Multipurpose water use in a system of reservoirs

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Abstract In the upper Tiber River basin there is a complex network of artificial and natural reservoirs that can be considered a laboratory in which reservoir tools and policies can be easily tested. In this context, a model at the basin scale has been developed for surface water resource management. This model has many features that allow the user to easily sketch the river network, to set up the management policies for each water use, and to retrieve the output. The model is based on three fundamental algorithms: the first models the river network in terms of the various uses within the river basin; the second calculates a water budget, understood as the difference between the total demand and the available water amount; and the third calculates the water resources in the basin. This last algorithm can also take into consideration the many political and administrative constraints that may limit the management criteria.

Key words environmental use; multipurpose uses; reservoir management; simulation model; water management

INTRODUCTION

Water resources management in a multipurpose scenario always represents an interesting issue (Simonovic, 2000), also because in Mediterranean countries water contributions to river basins are currently becoming more and more concentrated in short wet periods followed by longer periods of drought (Zelenhasic, 2002). This meteorological situation has led many countries, including Italy, to build several artificial reservoirs originally intended to supply agricultural uses. Lately, those reservoirs have been used more and more to satisfy several other water demands, such as the ever-increasing municipal use, resulting in a disadvantage for agricultural areas.

Besides these two traditional uses, we have to consider the amount of water that has to be released into the riverbed in order to guarantee compatible environmental conditions for the new recreational and social uses that are appearing lately along the river banks (Wohl *et al.*, 2005). These new conditions, related to a multipurpose use of the water resource stored in reservoirs, has led on the one hand to competition amongst the various uses during drought periods, and on the other hand to the need for new management policies and planning tools for the total available resource.

THE MODEL

The simulation model prepared for the water resources management at the basin or sub-basin scale is based on the outlining of the river network, which considers the node as the central element around which water is managed and utilized and the link as the connection element between nodes.

The main features of the model can be summarized in the following points:

– extremely friendly and flexible algorithm for outlining the river network;
– possibility of utilizing input data in the form of a time series, a typical year or both, so as to be able to use reliable time series data, even when partial in relation to the entire simulation period;
– possibility of setting the percent value of transportation losses that can be hypothesized in every link;
– weekly or monthly simulation time step;
– water budget algorithm between the water resources in the reservoir and the user node demands, with the budget calculated for a time window ranging from one simulation week up to the end of the irrigation period or a minimum 4 weeks;
– possibility of taking into account in the budget equation the recovery of water deriving from upstream nodes with usages that are not totally dissipative and any natural contributions deriving from tributaries that flow in between the reservoir and the user node;
– possibility of freely limiting the number of user nodes that are managed by the reservoir and thus contributing to the value of the total requirement in the budget equation;
– algorithm for water resources management in deficit conditions that can use a priority criterion or a criterion proportional to the requirements, or as a function of the pre-established percentage values;
– extremely flexible reading of output data on reservoir, user and river flow control nodes, both in graphic and numerical terms.

Referring to the specific bibliography for all detailed explanations regarding the model (Casadei & Bellezza, 2005), this article focuses on the water budget equation, which is fundamental for explaining how the model functions, and the procedures for priority management, which is then applied in the case study.

The budget equation is based on the calculation of the Total Requirement Volume (*TRV*) and of the Total Available Volume (*TAV*) in the reservoir (*S*). The *TRV* at week *i* is derived from the requirements of all the *n* users *j* present within the predetermined management basin; this calculation is done using the control time window $t = [i;\ i+k]$, with $k \geq 4$ weeks:

$$TRV(i) = \sum_{t=i}^{i+k} \sum_{j=1}^{n} FA_j^*(t) \tag{1}$$

The term $FA_j^*(t)$ represents the requirement of user *j* in the *t*th period, with $i \leq t \leq k$, increased by any losses in transportation along the links from the reservoir to the user. For this it is necessary to allow for the fact that some nodes could take advantage of any returns from other users upstream, as well as from contributions deriving from any natural incoming flows downstream from the reservoir and upstream from the user node:

