rule has been chosen and further refined. Effectiveness of the optimized and refined operating rule is evaluated in comparison with simulation of the system operated through a SOP. A scheme of the developed methodology is depicted in Figure 2.

Heuristic Optimization of Hedging Rules Parameters

Due the high number of decision variables characterizing the optimization problem heuristic optimization has been considered more suitable in order to tackle the problem.

Depending on the form of the specific hedging rule, optimized decision variables vary from 12 for *C*1 (12 V_n monthly trigger volumes) to 36 for *D*1 ($3\cdot12$ V_n monthly trigger volumes) to 60 for *D*2 and *C*2 ($3\cdot12$ V_n monthly trigger volumes + $2\cdot12$ a_{1n} a_{2n} monthly rationing factors).

A model based on an iterative application of Genetic Algorithms (GA) has been developed. GA are a particular class of evolutionary algorithms that use techniques inspired by evolutionary biology such as inheritance, mutation, selection, and crossover (Goldberg, 1989). In this study GA has been implemented as a simulation of the behavior of the water supply system, respecting priorities among demands and water sources, in which a population of representations of candidate solutions (rationing factors and/or trigger volumes depending on the specific operating rule) to the optimization problem evolves toward better solutions.

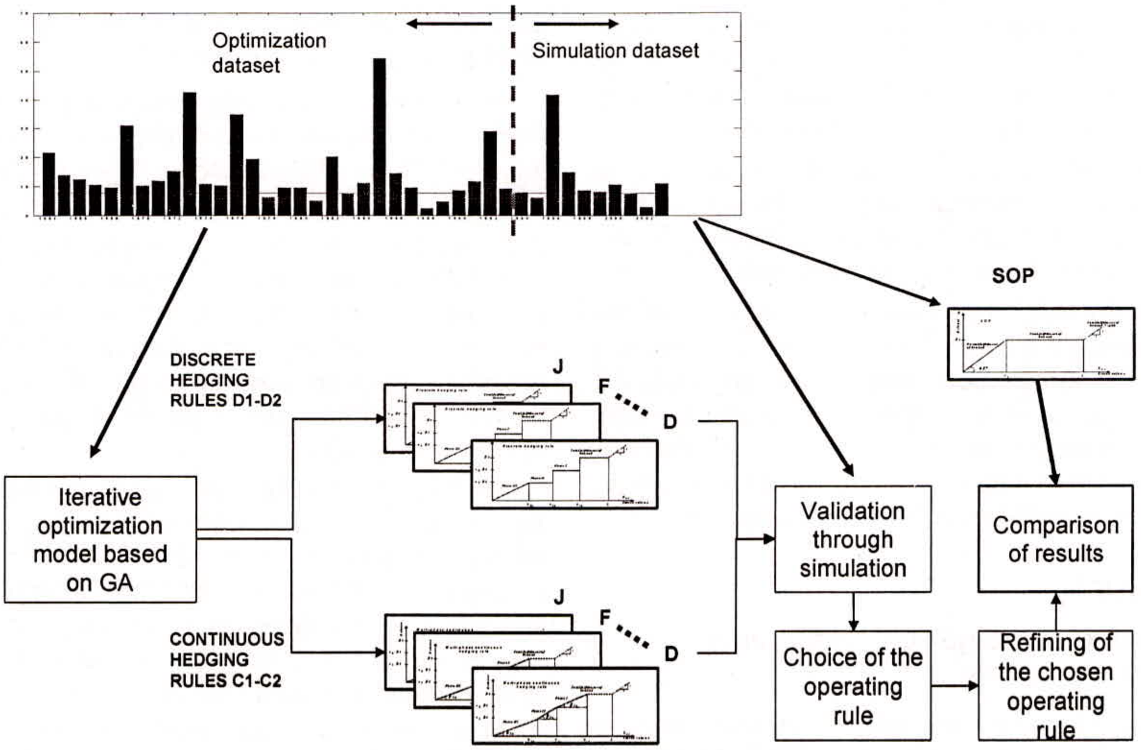


Fig. 2: Scheme of the developed methodology

The evolution usually starts from a population of randomly generated individuals and happens in generations. In each generation, the fitness of every individual in the population is evaluated, multiple individuals are stochastically selected from the current population (based on their fitness), and modified (mutated or recombined) to form a new population. The new population is then used in the next iteration of the algorithm. A typical genetic algorithm requires two main things to be defined:

- Genetic representation of the solution domain.
- Definition of a fitness function to evaluate the solution domain.

For the particular optimization problem some constraints regarding the relationship among the decision variables have been directly embedded within the algorithm for the generation of the population in order to guide the process towards feasible solutions. For instance the genetic representation of the possible solutions for each generation, among other trivial constraints, has to respect the following relationships,

$$0 < V_{3n} < V_{2n} < V_{1n} < C \quad 0 < \alpha_1 < \alpha_2 < D_n \quad \text{with} \quad n = 1 \rightarrow 12 \qquad \ldots (1)$$

The choice of a fitness function (objective function) that actually describes the desired goal to be achieved through the implementation of the operating rules to be developed is a crucial issue.

The following objective function has been designed in order to consider the fulfillment of the uses supplied by the system under investigation,

$$\min \sum_{i=1}^{k} \left[W_i \sum_{j=1}^{a*12} \left(\frac{\text{short}_j}{\text{dem}_j} \right)^2 \right]_k \qquad \ldots (2)$$

with k = number of supplied uses, j = month, a = number of years of the optimization dataset, W_i = weight to be assigned to each i-demand in order to respect priority among different uses supplied by the system, $short_j$ = monthly shortage, dem_j = monthly demand.

