Coupling real time control and socio-economic issues in river basin planning

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Abstract

In this paper an approach for coupling real time control and socio-economic issue is presented. It relies on the use of Bayesian networks (Bns) to describe in a probabilistic way the behaviour of the farmers within an irrigation district in response to some planning actions. The network is coupled with classical stochastic hydrological models in a decisional framework. The approach has been successfully applied to the Vomano water system (Italy) a multipurpose water reservoir system highly exploited for hydropower generation.

Key words: Integrated Water Resource Management, model integration, Bayesian networks, reservoir operation, participation

1 Introduction

Reservoir networks management is a key component of Integrated Water Resource Management (IWRM) and plays a central role in the implementation of the Water Framework Directive, as the alteration of the natural water regime it produces may have a direct influence on the quality status of the downstream ecosystem.

The wise and sustainable management of the water stored in a reservoir requires consideration of a large number of complex and inter-related issues and poses intricate technical and political problems (McCartney and Acreman, 2001). It must take account of water uses upstream and downstream of the dam, including water supply, agriculture and power generation, as well as the needs of aquatic habitats. As such, reservoir management has to be considered within the wider framework of river basin management and planning (World Commission on Dams, 2000).

To make balanced and fair decisions in river basin planning requires an integrated assessment procedure (Castelletti and Soncini-Sessa, 2005) that evaluates the positive and adverse effects of the actions on the table, among which reservoir management policies have to be included (Soncini-Sessa *et al.*, 2003). This is far from being a trivial task, since it is complicated by the uncertainty arising from incomplete knowledge on both the physical and socio-economic components of the river basin system.

Indeed, it may happen that the physical and socio-economic processes that occur in a component of a water system are poorly known and/or that it is not practicable to obtain raw data to characterize them better. In these cases it would be obviously problematic for the analyst to describe that component by means of a type of model that assumes that a good knowledge of its internal processes or many data are available, as are mechanistic, empirical and markovian models. However, in order to describe all the components of the water system with the same type of models, (s)he is often forced to formulate unrealistic simplifications.

To tackle with these situations a participatory modelling approach is presented in this paper that integrates Bayesian networks (Bns) (Pearl, 1988) with the other types of models commonly used in river basin modelling (Castelletti and Soncini-Sessa, *this issue*). Bns are used to model the system components for which the knowledge is limited or unstructured (e.g. farmers' behavior in the irrigation districts), while mechanistic and empirical models for the components on which the knowledge is well structured or many data are available (e.g. power stations and catchments). The advantages of such an approach are illustrated through the description of its application to the planning of the Vomano water system, in Central Italy, a multipurpose water reservoir system highly exploited for hydropower generation.

The paper is organized following the framework of the Participatory and Integrated Planning (PIP) procedure proposed in Castelletti and Soncini-Sessa (2005), which was actually adopted to address the planning problem. The second section of the paper is therefore devoted to a brief description of the physical system, the stakeholders, the conflicting issues and the planning actions proposed. The third to the identification of the stakeholders' criteria and indicators, while the fourth to the decomposition of the water system in components and the identification of the models of those components on which the knowledge is well structured. The Bn that describes the farmers' behaviour in response to the considered planning actions is described in the fifth section. The paper is closed by sketching out the remaining phases of the project, from the alternatives design to the end.

2 The Vomano water system

The Vomano water system (Fig. 1) is one of the four chief river basins of Abruzzo, the water richest region in the central part of Italy. It extends for about 785 km^2 from the easternmost slopes of the Appennines (Gran Sasso) to the Adriatic Sea. Its waters are heavily used for hydropower generation, to cover power demand during peak hours (from 11:30 a.m. to 3:00 p.m.), and to a smaller extent for agricultural production and drinking water supply.

Three barrages dam the river course, forming as many water reservoirs (Campotosto, Provvidenza and Piaganini) with a total storage capacity of 220 Mm^3 (217 of which are in the Campotosto reservoir only). Each reservoir supplies water to a downstream power station (Provvidenza, S.Giacomo and Montorio respectively, for a total installed capacity of 700 Mw) and is fed, other than by its own catchment, by one or two interceptor canals cutting across the basin slopes, respectively at 1350, 1100 and 400 meters a.s.l., and draining a number of relatively small rivers that otherwise would flow directly to the sea. The flow rate of the Eastern interceptor at 400 m. is partially reduced before it feeds the Piaganini reservoir by the Ruzzo Aqueduct withdrawal, which supplies drinking water to Teramo and all the coastline towns. Provvidenza and S.Giacomo plants use the off-peak (night-time) electricity available on the national grid to pump water back to their upstream reservoir, Campotosto and Provvidenza respectively, while the Montorio plant, which closes the hydropower system downstream, is only equipped with turbine units. The release from this latter is partially withdrawn by the Villa Vomano diversion that serves a 7000 ha irrigation district, while the remaining flows down to the Adriatic Sea. In the low-demand periods (see Fig. 3) a small amount of the water drawn into the irrigation district is passed through a small hydropower plant (S. Lucia).

To close this brief framing of the Vomano water system it is worth while noting that, as the hydropower system is interlinked with the national grid, which provides the off-peak electricity to the pumping plants, this latter should be included as a part of the system considered. However, this would considerably complicate the system description, while it is definitively easier to limit the boundaries of the area under analysis to the natural water divides of the river basin and to consider the off-peak electricity as an uncertain input.

2.1 Conflicting issues and feasible actions

The above description should have given a clear idea of how the Vomano water system is highly exploited for hydropower generation purposes. Immediately after the Second World War, Enel, formerly the national power company, now

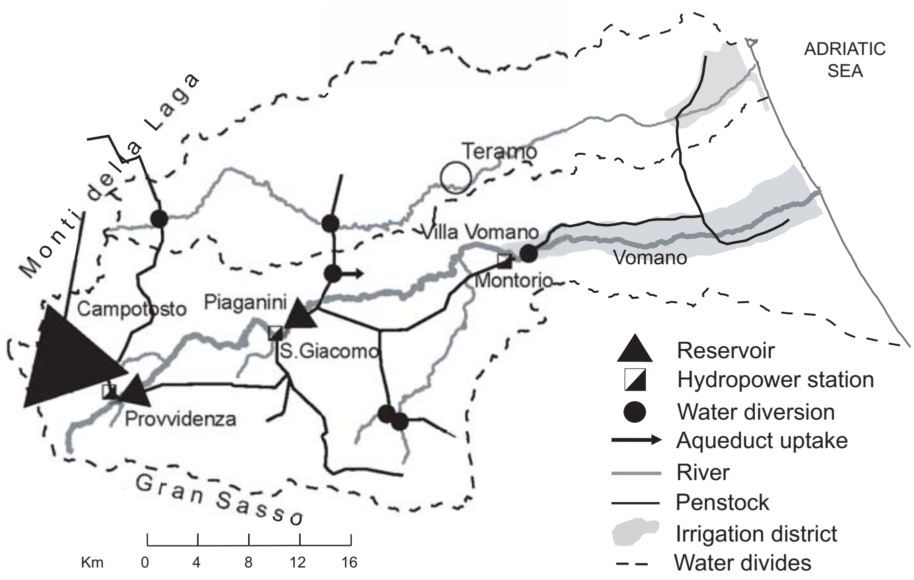

Fig. 1. The physical scheme of the Vomano water system.