$$FA_j^*(t) = \left\{ FA_j(t) - \sum_m \left[\left(\prod_{am=1}^{zm} (1-\gamma_{am}) \right) \cdot RES_m(t) \right] - \sum_s \left[\left(\prod_{as=1}^{zs} (1-\gamma_{as}) \right) \cdot IMM_s(t) \right] \right\} \cdot \prod_{aj=1}^{zj} \left(\frac{1}{1-\gamma_{aj}} \right) \tag{2}$$

where $FA_j(t)$ represents the net requirement requested by user *j*, while:

$$\left[\prod_{am=1}^{zm}(1-\gamma_{am})\right]\cdot RES_m(t) \tag{3}$$

$$\left[\prod_{as=1}^{zs}(1-\gamma_{as})\right]\cdot IMM_s(t) \tag{4}$$

represent, respectively, the "useful" part of the return of the upstream user *m*, and the "useful" contribution of any lateral incoming flows. With γ_{aj}, γ_{am} and γ_{as}, the coefficients are indicated for the transportation losses on the *z* watercourses pertaining, respectively, to the reservoir-user *j* course, upstream user-user *j* course and lateral incoming flow-user *j* course.

Finally, it can be pointed out how the quantity RES_m is a function of the type of user being considered, according to the following relations:

$$RES_m(t) = \begin{cases} FA_m(t)\cdot(1-\gamma_{mun})\cdot(1-\varepsilon_{mun}) & \textit{Municipal node} \\ FA_m(t)\cdot(1-\eta_{irr})\cdot\varepsilon_{irr} & \textit{Irrigation node} \\ FA_m(t) & \textit{Hydroelectric and environmental node} \end{cases} \tag{5}$$

where: γ_{mun} = distribution losses within the municipal node; ε_{mun} = water dissipated at the municipal node; η_{irr} = distribution/watering efficiency; ε_{irr} = return flow, the part of the losses that returns to the surface network.

The *TAV* in reservoir (*S*), in the same control $t = [i;\ i+k]$, taking into account the initial volume (S_S), the contribution deriving from flows into the reservoir (Q_S) and the losses due to evaporation (EV_S), as well as the volumes reserved for maintaining the Minimum Instream Flows (*DMV*) in the control sections, is given by the relation:

$$TAV_S(i) = S_S(i) + \sum_{t=i}^{i+k} Q_S(t) - \sum_{t=i}^{i+k} EV_S(t) - \sum_{t=i}^{i+k}\sum_{j=1}^{m} DMV_j(t) \tag{6}$$

Therefore the decision whether or not to manage and thus to reduce the distribution of water depends on the value taken on by the ratio between the Total Requirement Volume and the Total Available Volume.

$$\alpha_{rid}(i) = \frac{TAV_S(i)}{TRV(i)} \tag{7}$$

In the case that this ratio takes on a value less than 1, it is deemed necessary to reduce the releases to the users, in which the Available Volume to be managed in the simulation period *i* is a function of the value α_{rid} thus obtained.

$$AV(i) = \alpha_{rid}(i)\cdot\sum_{j=1}^{n} FA_j^*(i) \tag{8}$$

The priority management procedure adopted in reality interprets the priorities defined in the input stage in a flexible manner, i.e. it does not follow the logic of distributing the resource first to the most important user and then to all the other users in the pre-established order; rather, it reduces the requirement by a certain percentage, which varies from one user to the next, starting from the lowest priority user, repeating the budget each time until obtaining $\alpha_{rid} \geq 1$. The calculation proceeds for the subsequent cycles as illustrated in Fig. 1.