Minimizing the monthly ratios between shortage and demand enables to overcome the problem arising out of the typical uneven distribution throughout the year characterizing demands supplied by multiuse water systems. For instance irrigation use is generally concentrated during the dry season which lasts from April/May to September/October for Mediterranean areas, industrial and municipal uses are generally characterized by a more constant monthly pattern whereas, in general terms, ecological use is defined according to the pattern of streamflows with higher volumes during wet season and lower volumes during dry season.

The objective function has been considered non linear in order to favor a uniform distribution of shortages penalizing the concentration of shortages in single time stages of the optimization and also on the basis of the assumption that the relationship between water shortages and economic losses is non linear.

A strict constraint can be introduced in order to respect given performances on particular uses so that, for instance, high reliabilities can be guaranteed for the use with highest priority such as municipal.

Finally the weights W_i have been used to guide the optimization toward solutions that take into account the chosen priority among uses. To identify trade-off solutions among uses supplied by multiuse water systems and support decision makers on the decision process a specific sensitivity analysis of the operating rules to the definition of W_i has to be carried out.

CASE STUDY

Simulation of the Ragoleto-Mazzarronello Water Supply System

The water supply system selected as case study is located in the Acate river basin in the South-Eastern Sicily in Italy. The climatic conditions are typical of a Mediterranean semi-arid region, with a moderately cold and rainy winter and a generally hot and dry summer. The water supply system under study includes the Ragoleto reservoir located on the higher part of the Acate river and the Mazzarronello diversion on the Mazzarronello stream which is one of the many tributaries of the Acate merging into the main river downstream the reservoir.

Ragoleto dam and Mazzarronello diversion basins, respectively about 117.5 km^2 and 70.1 km^2 are characterized by heterogeneous soils with a generalized low permeability giving a typical torrent-like behavior to the Acate river and its tributaries. Available hydrological data include historical (1964–2003) monthly flows of the Acate river at Ragoleto dam and Mazzarronello stream at the diversion.

The flow series for the Acate river at Ragoleto dam has been obtained through a hydrologic balance at the reservoir carried out for its entire operational period, while flows at Mazzaronello diversion, due to the lack of records, have been estimated as a function of those obtained for the Ragoleto reservoir adjusted on the basis of the difference on precipitation over the two basins.

Ragoleto reservoir has a net design capacity of $21.7 \cdot 10^6$ m^3 which is currently limited, due to sediment transport phenomena, to a maximum storage of $20.4 \cdot 10^6$ m^3. Linked to the Mazzarronello diversion there is a small storage of about $600 * 10^3$ m^3 where water for irrigation use is stored.

Originally the Acate water system supplied irrigation (Land Reclamation Consortium n.8, LRC8) and industrial (National Hydrocarbon Agency, ENI) uses.

The amount of water to be allocated was been determined by an agreement stating that the water availability at Ragoleto reservoir was $12.5 \cdot 10^6$ m^3/year and that the total yearly amount was to be divided between the two uses according to a 48% to the irrigation use (corresponding to $6.0 \cdot 10^6$ m^3/year) and the remaining 52% to the industrial use (corresponding to $6.5 \cdot 10^6$ m^3/year).

Historical mean annual inflows to the water plants are respectively $15.02 \cdot 10^6$ m^3/year and $7.66 \cdot 10^6$ m^3/year ($7.74 \cdot 10^6$ m^3/year and $3.58 \cdot 10^6$ m^3/year with exceedance probability of 80%) for Ragoleto reservoir and Mazzarronello diversion. Considering that the total consumptive use was about $12.5 \cdot 10^6$ m^3/year the water system appears almost balanced. Nevertheless the water supply system has suffered several temporary water shortage periods such as in 1978, 1981, 1988–1990, 1994, 2001–2002 mainly due to the occurrence of drought spells and to the uneven distribution of streamflows throughout the year.

Moreover, due to frequent temporary water shortages affecting Gela municipality, a neighbouring coastal city that can be supplied by water coming from the Acate water supply system, a big pressure has been exercised in order to *"finalize the prevalent use of good quality water (from Ragoleto reservoir) to municipal use for population allocating recycled less quality water for industrial use"* as ratified by a document draft in 2007 by a group of stakeholders including representatives from Italian Ministry of environment, Sicilian Region, Municipality of Gela, ENI (Manager of Ragoleto reservoir) and LRC8.

According to this agreement a new order for the allocation of water has been determined considering a water availability at Ragoleto of $10.5 \cdot 10^6$ m^3/year to be divided among municipality of Gela ($2.0 \cdot 10^6$ m^3/year), LRC8 ($3.5 \cdot 10^6$ m^3/year) and ENI ($5.0 \cdot 10^6$ m^3/year) that is also supplied by a desalination plant.

The entire releases from Mazzarronello diversion are devoted to irrigation demand of LRC8. Both the water plants, Ragoleto reservoir and Mazzarronello diversion, have to release downstream flows for ecological use. In particular the mentioned document allocates $0.30 \cdot 10^6$ m^3/year to be released by Ragoleto whereas, in this study, lacking any other prescription, $0.22 \cdot 10^6$ m^3/year have been allocated for ecological use from Mazzarronello diversion with a monthly distribution for both IFRs that varies as a function of the monthly pattern of the total flow.

Figure 3 shows monthly distributions of consumptive and ecological uses.