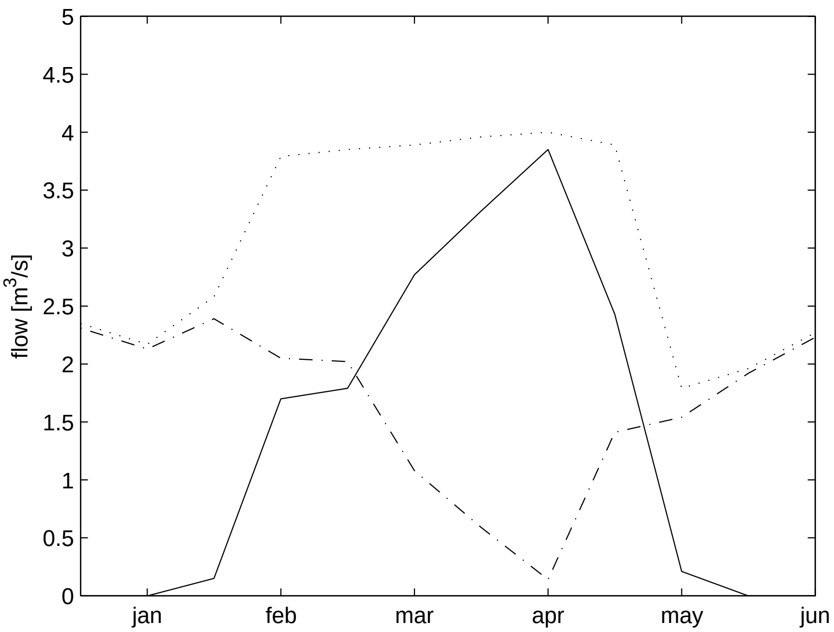

Fig. 2. The water withdrawal at the Villa Vomano diversion (dotted line), the flow supplied to the irrigation district (continuous line) and the flow passed through the S. Lucia hydropower station (dash-dotted line).

privatised, built on all the facilities to collect, store and exploit water and since then it holds all the rights on the water use. Without any agreement among the power company and the other downstream users, the water storage daily available into the system is obviously managed following the company business rationality, thus resulting in present and future conflicts over water uses and conservation that involves agricultural activities, environmental protection and drinking water supply against hydropower generation. Farmers and hydropower company compete for the water both during the late spring - summer months, when the crop growth is at its apex and Enel stores the inflow to satisfy the higher and profitable energy demand of the winter, and during the early spring, when the farmers are willing to create a water reserve to be used for the summertime irrigation, while Enel is still releasing, following the seasonal energy demand. At present, this conflict is only partially mitigated by an existing agreement, on the basis of which Enel ensures the water supply to the farmers in August at the selling cost of the winter peak hours. On the other hand, as the hydropower system is completely connected through penstocks (see Fig. 1), the Vomano river and its tributaries are often dried to a tickle during all the year, thus strongly compromising the river ecosystem status. Environmentalist associations as well as the two natural parks included in the river basin claim for restoring an acceptable level of environmental quality along the course of the river. Finally, the Ruzzo Aqueduct is not as much concerned with the water quantity problem, though it pays its water uptake to the power company, as interested in the water quality: during the draught periods, when the left hand interceptor, that usually feeds the Aqueduct, is not able to completely cover its water demand, the missing amount is provided by the Piaganini reservoir, and therefore its treatment is more costly.

All these conflicts refer to the current system configuration, but could increase or even explode whether new planning actions would be implemented as requested by the Italian law and solicited by some stakeholder in the river basin. More precisely, the Italian law (D. Lgs. 152/1999) assigns the Water Authorities the duty of defining a Minimum Instream Flow threshold (MIF) for all the rivers where such values have not been yet defined. This is the case of some river stretches in the Vomano water system, where the implementation of such a normative action is obviously strongly supported by the two parks and the environmentalist groups and equally opposed by the power company that fears a reduction in its power production potential. Precisely, a MIF has to be still defined for the river Fucino, the only natural outflow of the Campotosto reservoir, and downstream to the interceptors at 1100 and 400 m a.s.l. For its part, the farmer league (Consorzio di Bonifica Nord, in the following CBN), which represents the farmer's interests, is willing to enlarge the cultivated surface (structural action), from the current 7 000 *ha* up to 14 000 *ha*, with the purpose of improving the agricultural production of the region. In this way it would be also possible to have more remunerative crop rotations than those currently grown. To limit the consequent increase in the water demand this initiative would be coupled with the introduction of financial incentives (normative action) that should encourage the farmers to adopt more water-saving irrigation systems. Finally, as the implementation of any combination of these actions (MIF, irrigation district enlargement and

Table 1
The type of actions considered and their feasible values. The lower values correspond to the present situation.

Action	Dimension	Considered values
Irrigation district enlargement	[ha]	{7 000, 14 000}
Incentives	[€/ha]	{0÷600}
MIF - Fucino	[% of the mean flow]	{0÷30}
MIF - 1100 interceptor	[% of the mean flow]	{0÷30}
MIF - 400 interceptors	[% of the mean flow]	{0÷30}
Regulation policy	-	-

financial incentives) will inevitably result in a modification of the regulation policy through which the power company operate the three reservoirs, also the adoption of a new regulation policy has to be considered among the feasible actions. In conclusion the set of actions considered and the values characterizing them are listed in Tab. 1. In the following the term *alternative* is used to denote a coherent combination of the aforementioned actions.

At the time being, the decisional power of the Water Authority (Regione Abruzzo) is limited to the definition of the MIF values, but does not allow to modify the water rights held by the power company. However, in view of the future renewal of the rights, that will be inescapable matter of discussion in the preparation of the River Basin Management Plan (RBMP) required within 2009 by the Water Framework Directive (WFD, Directive/2000/60/EC), the Authority decided to explore the problem. In 2009 the Authority will play the role of Decision Maker (DM) and as such it will have to select an alternative (final political decision) among the ones that gather the largest consensus among the stakeholders. To identify these latter the likely impacts of each possible alternative has to be assessed on a set of indicators representing the major stakeholders' concerns and a negotiation process has to be carried out between them. This is the reason why the PIP procedure has been applied to the planning of the Vomano water system.

The above considerations are the results of the first two phases of the PIP procedure (see Castelletti and Soncini-Sessa, 2005).

3 Stakeholder criteria and indicators

To evaluate and compare the effects of the alternatives upon the system it is necessary first to identify, together with the stakeholders, a set of *evaluation* *criteria* that reflect their system of preferences. Then to identify quantitative *indicators* that allow to measure how much a given alternative satisfies each criterion. The list of the stakeholders and the relative criteria are given in Tab. 2, while the indicators are detailed in the following.

The power company

The evaluation criterion of the power company is to *meet the company's target*, which can be split in two lower level criteria: *energy production* and *economic return of the energy production*. Notice, that in each power station the production is made not only by turbining the natural inflows, but also the water volumes that were previously pumped into the upstream reservoir. The analysis of the historical records demonstrated that the water is often recirculated many times within the hydropower system. However, this recirculation is highly dependent on the off-peak energy delivered by the national grid, which can not be known in advance and might rapidly vary from day to day. To deal with this uncertainty the power company decided to adopt a risk aversion approach, that is to consider only the *certain energy production*, i.e. the energy which would be produced by operating the three reservoirs, without recirculating water among them. We will see in section 4 how the risk aversion can be expressed through the topology of the model components. Given for granted this fact, the satisfaction of the power company criteria can be evaluated through the following couple of indicators: the *average annual production* [gWh/year]

$$i_{hp1} = \frac{1}{N} \sum_{t \in H} \sum_{c \in C} E^c\left(q_t^c\right) \tag{1}$$

and the *average annual economic return of energy production* [€/year]

$$i_{hp2} = \frac{1}{N} \sum_{t \in H} \sum_{c \in C} R_t\left(E^c\left(q_t^c\right)\right) \tag{2}$$

Table 2
The stakeholders involved in the project and the relative criteria.