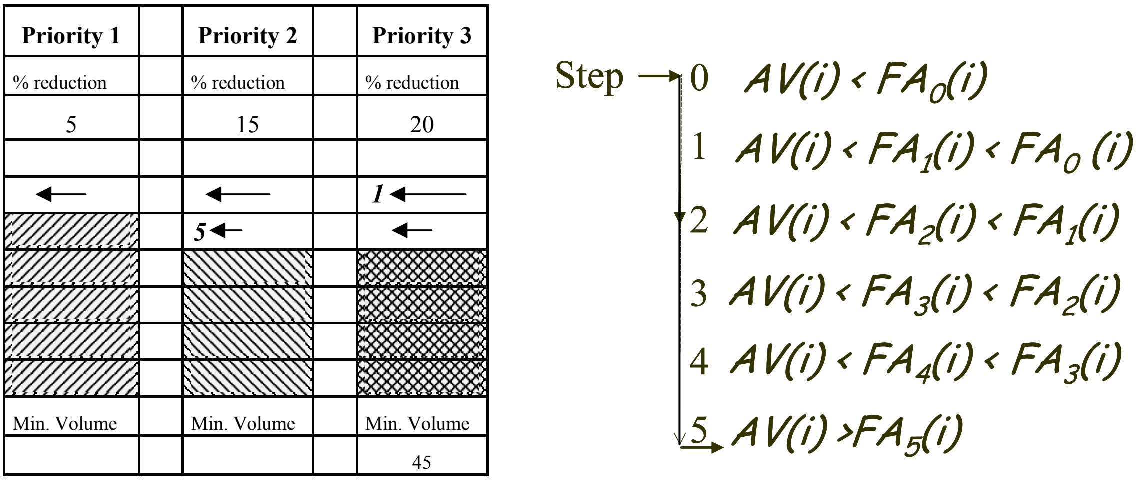

Fig. 1 Operating diagram of the "balanced" priority management, $AV(i)$ available volume for users at week i, $FA(i)$ user initial requirements and reduced requirements at week i.

It can be observed that the percentage fractions of the requirements to be subtracted from each user can be suitably differentiated, so as to balance the distribution among the more favoured and less favoured users. Furthermore, it is possible to insert, user by user, a reference value for the minimum volume stored in the reservoir below which the supply to the corresponding user is completely interrupted. For this reason, and also to differentiate from the management procedure illustrated by others in the references (Strzepek *et al.*, 1989; Diaz *et al.*, 1997), the term "priority-balanced" was adopted.

CASE STUDY

The model was validated and applied to a case study which provides for the management of water resources available in the system of artificial reservoirs, consisting of the Montedoglio reservoir on the Tiber River and the Casanova reservoir on the Chiascio River, with two other natural reservoirs present in the district, i.e. Lake Trasimeno and the lake of Chiusi-Montepulciano.

The management of the network associated with this reservoir system (Fig. 2) is rather complex. The entire network involves two different regional territories (Umbria and Tuscany); two different watersheds (Tiber and Arno); three separate municipal water supply system operators (ATO6 and ATO4 in Tuscany, ATO1 in Umbria); and a number of areas of high environmental sensitivity, represented by the two natural lakes and by the main rivers downstream from the artificial dams. Furthermore, the irrigation