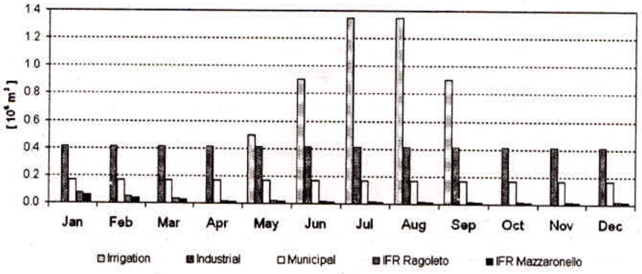


Fig. 3: Monthly distributions of consumptive and ecological uses supplied by the Acate water supply system

Figure 4 shows the scheme of the system adopted within the simulation model whatever is the implemented operating rule. Municipal use has the highest priority implemented through a strict constraint both in optimization and simulation models in order to guarantee time and volume based reliability for this use always greater than 0.99 for all the optimized rules.

Water available at Mazzarronello diversion, that cannot be stored, is firstly used to satisfy IFR and then allocated to irrigation use. Ragoleto reservoir, respecting the constraint on municipal use, satisfies IFR (rationed in some cases depending on the operating rule), the remaining demand of LRC8 and then industrial use. At a higher cost, industrial use can count on a further source of water from desalination plant.

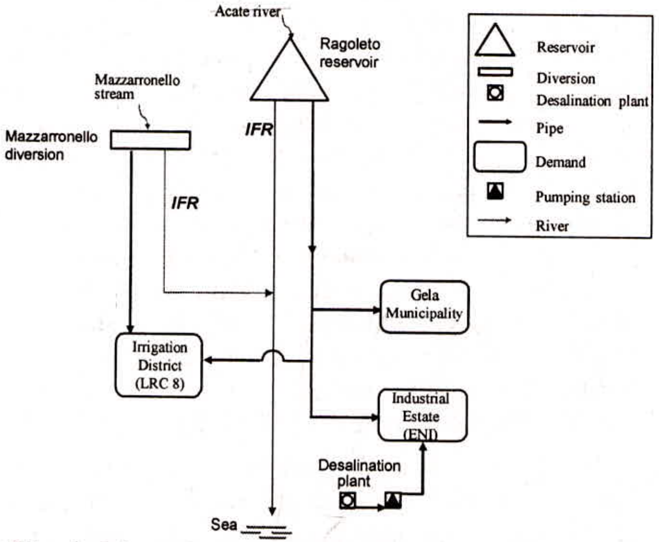


Fig. 4: Adopted schematization for the simulation of the Acate water supply system

Optimization and Validation of Proposed Hedging Rules

Optimization of hedging rules has been carried out through a repeated application of a model based on GA. In particular, for each type of hedging rule, the genetic algorithm has been run 500 times considering as best solution the one corresponding to the minimum among the calculated objective functions.

Both discrete (*D*1, *D*2) and continuous (*C*1, *C*2) hedging rules have been optimized considering a maximum number of generations equal to 500 with a population size of 100 individuals and a crossover factor equal to 0.7. Parameters of hedging rules optimized over the 30 year historical monthly data (1964–1993) are reported in Figure 5.

The four optimized hedging rules have been validated through simulation of the system over ten years (1994–2003) on a monthly time scale including two drought events (1994, 2001–2002). Results of simulations have been compared each other on the basis of several performance indices based on reliability, resiliency and vulnerability concepts (Hashimoto *et al.*, 1982; Alecci *et al.*, 1986) and through evaluation of probabilities of shortages of given severity.

Table 1 reports performance indices calculated for each hedging rule and, as a comparison, for the simulation of the system operated through a SOP.

Municipal use is guaranteed with high performances by HRP whereas no constraints are provided by SOP that shows a mean annual shortage on this use close to the 8% of the total year municipal demand and a maximum annual shortage close to the 20% of the total demand that could be not acceptable for municipal use.

For irrigation and industrial uses, as expected, all the hedging rules perform better than the SOP in terms of maximum and mean annual shortages. Time based reliability and volume based reliability perform slightly better through a SOP that tends to release always the whole inflows to the system. The SOP shows slight higher values for resiliency on these two uses with some exceptions (industrial use for *D*2) representing a lower expected value of the length of periods of shortages resulting from more concentrated severe shortages.

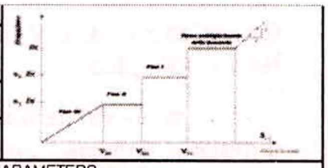
Operating rules *D*2 and *C*2 present the best results in terms of values of the objective function used within the optimization model (see Table 2) described by equation (2). Nevertheless these two rules results in too poor time based reliabilities calculated for irrigation and industrial use on simulation leading to

D 1

Discrete hedging rule

Number of decision variables

36



PARAMETERS

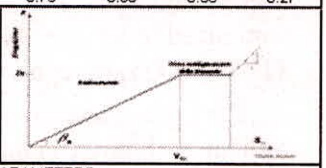
Month	α_1	α_2	β [°]	V_1 [10^6 m^3]	V_2 [10^6 m^3]	V_3 [10^6 m^3]
Jan	0.4	0.6	14.04	8.00	0.77	0.39
Feb			8.76	13.67	0.88	0.41
Mar			2.24	13.67	2.90	1.14
Apr			1.28	13.67	3.62	0.88
May			0.57	9.53	3.71	2.97
Jun			1.65	8.35	2.00	0.68
Jul			0.54	9.90	3.60	2.10
Aug			0.56	8.52	3.11	2.02
Sep			1.04	7.90	1.71	1.09
Oct			2.77	7.53	1.30	0.41
Nov			4.20	3.62	0.83	0.27
Dec			5.73	0.88	0.66	0.27

C 1

Continuous hedging rule

Number of decison variables

12



PARAMETERS

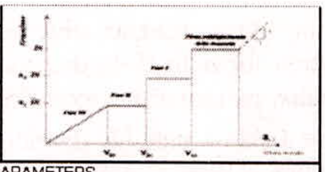
Month	β [°]	V_1 [10^6 m^3]
Jan	6.10	2.31
Feb	3.85	4.20
Mar	3.08	7.27
Apr	3.08	7.27
May	11.32	6.10
Jun	15.38	5.88
Jul	15.38	5.61
Aug	20.89	4.86
Sep	37.25	2.46
Oct	15.38	1.11
Nov	20.89	0.78
Dec	18.01	0.60