Stakeholder	Criterion
Power Company (ENEL)	Meet company's target
Farmers (CBN)	Satisfaction of farmers
Ruzzo Aqueduct	Drinking water production cost
Gran Sasso - Monti della Laga National park	Environmental protection
Vomano river park	Environmental protection
Environmentalist (WWF, Legambiente)	Environmental protection

Table 3
Hourly and seasonal energy price [€/MWh] variations. Winter is defined from October to March, summer from April to September. (data provided by Enel 1999)

Time-band	Winter	Summer	Sat./Sun./August
00:00-06:30	25.3	25.3	25.3
06:30-08:30	46.7	46.7	25.3
08:30-10:30	116.3	46.7	25.3
10:30-12:00	46.7	46.7	25.3
12:00-16:30	46.7	46.7	25.3
16:30-18:30	116.3	46.7	25.3
18:30-21:30	46.7	46.7	25.3
21:30-24:00	25.3	25.3	25.3

where q_t^c is the daily flow rate on day t through the turbines of the power station c, C is the set of the power stations, N is the number of years of the evaluation horizon H and $E^c(\cdot)$ is the following function that provides the energy [kWh] produced by the station c on day t

$$E^c\left(q_t^c\right) = \psi g \eta \gamma \check{q}_t^c H_t^c \tag{3}$$

In the previous expression ψ is a conversion rate (0.024 [hours]), g [m/s^2] the acceleration of gravity, η [-] the turbine efficiency, γ [kg/m^3] the density of water, H_t^c [m] the hydraulic head and $\check{q}_t^c$ the flow rate that actually goes through the turbines. This latter in turn is a function of both the maximum flow rate $Q_{\max}^c$ of the penstock feeding the station and of the minimum flow rate $Q_{\min}^c$ required to activate its turbines:

$$\check{q}_t^c = \begin{cases} 0 & \text{if } q_t^c < Q_{\min}^c \\ q_t^c & \text{if } Q_{\min}^c \leq q_t^c \leq Q_{\max}^c \\ Q_{\max}^c & \text{if } Q_{\max}^c < q_t^c \end{cases} \tag{4}$$

The function $R_t(\cdot)$ in the indicator (2) transforms the daily energy production in the corresponding economic return, by accounting for the variation of the energy selling price [€/MWh] within the day and over the year (Tab. 3). It can be determined by assuming that the power station manager adopts a rational behaviour in allocating the daily release decision within the day, i.e., that (s)he prioritizes the production in the more profitable price-bands. Thus, in day t, the economic return $R_t\left(E^c\left(q_t^c\right)\right)$ of the production $E^c\left(q_t^c\right)$ is given by

Table 4
Duration b_t^i of each price-band i when t is a winter weekly day.

Price-band	Price [€/MWh]	Duration [h]
i	p^i	b_t^i
1	116.3	4
2	46.7	11
3	25.3	9

the following piecewise linear expression

$$R_t\left(E^c\left(q_t^c\right)\right) = \begin{cases} E^c\left(q_t^c\right) \cdot p^1 & \text{if } E^c\left(q_t^c\right) \leq \tilde{E}^{c,1} \\ \tilde{E}^{c,1}p^1 + (E^c\left(q_t^c\right) - \tilde{E}^{c,1})p^2 & \text{if } \tilde{E}^{c,1} < E^c\left(q_t^c\right) \leq \tilde{E}^{c,2} \\ \tilde{E}^{c,1}p^1 + \tilde{E}^{c,2}p^2 + (E^c\left(q_t^c\right) - \tilde{E}^{c,2})p^3 & \text{if } E^c\left(q_t^c\right) > \tilde{E}^{c,2} \end{cases} \tag{5}$$

where $\tilde{E}^{c,i}$ is the maximum possible production in the i-th price-band, which in turn is given by the following expression

$$\tilde{E}^{c,i} = \left(\frac{b_t^i}{24}\right) \psi g \eta \gamma Q_{\max}^c H_t^c \tag{6}$$

In the latter the symbol b_t^i denotes the duration of the i-th price-band in day t, which, for example, when t is a winter weekly day assumes the values shown in Tab. 4.

The cost of the off-peak energy used for pumping purposes has been assumed equal to zero, though its selling price is not null, because such is its opportunity cost for the power company.

The environment

There are three different stakeholders concerned with the environment protection (see Tab. 2), who, however, expressed the same evaluation criterion: the *protection of the riverine ecosystem*. For this reason in the following they will be considered as a unique coordinated group of stakeholders denoted with the term environment (as in the title of this section). For a given alternative A, the evaluation of their criterion can be made by assessing the distance between the reference status (WFD, Directive/2000/60/EC)) of the ecosystem and the status that A would create. As reference status the natural conditions of the river before the construction of the hydropower facilities was assumed. For example, in the case of the river Fucino, that was dam by the Campotosto reservoir, the indicator is the *average annual flow rate subtracted by the Campotosto reservoir to the river with respect to the natural condition* [m^3/s] that takes the following form

$$i_{env}^{Fucino} = \frac{1}{H} \sum_{t \in H} \left(a_t^n - q_t^{Fucino} \right) \tag{7}$$

where a_t^n is the flow rate the river would have at time t if it were in its natural condition and q_t^{Fucino} is the flow released into the river from Campotosto at the same time. The value of this latter depends upon the value of MIF stated in the considered alternative. More precisely, it will be always equal to the MIF value, but when the outflow from the natural catchment is lower than the MIF itself or the reservoir is spilling. The indicators for the interceptor at 1100 m and for the two (left and right) at 400 m are analogously defined, on the basis of the flows q_t^{1100}, q_t^{r400} and q_t^{l400} released downstream of them.

The aqueduct

As already mentioned, the Ruzzo Aqueduct is concerned with the drinking water production cost. It withdraws water from the left interceptor at 400 m. a.s.l (see Fig. 1), but in the drought periods, when this flow does not completely cover its demand, it pumps back water from the Piaganini reservoir. Hence the drinking water production cost increases. The Aqueduct is therefore willing to minimize such a cost, which is directly related to the *average annual water supply from the Piaganini reservoir* [Mm^3/year]:

$$i_{aq} = \frac{1}{N} \sum_{t \in H} \max \left(0; w_t^{aq} - a_t^{l400} \right) \tag{8}$$

where w_t^{aq} is the daily water demand of the aqueduct and a_t^{l400} is the flow rate at time t on the left interceptor. Note that a_t^{l400} is only influenced by the MIF value imposed downstream from that interceptor, but not by any other of the actions considered.

The farmers

The evaluation criterion of the farmers is their *satisfaction*, which can be split into lower level criteria: the *economic return of the harvest* of each crop and the *net economic return of the energy produced at S. Lucia*. The latter, in fact, is sold to the power company when it overcomes the energy required to lift water to the fields (see Fig. 2), while energy is bought in the opposite case. The most natural way of ascertaining the first group of criteria is to assess the average economic return of each crop, i.e. the following indicators

$$i_{irr1-i} = \frac{1}{N} \sum_{j=1}^{N} \gamma_j h_j^i \qquad i = 1, \ldots, n \tag{9}$$

where h_j^i is the harvest [tons] of the i-th crop and γ_j is its unitary price [€/ton] in the j-th year.

The second criterion can be verified by considering the following indicator

$$i_{irr2} = \frac{1}{N} \sum_{t \in H} R_t \left(|E \left(q_t^{sl} \right) - E \left(q_t^{irr} \right) | \right) \tag{10a}$$

where $E \left(q_t^{sl} \right)$ is the energy produced by turbining the flow rate q_t^{sl} in the S. Lucia power station and $E \left(q_t^{irr} \right)$ is the energy required to lift the supply q_t^{irr} to the district. Finally, q_t^{sl} and q_t^{irr} are specified by the following relations

$$q_t^{irr} = min \left[W_t, q_t^v \right] \tag{10b}$$

$$q_t^{sl} = max \left[q_t^v - W_t, 0 \right] \tag{10c}$$

4 Modelling the system

By a mathematical point of view, all the above indicators are functionals of the trajectories of the system variables over the evaluation horizon H. Therefore, the computation of their values for a given alternative requires that a model of the system be available and that in this model the actions that such an alternative implies are represented.

4.1 The system topology

Accordingly to Castelletti and Soncini-Sessa (*this issue*) the model of the Vomano water system was designed starting off from the decomposition of the physical system (Fig. 1) into interconnected components. Each of these components serves a precise function with respect to the criteria specified by the stakeholders and the decomposition of the system was essentially based on the identification of these functions. It would be here too long and cumbersome to describe all the considerations that brought to the final system topology, however it is worth while going through some of them to give an idea of how the decomposition was actually carried on.