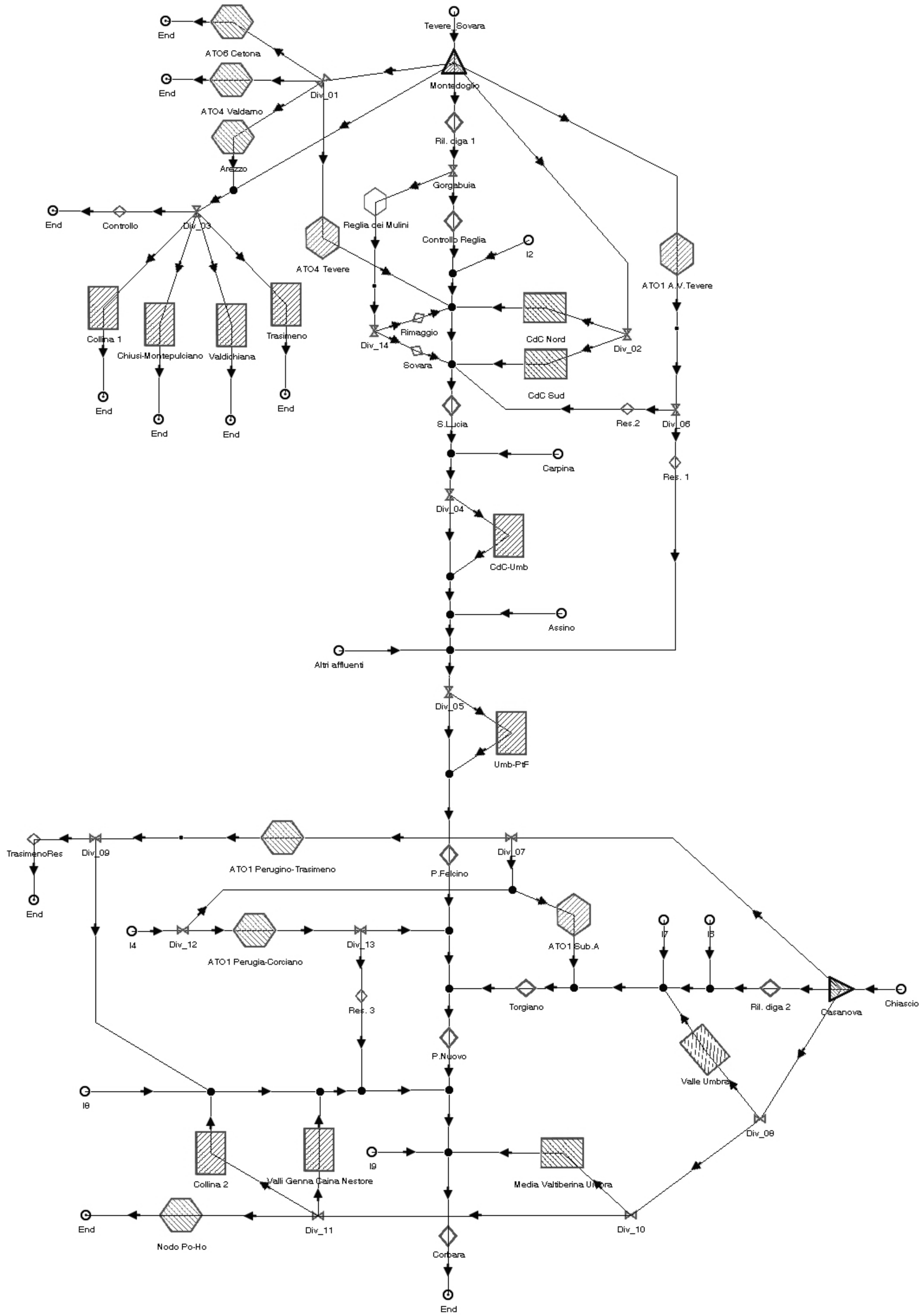

Fig. 2 Flow network in the case of study.

situation varies greatly from one zone to the next, with numerous uncertainties regarding the current and (above all) future water requirements (Linoli, 2006).

In these circumstances, it is extremely complex to obtain the data needed for calculations, whereas the model described previously makes it possible to hypothesize numerous simulation scenarios on the basis of the different combinations of water requirements for different uses, considering artificial reservoir management as well as the requests of the various users, including those of an environmental nature.

Over 100 simulations were done on a time series of 33 years, attempting to evaluate various scenarios in a perspective of the evolving of requirements over time and of different sensitivities to the environmental usage of the water, with the latter being understood as the increase of the minimum releases in the river downstream from the artificial dams.

RESULTS AND DISCUSSION

The first result to be examined in the range of simulations produced concerned the behaviour of the reservoirs in regard to the increasing demand for water for various uses. In particular, considering a decrease in the irrigation requirements following the adoption of more efficient irrigation methods, and an increase in municipal requirements, the behaviour of the individual reservoirs does not change substantially, although minimum or maximum releases into the river downstream from the dams are hypothesized. There is always a heavy demand on the Montedoglio reservoirs (Fig. 3) with evident oscillations in the volume, and consequently in the levels, even in rather short periods of time; on the contrary, the Casanova reservoir remains constantly above the dead volume (Fig. 4), thus showing potential regarding additional uses, which could also be envisaged in an integrated manner with the previous reservoir.