D 2

Discrete hedging rule

Number of decision variables

60



PARAMETERS

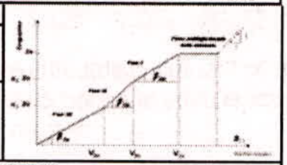
Month	α_1	α_2	β [°]	V_1 [10^6 m^3]	V_2 [10^6 m^3]	V_3 [10^6 m^3]
Jan	0.87	0.92	7.36	18.19	4.98	1.65
Feb	0.49	0.87	1.53	13.85	4.98	2.86
Mar	0.49	0.87	1.89	14.11	6.48	1.65
Apr	0.14	0.65	0.13	6.48	3.18	2.86
May	0.67	0.93	1.33	14.45	6.26	2.16
Jun	0.67	0.92	0.68	14.72	5.64	2.77
Jul	0.49	0.92	0.81	19.36	5.30	1.71
Aug	0.87	0.87	0.55	10.93	5.30	4.41
Sep	0.93	0.93	0.95	10.71	7.84	2.77
Oct	0.05	0.67	0.39	1.08	0.43	0.37
Nov	0.67	0.92	4.51	19.30	1.08	0.42
Dec	0.65	0.65	5.83	4.98	2.66	0.43

C 2

Continuous hedging rule

Number of decision variables

60



PARAMETERS

Month	α_1	α_2	V_1 [10^6 m^3]	V_2 [10^6 m^3]	V_3 [10^6 m^3]
Jan	0.08	0.78	17.41	1.74	0.42
Feb	0.05	0.45	7.38	2.84	1.11
Mar	0.03	0.48	17.41	1.74	1.21
Apr	0.00	0.63	16.43	4.44	1.21
May	0.06	0.41	8.53	0.62	0.43
Jun	0.08	0.48	17.14	3.50	2.96
Jul	0.03	0.53	14.48	2.61	0.45
Aug	0.03	0.48	11.77	1.09	0.75
Sep	0.24	0.75	9.87	2.25	0.44
Oct	0.02	0.75	13.60	0.61	0.14
Nov	0.08	0.56	9.46	0.42	0.06
Dec	0.56	0.83	17.41	0.70	0.61

Fig. 5: Parameters of the optimized discrete (*D*1, *D*2) and continuous (*C*1, *C*2) hedging rules on 1964–93 historic period

an unacceptable frequency of rationing. On the other hand *D*2 and *C*2 show the higher total spills from Ragoleto reservoir on 1994–2003 simulation (see Table 2). For these reason and for the lower numbers of parameters to be optimized operating rule *C*1 seems to be preferable in terms of its overall behavior.

*C*1 shows generalized good results also in respect to ecological use for Ragoleto despite the fact that this is not been directly included within the objective function of the optimization model.

Being not affected by the particular operating rule adopted for Ragoleto reservoir ecological use for Mazzarronello shows the same results both for SOP and HRP.

Continuous hedging rule *C*1 has been considered as the best candidate hedging rule to be fine tuned through a sensitivity analysis in respect to the weight to be assigned to the two consumptive competing uses irrigation and industrial supplied by the system given that municipal is always guaranteed with high standards.

Sensitivity Analysis of Continuous Hedging Rule *C1*

Equation (2) includes weights W_i in order to take into account for the different priorities between the several water uses supplied by multiuse water systems. The ranking priority among uses supplied by a given water system is generally established by law or by specific agreements among stakeholders. The specific ratio among weights to be attributed to the different uses has to be the subject of a sensitivity analysis in order to avoid unacceptable penalization of uses characterized by lower priority. In the case of the Acate water supply system the priority accorded to municipal use has been introduced as a constraint within the optimization model based on GA whereas the ratio between the weights to be attributed to irrigation and industrial uses has been analyzed for the specific continuous hedging rule *C*1.

The refinement of the continuous hedging rule *C*1 has been carried out through several optimizations varying the ratio among weights attributed to the irrigation and industrial uses.

Table 1: Performance Indices Obtained by Simulations of the System on 1994–2003 by Using Discrete, Continuous Hedging Rules and SOP

Use	*Operating Rule*	*Performance Indices*					
		Sum of Squared Shortages [10^6 m^6]	*Max. Annual Shortage [%]*	*Mean Annual Shortage [%]*	*Time Based Reliability*	*Volume Based Reliability*	*Resiliency*
Municipal	D1 D2 C1 C2	0.00	0.00	0.00	1.00	1.00	–
	SOP	0.48	18.13	7.98	0.95	0.98	0.50
Irrigation	D1	3.27	37.80	13.98	0.66	0.86	0.29
	D2	2.54	4054	12.55	0.36	0.87	0.31
	C1	3.47	39.39	11.70	0.74	0.88	0.23
	C2	2.69	40.91	13.96	0.44	0.86	0.25.
	SOP	5.80	45.04	12.43	0.84	0.88	0.38
Industrial	D1	2.65	23.33	15.50	0.63	0.85	0.20
	D2	1.85	15.79	11.73	0.43	0.88	0.35
	C1	2.17	12.16	9.43	0.78	0.91	0.15
	C2	1.90	16.04	13.27	0.37	0.87	0.16
	SOP	1.73	53.27	31.20	0.88	0.91	0.21
IFR Reservoir	D1	0.01	43.89	17.27	0.63	0.83	0.20
	D2	0.01	37.31	13.64	0.43	0.86	0.35
	C1	0.01	21.42	9.95	0.78	0.90	0.15
	C2	0.01	40.50	13.88	0.37	0.86	0.16
	SOP	0.00	13.08	5.90	0.88	0.94	0.20
IFR Diversion	D1 D2 C1 C2 SOP	0.00	16.32	2.93	0.93	0.97	0.88