The hydropower system

Consider the three reservoirs and their power stations. The more intuitive way of modelling this subsystem would be to adopt an hourly time-step and consider each reservoir and power station as a single component, whose functions are respectively to store/release water and to turbine/pump water (exception is made for the Montorio power station that is only equipped with irreversible turbines). However, as observed in the previous section, the power company is interested in the *certain energy production* and in its *economic return*, i.e. the energy which would be produced without recirculating water among the reservoirs. To express this point of view a number of variations have to be introduced in the above intuitive scheme: the modelling time-step must be daily and of the water volume released from the Campotosto reservoir only the amount that reaches the Montorio power station, passing through the Provvidenza and S.Giacomo power plants (and Provvidenza and Piaganini reservoirs) has to be considered. The remaining amount, which is stopped into the Provvidenza (or Piaganini) reservoir and may be pumped back to Campotosto (or Provvidenza) during next night, is not accounted for. This setting is comforted by the short water storage and release cycles (less than one day) of the Provvidenza and Piaganini reservoirs. As a consequence, these two reservoirs are treated as simple water diversions that divide their natural inflows between the turbines (of the downstream plant) and the pumps (of the upstream one). An analysis of the historical records demonstrated that the off-peak energy is always sufficient to pump all their inflows up to Campotosto.

As a consequence of the above setting also the modelling of the power stations has to be reconsidered with respect to the initial intuitive scheme. Precisely, the Provvidenza power station has been described by means of two different components, that are respectively responsible for pumping water from Provvidenza to Campotosto and for turbining the release from Campotosto. A new logical component has been introduced that represents the cascade of the Provvidenza and S. Giacomo pumping stations, by means of which water is pumped back from Piaganini to Campotosto. The last component describes the S. Giacomo turbines. Obviously constraints have to be posed in order to guarantee the physical feasibility of the pumped volumes. The resulting topology of the hydropower system is depicted in Fig. 3. Although it may appear unnatural, this scheme not only embeds the risk aversion of the power company in planning the system, but also represents the way it actually manages the system. This statement is proved by the graph in Fig. 4, where the trajectories of both the daily and weekly storage variations in the Provvidenza reservoir are plotted for a period of one year. It easy to see how there is no regularity in the pattern of the daily variations, while the weekly variations are very small. Such a behaviour confirms that the Provvidenza reservoir (but the same can be proved for Piaganini) is practically used as a daily charge-discharge reservoir. A further validation is provided by the draining time (Tab. 5) of each reservoir: it is evident that only the Campotosto reservoir was built to be operated on long storage and release cycles, while the other two reservoirs can be filled in and drained more than once in a day. Finally, observe that the adopted topology provides the power company with a potential amount of

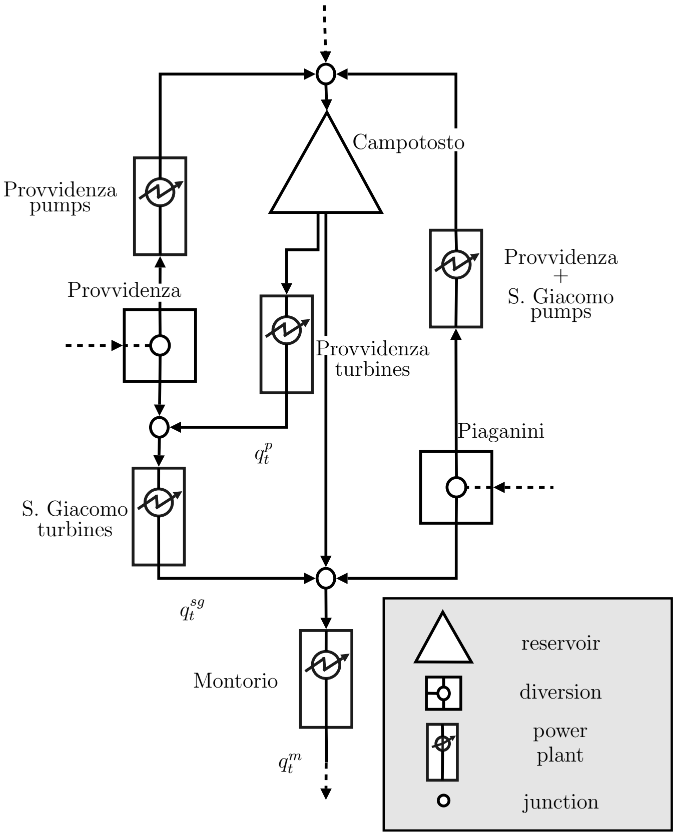

Fig. 3. The topology of the hydropower system. The variables relevant for the calculation of indicators (1) and (2) are set in evidence.

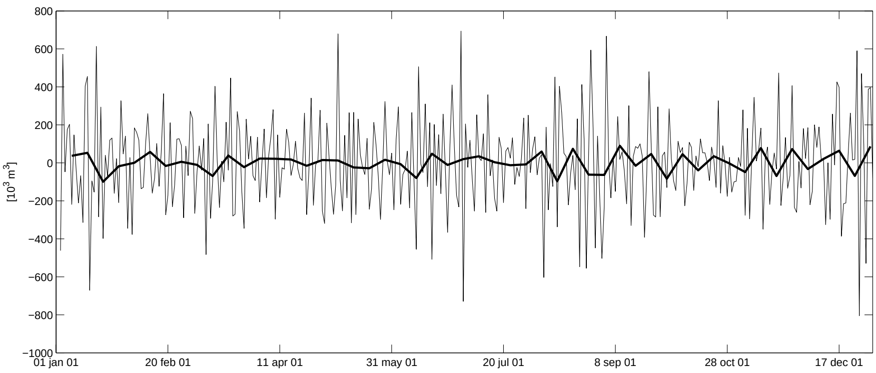

Fig. 4. The trajectories of the daily (thin line) and weekly (heavy line) storage variations of the Provvidenza reservoir (2001).

Table 5
The draining time of Campotosto, Provvidenza and Piaganini reservoirs.

	Active storage [Mm^3]	Maximum release [m^3/s]	Draining time [h]
Campotosto	217	61.8	975.4
Provvidenza	1.69	85	5.5.
Piaganini	0.95	54	4.9

water that can be freely managed on the basis of its daily needs, but can not be exploited by the other users. For this reason it was of crucial importance that all the other stakeholders be aware of and accept the assumptions upon which the adopted topology is based.

The catchments

The decomposition of the whole system in single components was also conditioned by the types of data available to describe each potential component. For example, the Provvidenza reservoir is fed by the interceptor at 1100 m a.s.l. (Fig. 1), by the river Vomano and by a smaller river (Chiarino). One would naturally describe this physical configuration by considering the catchment of each tributary as an individual component. However, this would require that flow measurements be available for each single tributary, while the only data historically recorded are the total daily inflows to the Provvidenza reservoir obtained through the daily closure of the water mass balance. For this reason an individual catchment component was introduced that describes as a whole the inflow to the Provvidenza reservoir. Analogously it was made for Campotosto, as also for its tributaries disaggregated data of inflow were not available. For Piaganini this assumption was instead not acceptable, though suggested also in this case by the type of data available, because the single contribution of the left hand interceptor is required by the indicator (8) specified by the aqueduct. Therefore, the total inflow feeding the Piaganini reservoir has been divided into the separate contributions of the two interceptors on the basis of a regional analysis, whose results were presented and discussed with the stakeholders.

The final system topology is the one depicted in Fig. 5. It includes the topology of the hydropower system, the four catchments and the Villa Vomano diversion, which feeds the irrigation district and the S. Lucia power station. Though it is not yet a model of the system, it is however the first formalization of reality and as such it is of crucial importance that be understood, accepted and regarded as true by all the stakeholders. These should also agree on the validity and relevance of the data associated to each component, as the trustability of the model depends on their accuracy, availability and quantity. An interesting example is once again provided by the Provvidenza catchment.