These considerations clearly show the opportuneness of considering the overall network as an integrated system, and at the same time direct us toward the reading of the second result of the simulations, i.e. the analysis of the deficit in the user nodes.

The trend of the available volumes for the various users, as well as the relative deficits, can be analysed in terms of time series of weekly data, in order to better understand the frequency in relation to seasonal periods, or it can be cumulated in annual values, or analysed in terms of weekly or yearly extreme values. In any event, the approach investigated more in-depth closely links the user with the reservoir, showing in a graph the trend of the annual deficit per user as a function of the reservoir volume in one week, which can be freely chosen. Figure 5 shows an example of this representation for one irrigation node, taking as a reference the volumes stored in Montedoglio at the 18th week, i.e. near the start of the irrigation season. As can be seen, there are many years with a deficit, as could be expected given the lower priority of irrigation use and especially the high-stress situation of the Montedoglio reservoir; however, the most interesting point is that once a critical deficit threshold has been set (e.g. 20%), one can read the value of the reservoir volume at the 18th week (approx. 93 Mm^3) below which it is probable that this threshold is exceeded, with increases in the deficit more or less linear with the decrease in the available volume at the 18th week.

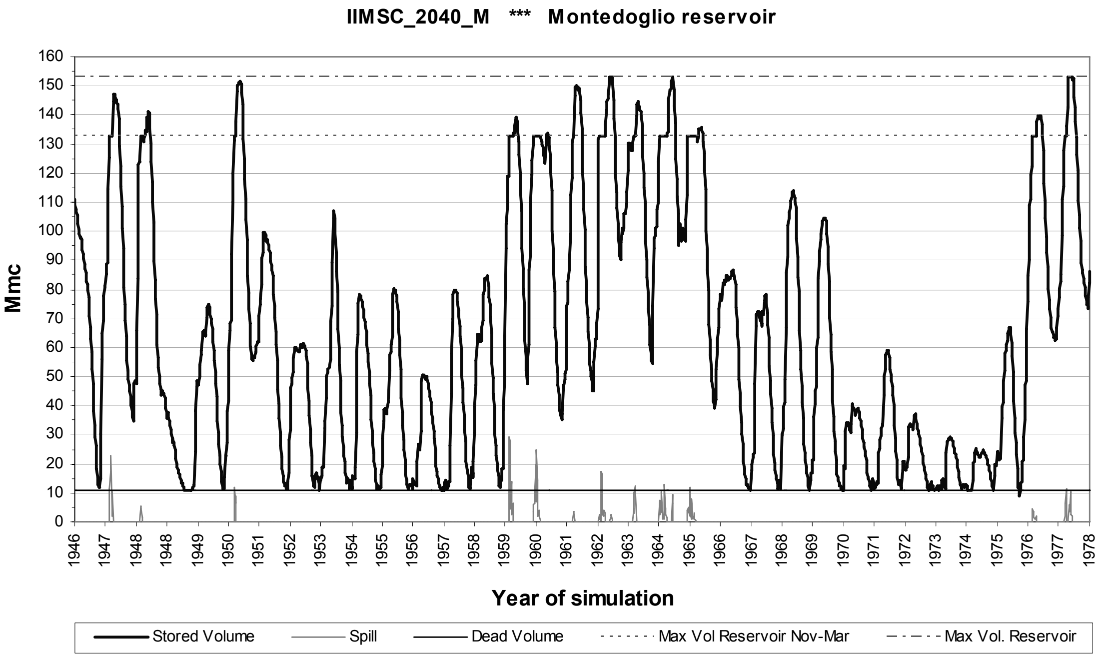

Fig. 3 Trend of the volumes, in the simulated time series, for the Montedoglio reservoir.