Table 2: Objective Function Values Calculated for 1963–1993 Optimization and Total Spills from Ragoleto Reservoir for 1994–2003 Simulation Operated Through Proposed Discrete and Continuous Hedging Rules

	D1	*D2*	*C1*	*C2*
Objective function values for 1963–1993 optimization	20.640	11.113	14.410	14.063
Total spills from Ragoleto reservoir for 1994–2003 simulation [10^6 m^3]	21.46	18.82	17.64	20.06

In particular, always respecting the strict constraint on municipal use, being irrigation use characterized by an higher priority in respect to industrial, the ratio,

$$1 \leq \frac{W_{irr}}{W_{ind}} \leq 3 \qquad \ldots (3)$$

has been always considered greater than one with a maximum value equal to three.

The sensitivity of hedging rule $C1$ to the variation of the ratio between weights attributed to irrigation and industrial uses has been evaluated on the basis of indices calculated as result of the simulation of the system behavior operated through $C1$-type hedging rules which parameters have been calibrated according to several value of the ratio reported in (3).

Figure 6 shows the pattern of several indices in respect to growing values of the ratio that means more irrigation-oriented $C1$ hedging rules.

When the ratio grows, sum of squared shortages, that can be considered a good proxy variable of the economic damages corresponding to water shortages, shows a peculiar pattern with a minimum of the

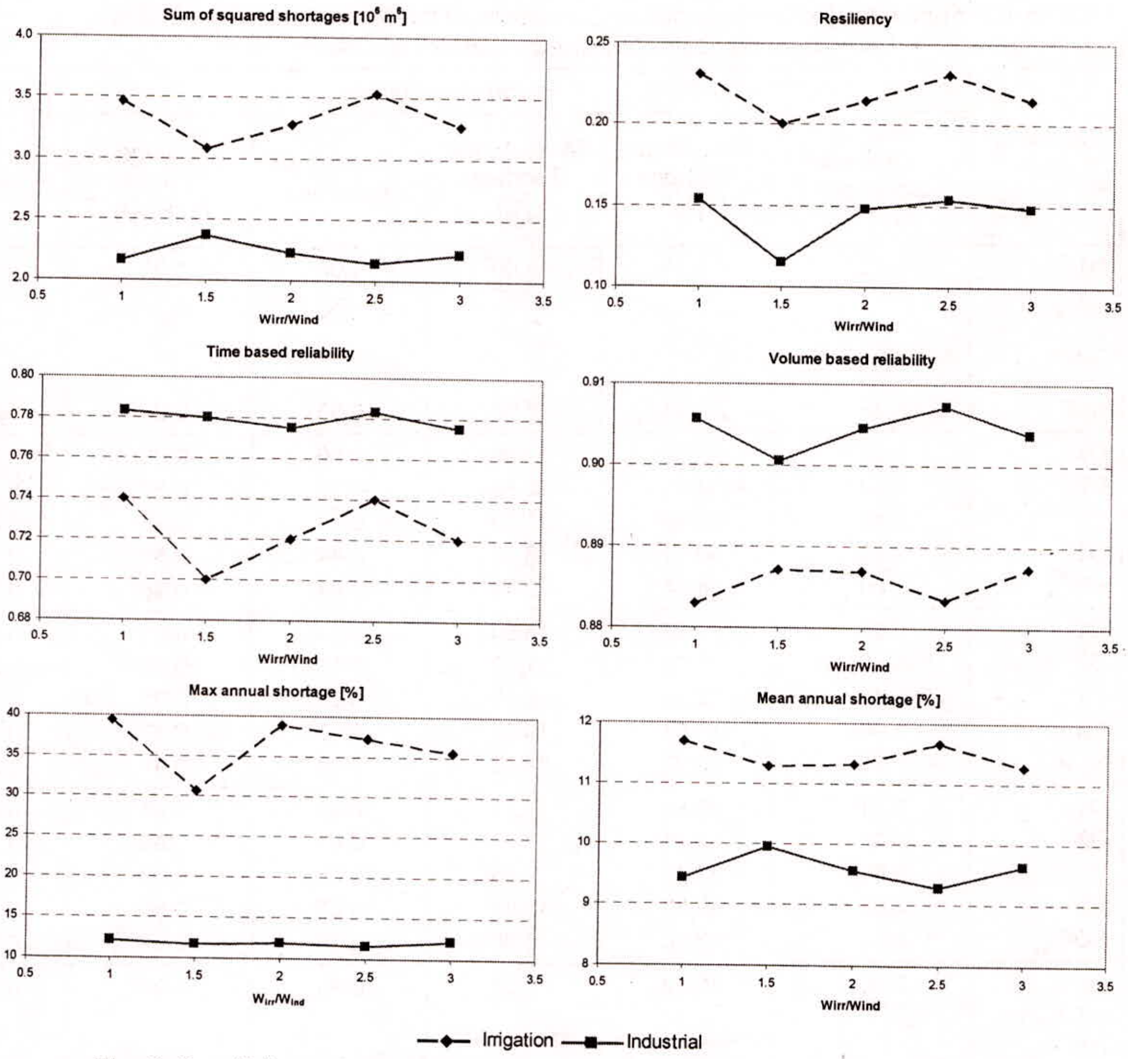


Fig. 6: Sensitivity analysis of continuous hedging rule *C*1 in respect to the growing ratio between weights attributed respectively to irrigation and industrial use

difference between the values of the index calculated for the two uses for the ratio close to 1.5.