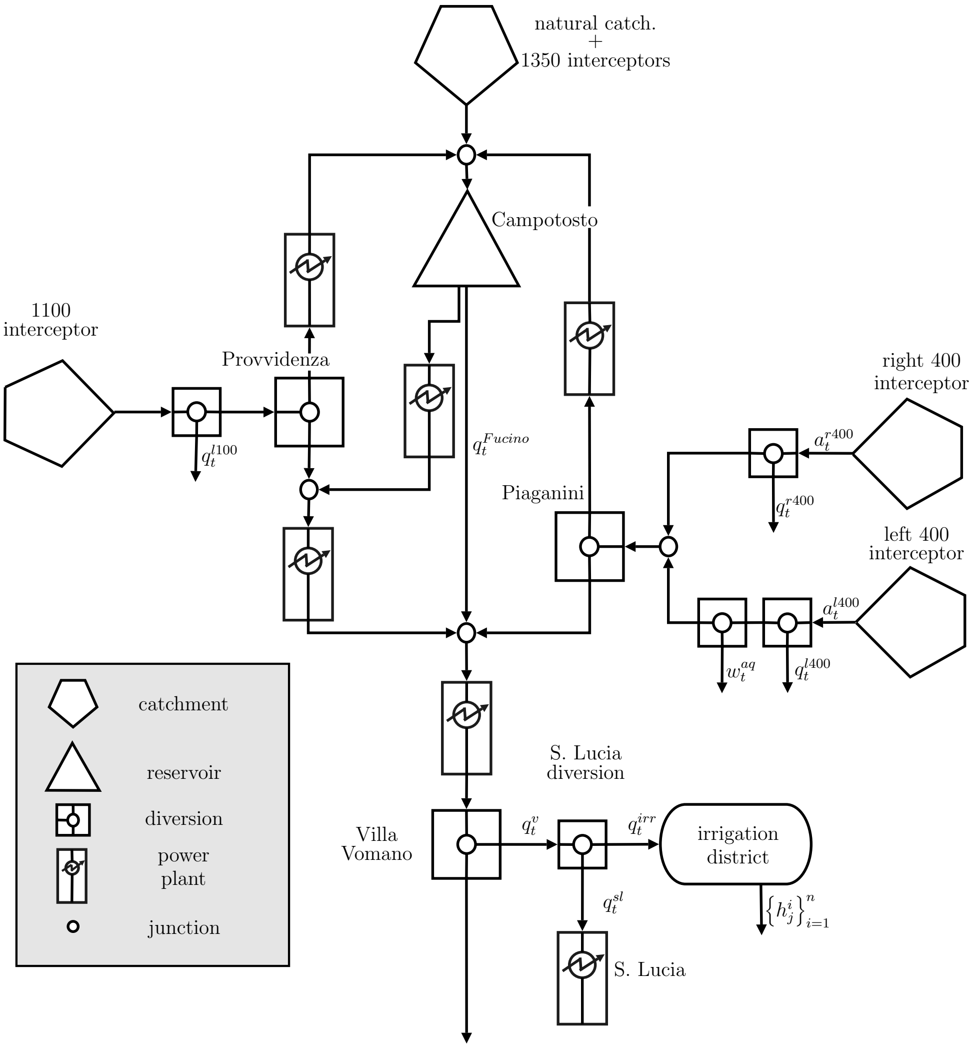

Fig. 5. The topology of the Vomano water system. The variables relevant for the calculation of all the indicators, but the power company ones, are set in evidence.

Its daily inflow data, as already noted, are calculated by the power company through a daily water mass balance. More precisely, the daily inflow is estimated by extending to 24 hours the inflows computed by closing the water balance over two night-time hours, when the pumps are not working. All the stakeholders, but the power company, questioned the validity of such data, because, they said, they underestimate the evaporation in the summer-time and the snow-melt in the winter period. To ascertain and correct, if it is the case, these inaccuracies the daily water mass balance was computed over 24 hours, thereby taking into account also the water amount produced by the operation of the power plants (i.e. the daily release from and to Campotosto and Piaganini). The trajectories of the inflows so obtained were plotted over the data originally provided by the power company (Fig. 6a). The underestimation of the evaporation and of the snow-melt appeared evident. The data however

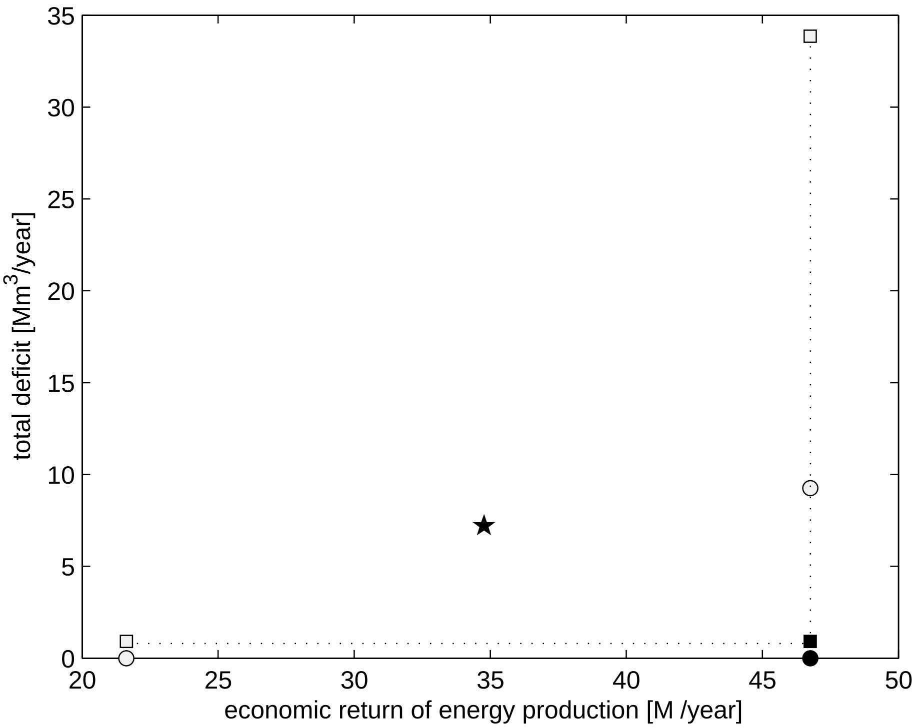

Fig. 6. A sample of the trajectories of the daily inflows provided by the power company (continuous lines) and of the daily inflow computed by closing every 24 hours the water mass balance to the Provvidenza (a) and Piaganini (b) reservoirs (dotted lines).

were very noisy, probably due to not systematic errors in the estimation of the water pumped back to Campotosto [1] and therefore not usable at all. The same procedure was adopted to estimate the inflow to Piaganini. In this case (Fig. 6b) the data showed a more regular behaviour and were therefore used to estimate the specific evaporation [m/day] of the reservoir. Provided that the two reservoirs have similar dimension and are located in a similar context the data of Provvidenza were corrected assuming the same specific evaporation of Piaganini.

4.2 The models of the components

Once the system typology has been specified, one may proceed with the identification of the model of each single component. This process includes a first phase, which is still qualitative, during which the cause-effect relationships linking the variables of each component are described through a causal net-

[1] This conjecture was confirmed by the fact that a similar noisy behaviour was observed by calculating the inflow to Campotosto with the same procedure.

work, and a quantitative phase, during which such relationships are parametrized by means of a properly selected model type and then calibrated (Castelletti and Soncini-Sessa, *this issue*). The model types to be adopted to describe each component in the scheme of Fig. 5 were selected following the criteria specified in the above mentioned paper. More precisely, mechanistic models were used to describe the Campotosto reservoir, the water diversions (both controlled and uncontrolled), the hydropower plants and all the junctions, while the outflows from the four catchments were modelled as stochastic disturbances. Finally the irrigation district was described by integrating mechanistic models and Bns, as it will be detailed in the next section.

5 The model of the irrigation district

In order to evaluate the indicator (9), it is necessary to be able to assess the harvest values h_j^i in correspondence of each given alternative. This requires that a model of the irrigation district is identified. It was done by following the approach suggested in Castelletti and Soncini-Sessa (*this issue*): a block-diagram is first built up, each block is then exploded in a causal network and the type of model to represent it is selected. Finally the models are calibrated and validated.