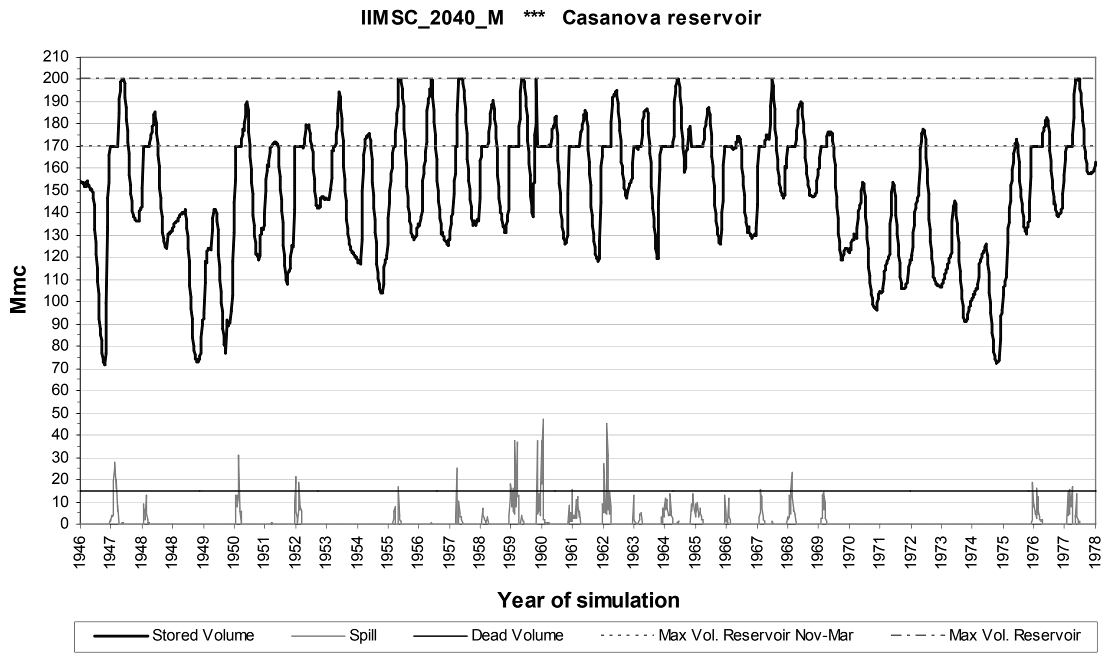

Fig. 4 Trend of the volumes, in the simulated time series, for the Casanova reservoir.

This result can be used both in the planning stage for evaluating the degree to which the various users suffer in the overall context of the network and the hypothetical priorities assigned, and in the management stage as a decision support system, especially in multiyear drought cycles.