As opposite to the sum of squared shortages pattern, time-based reliability and resiliency indices show a minimum for 1.5 due to more frequent less severe shortages. Time based reliability is still greater than 0.70 a value that can be considered acceptable for irrigation considering that the index is evaluated on a ten years simulation including two drought events. Volume based reliability is always greater for industrial use than irrigation due to the latter uneven distribution throughout the year giving to irrigation use a more fragile feature.

Maximum annual shortage, expressed as percentage of the demand, is almost constant for industrial use whereas shows a minimum for 1.5 for irrigation use. Mean annual shortage is not very sensitive to the variation of the ratio with values close to the 10% of the monthly demand for both irrigation and industrial use.

On the basis of these analyses a continuous hedging rule *C*1 characterized by a ratio among the weights attributed to irrigation and industrial uses equal to 1.5 has been considered the most efficient among the investigated rules.

The twelve parameters of the refined continuous hedging rule *C*1_1.5 have been reported in Table 3 and, in graphical form in Figures 7.

The area shown in Figures 7 is an helpful, easy to understand and clear support to the actual operation of the Ragoleto reservoir. In particular for each month two zones of the reservoir, varying throughout the year, are identified to which correspond monthly rationing factors defined through the b-angles reported in Figure 8.

As shown by points in Figure 7, which represent stored volumes during the 1994-2003 ten year simulation, proposed hedging rule is not very strict, indeed, rationing occurs at maximum three years during irrigation season for a period showing at least two historic drought periods.

The most crucial months are those just before the beginning of irrigation season, namely March and April where the proposed hedging rule imposes rationing for stored volumes below 7 10^6 m^3 (about 34% of the maximum capacity) with low slopes (see Figure 8) that means severe rationing.

Table 3: Parameters of Refined Continuous Hedging Rule *C*1

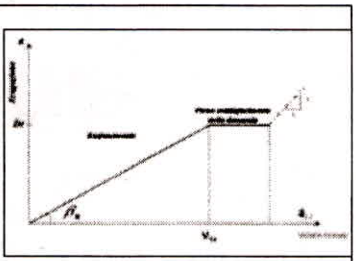
<table>
<tr><td colspan="2"><i>C1</i></td><td rowspan="4"></td></tr>
<tr><td colspan="2"><i>Continuous hedging rule</i></td></tr>
<tr><td><i>Obj. func. Value</i></td><td><i>Number of variables</i></td></tr>
<tr><td>$\frac{W_{irr}}{W_{ind}} = 1.5$</td><td>12</td></tr>
<tr><td colspan="3"><i>Parameters</i></td></tr>
<tr><td><i>Month</i></td><td>β
[°]</td><td>V_1
$[10^6\ m^3]$</td></tr>
<tr><td>Jan.</td><td>16.30</td><td>2.47</td></tr>
<tr><td>Feb.</td><td>6.63</td><td>5.01</td></tr>
<tr><td>Mar</td><td>4.78</td><td>6.97</td></tr>
<tr><td>Apr.</td><td>4.78</td><td>6.97</td></tr>
<tr><td>May</td><td>8.79</td><td>7.00</td></tr>
<tr><td>Jun.</td><td>13.30</td><td>6.27</td></tr>
<tr><td>Jul.</td><td>18.71</td><td>5.71</td></tr>
<tr><td>Aug.</td><td>26.68</td><td>3.85</td></tr>
<tr><td>Sep.</td><td>29.70</td><td>2.60</td></tr>
<tr><td>Oct.</td><td>35.00</td><td>0.83</td></tr>
<tr><td>Nov.</td><td>44.85</td><td>0.59</td></tr>
<tr><td>Dec.</td><td>26.68</td><td>1.16</td></tr>
</table>

Figure 8 reports monthly slopes for the refined continuous *C*1_1.5 hedging rule. b-angles close to 45° means more SOP-like rules; this is the case of autumn months during which greater expected inflows to the reservoir during winter months discourage storing water, whereas during spring months rationing is prescribed so to make available for the raise of the demand during the irrigation season.

Figure 9 shows the occurrence probability of shortages belonging to classes defined in terms of percentage of the total monthly demand for the refined continuous hedging rule *C*1_1.5 and the SOP.

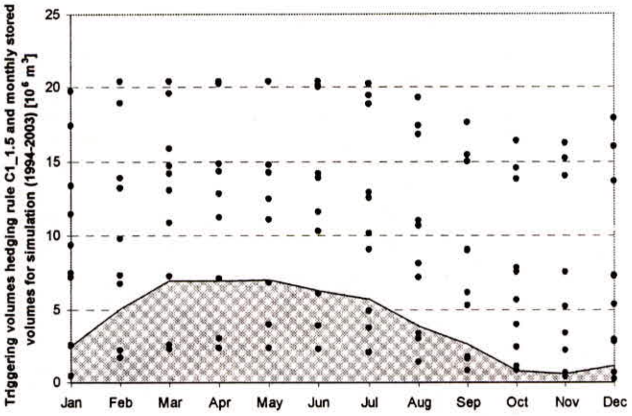


Fig. 7: Triggering volumes for Ragoleto reservoir according to the refined *C*1_1.5 continuous hedging rule and monthly stored volumes (dots) during simulation 1994–2003