5.1 The block diagram

Let's start by singling out the network output and the inputs. The former is the vector of the harvests h_j^i, $i = 1, ..., n$, the latter are the meteorological variables (temperature, precipitation, solar radiation, etc.) and the variables that influence the behavior of the farmers. Of this last group, the first variable is the *extension* of the district. The second is the *expectation* that the farmers have for the water supply, a qualitative variable which expresses how probable the farmers think it is, given the power company interests, that the demand of irrigated crops would be effectively satisfied: with a low expectation, few farmers would choose to plant wet crops. The third is the amount of *incentives* that will be offered to the farmers to improve their irrigation systems or to create it from the scratch. The first and the last are two actions of the project, the second reflects a psychological condition of the farmers, which is the effect of their past experience.

Once the inputs and output have been defined the processes that link them can be identified. Through interviews with experts, the existing literature, and the analysis of the problem, the block diagram in Fig. 7 was obtained.

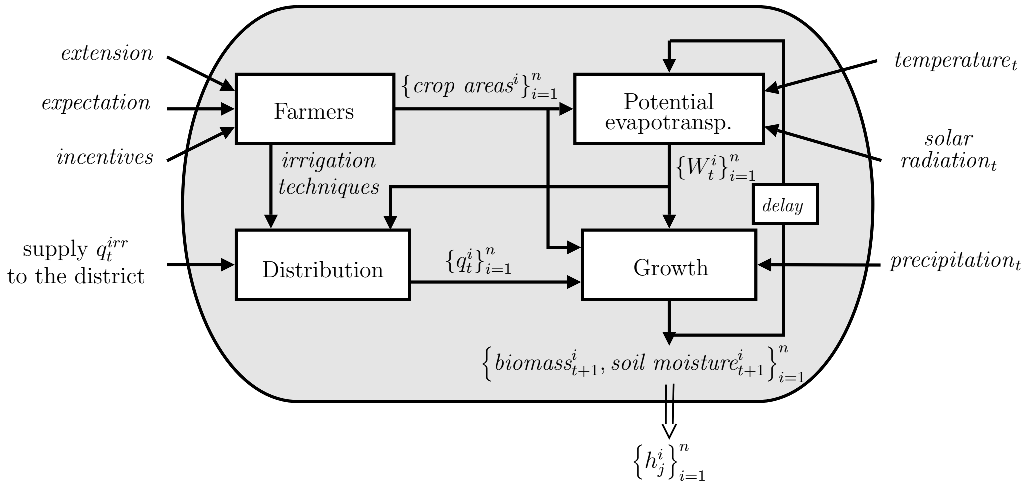

Fig. 7. The block diagram of the irrigation district; the index i denotes the different crops.

In response to the last three above-mentioned inputs, the first block (Farmers) provides the decision of the farmers: the area dedicated to each crop and the mix of irrigation techniques (micro-irrigation and sprinklers) with which each crop will be served. At each time t, for each crop, the second block (Potential evapotranspiration) provides the demand W_t^i, taking into account temperature, solar radiation, its biomass and soil moisture. The third block (Distribution) describes how the supply q_t^{irr} to the district is split in the flows $q_t^1, \ldots, q_t^n$ that supply the n crops, taking into account for the leakages in the distribution net. The fourth (Growth) provides, for each crop, the growth in the biomass and the variations in the soil moisture in response to the supply q_t^i and the precipitation that it receives. Lastly, from the trajectories of the $biomass_t^i$, the trajectories of the harvest h_j^i can be obtained all over the N years of the evaluation horizon H, by simply noting that for each crop the harvest h_j^i in the j-th year is nothing, but the biomass of that crop in the harvest day t_h^j of that year. Note that the resulting district model is dynamic and its state $\mathbf{x}_t$ is the vector of the biomass and soil moisture values for each crop. Furthermore, the model is time-variant because, once the inputs are given, the evapotranspiration and the growth depend on the phenological phase of the crops.

To identify the model the four blocks would have to be analyzed one by one, in strict collaboration with the farmers, to single out within each block, the cause-effect relationships among inputs, outputs and internal variables. Then, these relationships would have to be quantified by selecting and calibrating the type of model (Bayesian network, mechanistic, empirical or markovian) that is presumed to be the more suited for their description accordingly to the selection criteria specified in Castelletti and Soncini-Sessa (*this issue*). However, in the case at hand, the farmers were already used to adopt some mechanistic model: CROPWAT (FAO, 1995) CROPSYST (Stckle and Nelson, 1997).

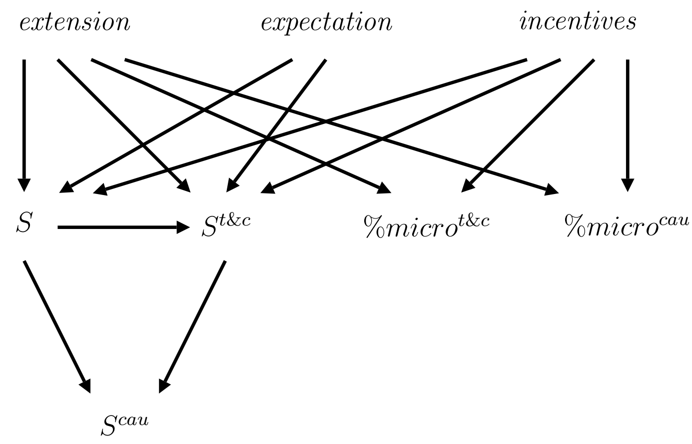

Fig. 8. The causal network of the Farmers block when they must choose between two irrigated crops: cauliflower (*cau*) or the rotation between tomato and corn ($t\&c$).

Therefore we decided to adopt them to describe the Potential evapotranspiration and the Growth blocks, and to adopt a simple algebraic description of the Distribution block. Thus only the Farmers block had to be described from the scratch.

5.2 The Bn of the farmers' behavior

Each farmer can grow on her/his estate several crops, chosen among dry crops (mainly oil trees and wheat) and irrigated crops (mainly fruit and vegetables, corn and vines). All of the possible crops were considered in the project, but here, in order to simplify the presentation, only two irrigated crops will be considered (the cauliflower (*cau*) and the rotation tomato-corn ($t\&c$)) and the dry crops, among which it is not necessary to make a distinction. The causal network that describes the farmer decision is shown in Fig. 8, where S is the total area devoted to irrigated crops, S^{cau} and $S^{t\&c}$ are the areas cultivated with cauliflower and tomato-corn respectively, $\%micro^{cau}$ and $\%micro^{t\&c}$ the fractions of these areas that are served by micro-irrigation. Among such variables the following constraints hold: $S <extension$, $S^{t\&c} \leq S$ and $S^{cau} = S - S^{t\&c}$. Note that decision on the area devoted to dry crops is reflected by the difference between *extension* and S.

Since there are no physical laws that describe the farmers' behaviour in response to the actions considered and their psychological condition, the best solution is to model it by directly asking the framers how they think could be their reaction to the above actions (extension and incentives), in different psychological condition (expectation). Their replies can be formalized in a Bn, whose inputs are *extension*, *expectation* and *incentives*, and whose outputs are $S^{t\&c}$, S^{cau}, $\%micro^{t\&c}$ and $\%micro^{cau}$, as required by the block Farmers in Fig. 7.

Table 6
The *states* of the variables in the causal network of Fig. 8.

Variable	States				
expectation [-]	low	medium	high		
extension[ha]	7 000	14 000			
incentives [€/ha]	none	300	600		
S, $S^{t\&c}$, S^{cau} [ha]	0	3 500	7 000	10 500	14 000
$\%micro^{t\&c}$, $\%micro^{cau}$ [%]	0-50	51-100			

The first step to transform this causal network into a Bn is to discretize all the variables in a finite number of classes (*states* in jargon). In the real model the discretization required tenths of values, but here for the sake of simplicity only the values in Tab. 6 are considered. The next step is the specification of the conditional probabilities that quantify the relationships among the variables; an activity that in jargon is known as *network population* and is nothing, but the model calibration.