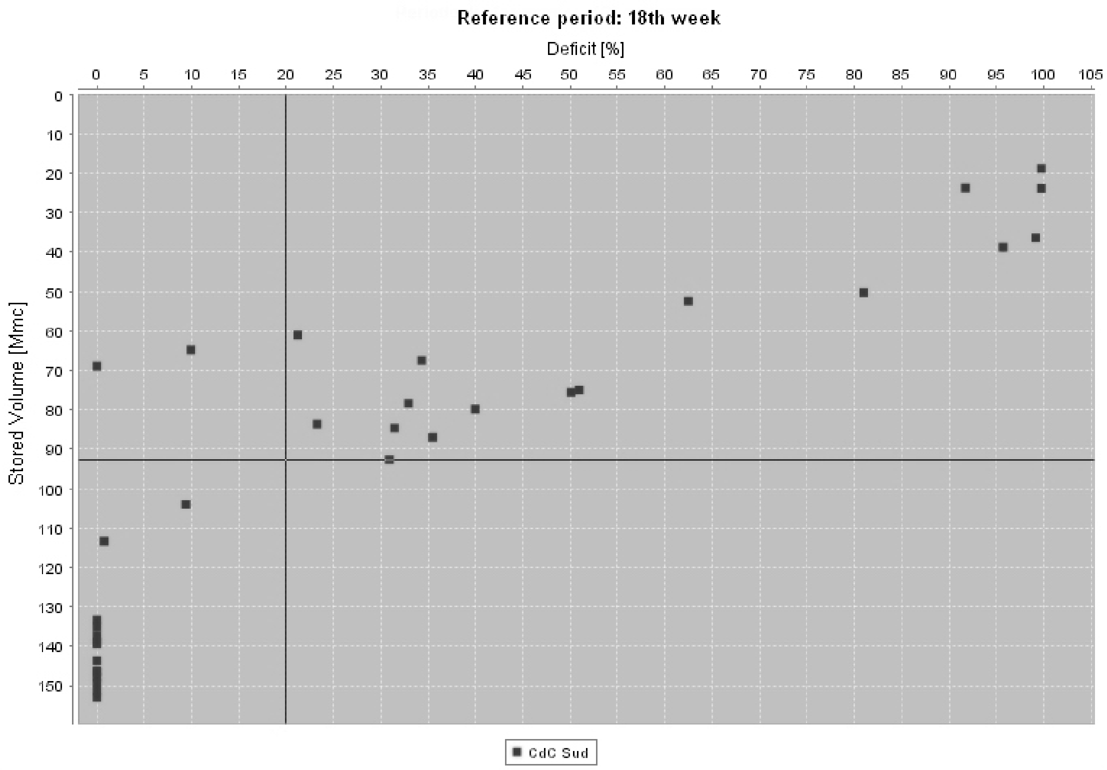

Fig. 5 Trend of annual deficits at an irrigation node as a function of the reservoir volumes at the 18th week.

Another aspect the authors wished to investigate within the simulated scenarios was that which connects the release increases downstream from the artificial dams with the deficits of the various users. In recent years there has been more and more awareness regarding the environmental state of rivers and their surrounding areas, where activities are often carried out which make direct use of these areas (Ministero dell'Ambiente, 2002). Thus new needs have arisen, which demand greater flows than those of the hypothetical minimum instream flows downstream from the dams. Given the objective difficulties in making a comparative evaluation between this usage of water and traditional usages, it was preferred to point out the effects on other types of water resource usage.

The results were summarized in terms of maximum deficit found in the simulation time series as a function of a variability of releases downstream from the reservoirs, from a minimum value (m) to a maximum value (M). In Fig. 6 the situation can be observed with reference to municipal nodes, with a clear tendency toward a considerable increase in the maximum deficit, but without a differentiation between the various nodes, by virtue of a substantial balancing between the priority hypotheses.

Figure 7 shows the same results for irrigation nodes, with an evident greater sensitivity to the phenomenon, both in absolute terms and in terms of trends, compared to the municipal nodes in the previous graph. Furthermore, in the case of irrigation nodes the maximum deficit absolute values are differentiated among the various users by virtue of the hypothesized assigned priorities.