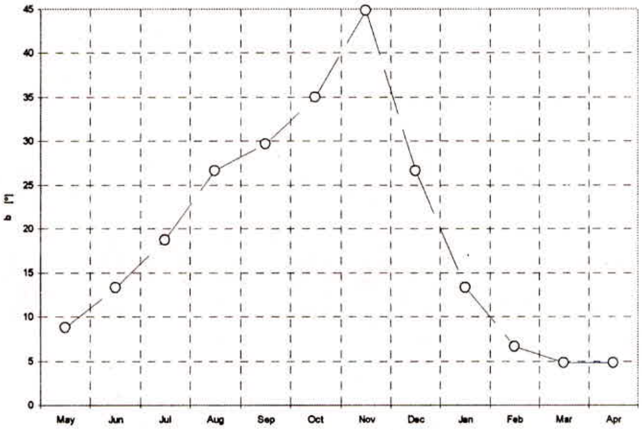


Fig. 8: Monthly slopes continuous hedging rule *C*1_1.5

It should be noticed that due to the constraint imposed within the optimization model of the parameters of the *C*1_1.5 rule no municipal shortages occur even during droughts whereas shortages also belonging to the class 80–100% of the monthly demand appear for August if the system is operated through a SOP.

Results obtained for irrigation use reflect the features requested to the hedging rule through the objective function chosen within the optimization model. Minimizing the sum of the squared ratio between monthly shortage and demand fosters the spreading of shortages throughout the entire irrigation season. For instance if the system is operated through SOP probability of shortage during the last four months of the irrigation season is about 20% whereas if the system is operated through *C*1_1.5 shortages are more likely (about 30%) and include also May.

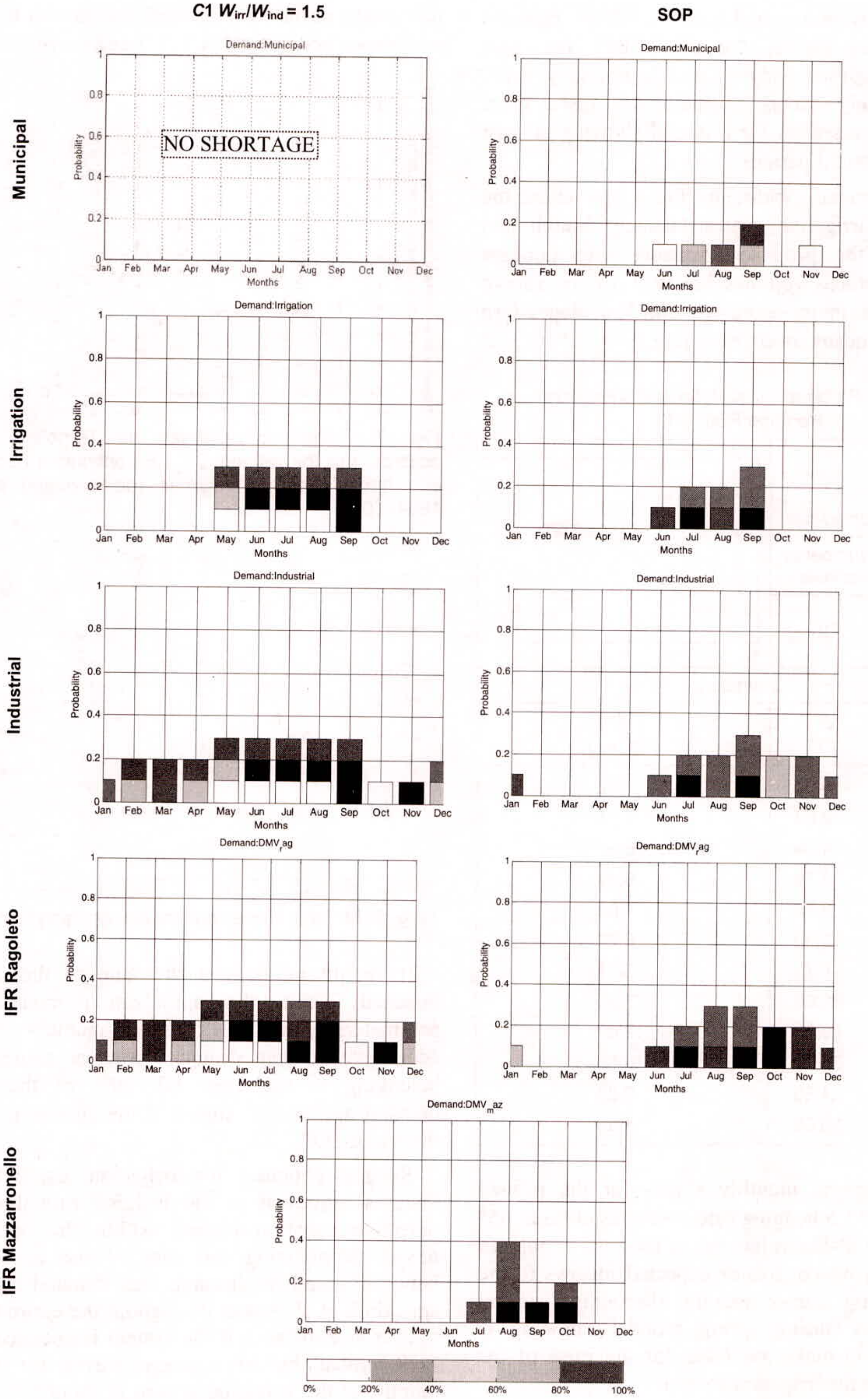


Fig. 9: Occurrence probability of shortages belonging to classes defined in terms of percentage of the total monthly demand for the refined continuous hedging rule *C*1_1.5 and SOP

On the other hand the greater part of this probability is actually constituted by slight shortages belonging to the class 0–20% of the monthly demand that is much more tolerable by crops than the very severe shortages (belonging to the class 80–100%) for July, August and September occurring implementing a SOP. Avoiding peaks of shortages in favor of more frequent slight shortages is a desirable goal. Furthermore slight shortages belonging to the white class could be considered with the same order of magnitude that reasonable achievements obtainable through a better management of the networks to reduce losses in delivery of volumes devoted to irrigation. Implementation of the proposed $C1\_1.5$ slightly increases the overall probability of shortages for industrial use but enables a better distribution throughout the year of the probability of not very severe shortages reducing the occurrence of shortages belonging to the most severe class.