Populating the Bn

The populated Bn is described by the 5 Conditional Probability Tables (CPTs) shown in Fig. 9, the values of which were determined through different ways. When a CPT represents a deterministic relationship, its elements were defined on the basis of it: this is the case of table (e) in Fig. 9, which expresses the relationship $S^{cau} = S - S^{t\&c}$. Note how a so simple relationship is expressed by a relatively awkward table. One of the disadvantages of the Bns is just this: the representation of algebraic relations is extremely onerous (Castelletti and Soncini-Sessa, *this issue*). Some probabilities (those corresponding to the dark grey cells in Fig. 9) were a-priori fixed as either null or irrelevant on the basis of the existing constraints. They are null when the constraint acts on the conditioned variable, such as in table (a), where the constraint $S < extension$ prevents the irrigated crop area S from assuming the values 10 500 and 14 000 when *extension* is equal to 7 000. Instead, they are irrelevant when the constraint concerns only the conditioning variables, as for example in table (e), where the constraint $S^{t\&c} < S$ makes it impossible that pairs ($S^{t\&c}$, S) with $S^{t\&c} > S$ could ever occur. Therefore, arbitrary values have been assigned to the elements in the corresponding columns, taking care only that the sum of such values were equal to one [2]. As far as the remaining values are concerned, they were obtained from interviews to the farmers.

[2] This condition is conceptually irrelevant, but practically useful for the formal verification of the accuracy of the table in the calculation codes.

(a)

		extension 7000			extension 14000		
		expectation			*expectation*		
		low	medium	high	low	medium	high
S	0	0.9	0.7	0.5	0.5	0.3	0.1
	3500	0.1	0.3	0.5	0.4	0.4	0.3
	7000	0	0	0	0.1	0.2	0.4
	10500	0	0	0	0	0.1	0.1
	14000	0	0	0	0	0	0.1

incentives

(b)

		extension 7000			extension 14000		
		expectation			*expectation*		
		low	medium	high	low	medium	high
$S^{t\&c}$	0	0.8	0.7	0.5	0.4	0.3	0
	3500	0.2	0.3	0.4	0.3	0.3	0.4
	7000	0	0	0.1	0.3	0.2	0.3
	10500	0	0	0	0	0.2	0.2
	14000	0	0	0	0	0	0.1

incentives

(c)

		extension 7000			extension 14000		
		incentives			*incentives*		
		none	300	600	none	300	600
$\%micro^{t\&c}$	0-50	0.9	0.7	0.5	0.9	0.7	0.5
	51-100	0.1	0.3	0.5	0.1	0.3	0.5

(d)

		extension 7000			extension 14000		
		incentives			*incentives*		
		none	300	600	none	300	600
$\%micro^{cau}$	0-50	0.9	0.5	0.2	0.9	0.5	0.2
	51-100	0.1	0.5	0.8	0.1	0.5	0.8

(e)

		S = 3500					S = 7000					S = 10500					S = 14000				
		$S^{t\&c}$					$S^{t\&c}$					$S^{t\&c}$					$S^{t\&c}$				
		0	3500	7000	10500	14000	0	3500	7000	10500	14000	0	3500	7000	10500	14000	0	3500	7000	10500	14000
S^{cau}	0	0	1	1	1	1	0	0	1	1	1	0	0	0	1	1	0	0	0	0	1
	3500	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0
	7000	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0
	10500	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
	14000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0

Fig. 9. The conditional probability tables (CPTs) of the Bn that describes the farmers' behavior in the simplified case considered in the text. The dark grey cells correspond to violations of a constraint.

(a)

	expectation low	medium	high
S			
$S^{t\&c}$			

incentives

(b)

	incentives none	300	600
$\%micro^{t\&c}$			
$\%micro^{cau}$			

Fig. 10. The tables for the interview with the farmers (simple approach).

The questions to the farmers could have been posed in two different ways, one simple and the other more complicated, depending on the farmers' attitude with probabilities. The simpler approach consists in showing to each farmer the two tables in Fig. 10 and asking her/him to fill them in. Table (a) requires the farmer to specify, for every possible value of *expectation*, the number of hectares that (s)he intends to dedicate to wet crops, and, in particular, to

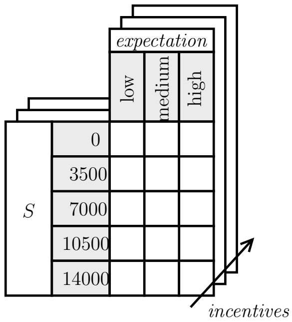

Fig. 11. One of the tables for the interview with the farmers (complex approach).

tomato-corn. Table (b) requires to specify for every possible value of *incentives*, the percentage of area of each crop that (s)he intends to irrigate by means of the micro-irrigation. In the more complex approach the tables are formulated so that the farmer's reply could be a probability distribution, not just a value. An example is provided in Fig. 11, where the table used for requesting the area dedicated to the wet crops is shown. The more complex approach was selected and the interviewed farmers were asked to fill in each cell of the table with a subjective estimation of the probability that their choices fall into that class. By statistically elaborating these data the conditional probability in Fig. 9 were obtained.

The reader may note that in Fig. 11 does not appear the variable *extension*, as a conditioning one. The reason is that the interviewed farmer obviously knows if her/his plot of land is located in the present district or in the enlargement and therefore her/his answers are naturally conditioned by this fact, i.e. by the value of the variable *extension*. Note, however, that this is true only because the farmers' league already stated that in the enlarged district, in the case of a supply deficit, priority of supply will be assured to the farmers of the present district. If it were not, the reply of a farmer, whose estate is in the present district, might differ according to whether the question is posed assuming that the district is enlarged or not.

Once populated, the Bn was used as a "top-down" inference tool (see again Castelletti and Soncini-Sessa, *this issue*) to compute, through belief propagation, the probability of its two output vectors (*irrigation technique* and *crop areas*, see Fig. 7), given the evidence on its inputs. These outputs act as stochastic disturbances on the models describing the blocks Potential evapotranspiration and Distribution. The latter is fed with the supply q_t^{irr} to the district (that is produced by the part of the system upstream of the S. Lucia diversion, see Fig. 5) and produces as output the daily supplies (q_t^i) to each crop. These are in turn stochastic variables acting as inputs on the model that describes the Growth block, which receives as a further stochastic input the daily water demand of each crop and produces as output the biomass and soil moisture of the next day. Temperature, solar radiation and precipitation were treated as deterministic time-varying, periodic, disturbances that were set equal to the historic daily averages. Note that the district model is a dynamic model, whose state are the biomass and soil moisture of each crop.

6 The model of the Vomano water system

Once the models of the system components have been all identified, they are aggregated to form the *global model* of the Vomano water system. The inputs to such model can be partitioned in the set of the decisions, i.e. the variables and the functions that describe an alternative (i.e. MIF, incentives, district enlargement, regulation policy), and the set of the drivers, i.e. those input variables that are not affected by the alternatives and describe the background scenario on which the system evolves (e.g. the aqueduct daily water demand w_t^{aq}, the energy prices, etc.). By combining in all the possibile ways the values of the decisions the whole set of the alternatives to be evaluated is obtained, while by fixing a value for the drivers the scenario over which to perform the evaluation is set up. However, the number of regulation policies, through which the system can be operated, is fairly high, in theory infinite, and therefore they can not be exhaustively evaluated, but a screening has to be carried out. In order for this latter not to be based upon the modeller's criteria, but to reflect those of the stakeholders, all and only the policies that would be chosen by at least of them, i.e. the ones non-dominated in the Pareto sense, have to be considered. These policies can be identified by solving a multi-objective optimal control (MOOC) problem, for any given combination of the structural (district enlargement) and normative (MIF and incentive settings) actions. As the computational time required to solve a single MOOC problem grows exponentially with the order of the global model (i.e. the number of its state variables), it is essential to keep such order at a minimum. The state of the global model is composed by five variables: the biomasses and the soil moistures of the two crops, and the storage of the Campotosto reservoir. An estimate of the computational time required to obtain a single point of the Pareto boundary associated to the MOOC problem defined by a given combination of structural and normative actions turned out to be of the order of 200 years. Therefore a simplification of the model appeared mandatory: some of the state variables have to be neglected.