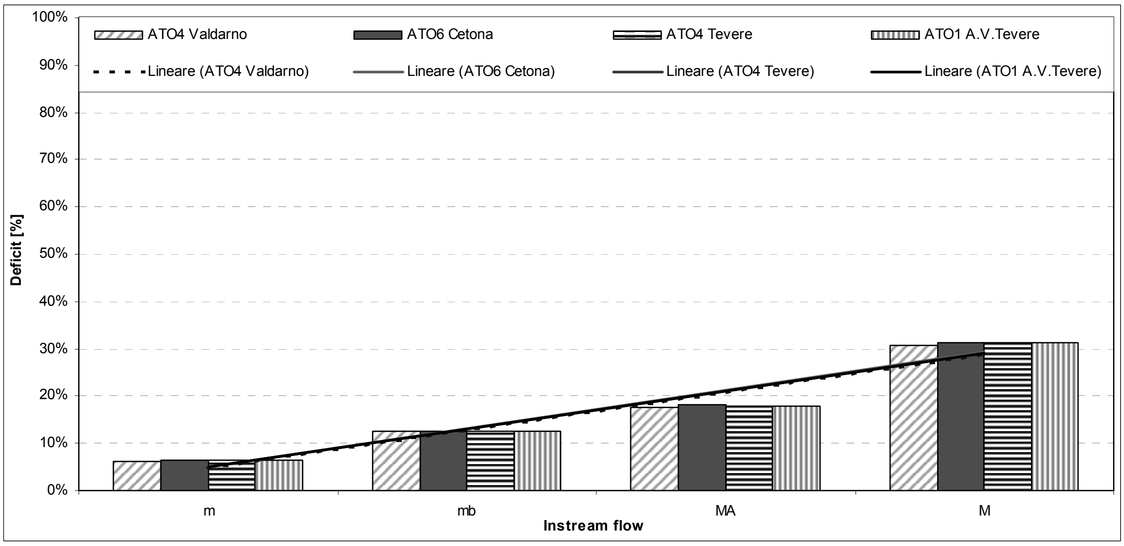

Fig. 6 Trend of maximum annual deficits at municipal nodes as a function of releases downstream from reservoirs.

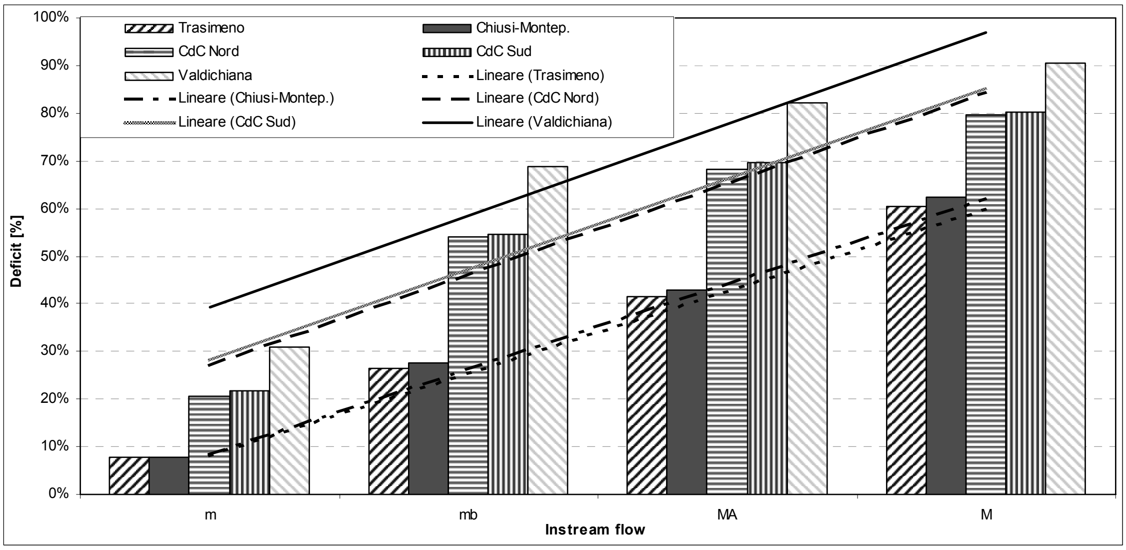

Fig. 7 Trend of maximum annual deficits at irrigation nodes as a function of releases downstream from reservoirs.

CONCLUSIONS

The concluding considerations of greatest interest are of a methodological nature and may be summarized in a cycle of four steps: modelling; water requirements; management hypotheses; simulation results. Indeed, the support instrument prepared for making decisions is based on the concept of simulation through a model that is easy to use and simple to interpret as regards input and results; the results must in turn be analysed in order to be used as a source for new simulation ideas, especially in a context in which requirements and management hypotheses are extremely varied and uncertain.

In addition, the model also offers effective opportunities for its use in the reservoir management stage; the determining of critical reservoir thresholds for each user node may make it possible to plan emergency management and to simulate hypotheses for the distribution of the deficit of each node on an annual or multiyear basis. This aspect may be investigated further in the continuation of the study, with the implementing of suitable algorithms for the optimization of the available resources for each node on an annual or multiyear basis.

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