Ecological use for Ragoleto reservoir can be considered even more sensitive to concentrated shortages than other uses. A single very sever shortage can indeed destroy very fragile river ecosystems.

CONCLUSIONS

Several form of hedging rules have been considered and analyzed for the operation of a reservoir making part of a multiuse water supply system. The main aim of the proposed hedging rules has been to reduce the impacts to water uses with different priorities and distribution throughout the year due to likely water shortages caused by the variability of streamflows characterizing rivers in drought-prone areas.

Parameters of discrete and continuous hedging rules have been optimized by means of an heuristic optimization model based on genetic algorithms. On the basis of performance indices, evaluated on the results of simulation of the water supply system, a continuous hedging rule has been chosen as the best candidate to operate the system also considering the less number of parameters to be calibrated.

The proposed continuous hedging rule guarantees, through the introduction of adequate constraints, the respect of high standards for municipal water supply and has been further refined in order to explore its sensitivity to the ratio between the weights attributed to irrigation and industrial use during its calibration.

Refined continuous hedging rule has been then implemented within a new simulation and compared with results obtained operating the system through a SOP.

Results show that beside guarantee municipal use the proposed continuous hedging rule performs better than SOP avoiding peaks of shortages favouring more frequent less severe temporary water shortages.

A further development of the present study should take into account within the optimization of the parameters of the rules the different marginal damage deriving from a shortage occurring during a given month in respect to another month.

In order to cope with climate changes and to improve the reliability of the models with a greater size of records any operating rule should be continuously updated through a re-calibration of its parameters as soon as new data are available.

REFERENCES

Alecci, S., Reitano, B. and Rossi, G. (1986). "Evaluation of alternatives in management of water resources systems through performance indices". *Proc. of the Int. Conf. on water Resources Needs and Planning in Drought Prone Areas*, Khartoum.

Bayazit, M. and Unal, N.E. (1990). "Effects of hedging on reservoir performance". *Water Resour. Res.*, 26(4), 713–719.

Bower, B.T., Hufschmidt, M.M. and Reedy, W.W. (1962). "Operating procedures: Their role in the design of water-resource systems by simulation analyses". *Design of water resources systems*, A. Maass, M.M. Hufschmidt, R. Dorfman, H.A. Thomas Jr., S.A. Marglin and G.M. Fair, eds., Harvard University Press, Cambridge, Mass.

Cancelliere, A., Ancarani, A. and Rossi, G. (1998). "Susceptibility of water supply reservoirs to drought conditions". *J. of Hydrol. Engineer,* 3(2), 140–148.

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

Hashimoto, T., Stedinger, J.R. and Loucks, D.P. (1982). "Reliability, resiliency, and vulnerability criteria for water-resource system performance evaluation". *Water Resour. Res.*, 18(1), 14–20.

Ilich, N., Simonovic, S.P. and Amron, M. (2000). "The benefits of computerized real-time river basin management in the Malahayu reservoir system." *Can. J. Civ. Engg.*, 27(1), 55–64.

Klemes, V. (1977). "Value of information in reservoir optimization". *Water Resour. Res.*, 13(5), 857–850.

Labadie, J.W. (2004). "Optimal operation of multi-reservoir systems: state-of-the-art review". *J. Water Resour Plng Mgmt*, 130(2), 93–111.

Loucks, D.P., Stedinger, J.R. and Haith, D.A. (1981). *Water resource systems planning and analysis*. Prentice-Hall, Englewood Cliffs, N.J.

Lund, J.R. and Guzman, J. (1999). "Derived operating rules for reservoirs in series or in parallel". *J. Water Resour. Plng. Mgmt.* 125(3), 143–153.

Lund, J.R. (2006). "Drought storage allocation rules for surface reservoir systems". *J. Water Resour. Plng. Mgmt.* 132(5), 395–397.

Maass, A., Hufschmidt, M.M., Dorfman, R., Thomas, H.A., Jr., Marglin, S.A. and Fair, G.M. (1962) . *Design of water resources systems*. Harvard University Press, Cambridge, Mass.

Neelakantan, T.R. and Pundarikanthan, N.V. (1999). "Hedging rule optimisation for water supply reservoirs system". *Water Resour. Mgmt.*, 13(6), 409–426.

Paredes, J. and Lund, J.R. (2006). "Refill and drawdown rules for parallel reservoirs: Quantity and Quality". *Water Resour. Mgmt.* 20, 359–376.

ReVelle, C., Joeres, E. and Kirby, W. (1969). "The linear decision rule in reservoir management and design. I. Development of the stochastic model." *Water Resour. Res.*, 5(4), 767–777.

Shih, J.S. and Revelle, C. (1994). "Water supply operations during drought: a continuous hedging rule". *J. of Water Resour. Plng. and Mgmt.*, 120(5), 613–629.

Shih, J.S. and Revelle, C. (1995). "Water supply operations during drought: a discrete hedging rule". *Eur. J. of Oper. Res.*, 82, 163–175.

Stedinger, J.R. (1984). "The performance of LDR models for preliminary design and reservoir operation". *Water Resour. Res.*, 20(2), 215–224.

Tu, M.-Y., Hsu N.-S., Tsai F. T.-C. and Yeh W. W.-G. (2008). "Optimization of Hedging Rules for Reservoir Operations, *J. of Water Resour. Plng. and Mgmt.*, 134(1), 3–13.