6.1 Model simplification

The reduction of the number of state variables should be performed in such a way to minimize its impact on the description of the behavior of the system. Since the storage of the Campotosto reservoir can not be obviously removed, the choice inevitably falls on the irrigation district state. However, the removal of this latter would make impossible the computation of the harvest values h^i_j, required to evaluate the indicators described by equation (9). Then the first step towards simplifying the model is to substitute for each crop that indicator with a proxy of it: the *average annual deficit* of the crop. More precisely, the set of indicators expressed by (9) is substituted by the following

$$i_{irr3-i} = \frac{1}{N} \sum_{t \in H} d^i_t \qquad i = 1, \dots, n \tag{11a}$$

with

$$d^i_t = max \left[0, (W^i_t - q^i_t - precipitation_t) \right] \tag{11b}$$

where W^i_t is the water demand of the i-th crop and q^i_t is the water supply to it, which, in turn, depends upon the supply q^{irr}_t to the district and the internal distribution policy of the farmers, represented in the block Distribution. Equation (11b) states the obvious fact that, when the sum of the supply and the precipitation overcomes the demand, the deficit is null. As a consequence of the above propositions the block diagram of Fig. 7, which corresponds to the *complete district model*, may be substituted by the scheme in Fig. 12, on the basis of which a *simplified district model* will be constructed. In the new scheme the block Deficit, which simply represents equation (11b), takes the place of the Growth block in Fig. 7. Thereby the state of this latter is avoided. The last statement seems however to be not completely true, because in Fig. 12 the biomass and soil moisture of each crop still appear as inputs of the Potential evapotranspiration block. This difficulty is overcome by assuming their trajectories as a priori given, exactly as they were scenario variables. As first trial these trajectories may be assumed to be those determined by running the complete district model in optimal conditions, i.e. under the assumption that the supply always meets the demand. With this simplification four state variables are removed, so that the new global model (from now on called *simplified global model* to distinguish it from the previous one, the *complete global model*) turns out to have only one state variable. As a consequence the estimate of the computational time required to compute a single point on the Pareto boundary dramatically drops down to 7 hours.

The simplification, however, is not void of drawbacks on the estimation of the indicators (11a). Obviously, there are no drawbacks when the regulation policy designed (see next section) with the simplified global model produces supplies that always meet the demands, as in this case the values of all the indicators (11a) are null. The error in the estimate of the i-th of them could still be considered negligible when the supply to the corresponding crop only marginally differs from its optimal water demand, but it will not in the opposite case. In fact, if for several days the water demand of a crop is not satisfied, its demand increases over the demand of a regularly watered crop. In that case the values of its indicator would lose meaning. However, such error can be

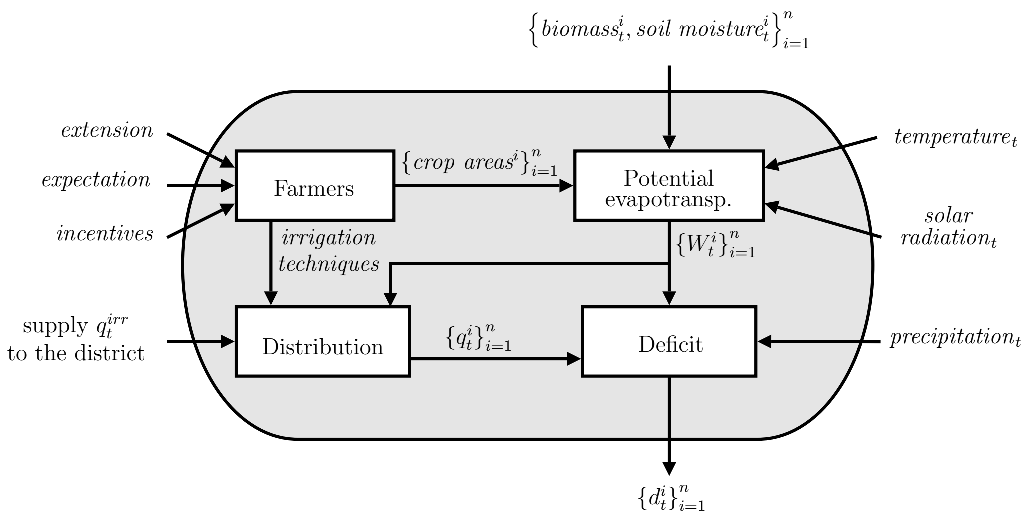

Fig. 12. The simplified block diagram of the irrigation district; the index i denotes the different crops.

corrected by re-assessing, through the complete district model, the biomass and soil moisture trajectories under the supply conditions determined by the regulation policy. Then the regulation policy itself is re-designed, again with the simplified global model, but under this new scenario and the procedure is iterated until the supply condition, under which the biomass and soil moisture trajectories are assessed, and the supply condition produced by the designed policy are (sufficiently) coherent. In the Vomano case this iterative procedure was necessary only in a few cases and required only few iterations.

Validation of the simplified district model

The simplified district model was validated by checking if the total demand it produces, when it is fed with the historical trajectory of its inputs, was not to far from the demand historically observed (see Fig. 13). This latter was assumed to correspond to the average flow q_t^{irr} supplied to the district in the years 1993-2002, because in that period the farmer league always bought water from the power company each time it feared for a deficit. By feeding the simplified model with the historic series of meteorological variables in the same years and the values for *incentives*, *extension* and *expectation*, which correspond to the historical situation (respectively "none", "7 000 ha"and "high"), the trajectory of the average total demand of the district was obtained (dashed line in Fig. 13). The comparison between the two curves shows that the model is satisfactory. Note, in particular, that the summer peak of 4.5 m^3/s in the demand is not covered by the supply, because the farmer league concession is only 4.1 m^3/s. Thus, the model suggests the presence of a structural deficit in the summertime, confirmed also by the farmers. Finally, it is important to point out that the validation can only confirm those "modes" of the model behaviour that were excited in the validation experiment. There-

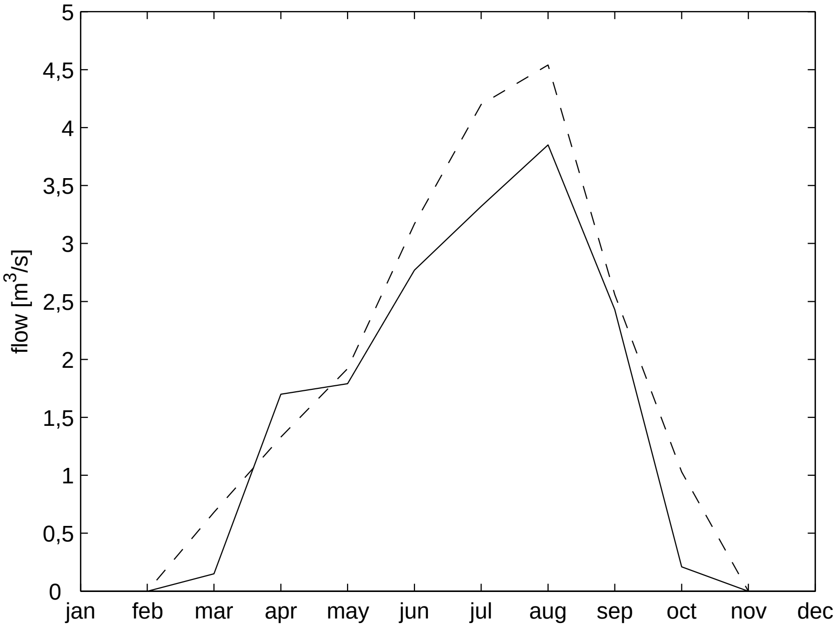

Fig. 13. The calculated demand (dashed line) of the irrigation district and the historic supply (continuous line).

fore, it does not provide any information about the effective capacity of the model to describe what could happen when the variables *incentives*, *extension* and *expectation* take different values (e.g., "high" *incentives*) with respect to the historic ones.

7 From the alternative design to the project conclusion

Given the nature of the global simplified model, the indicators specified in section 3 are stochastic variables, not only because such are the outflows from the four catchments, but also due to the intrinsic stochasticity of the output of the Bn that describes the farmers' behavior. Thus a proper statistic had to be considered in order to transform the indicators into the MOOC problem objectives. Moreover, in order to further simplify the solution of such a problem, only some of the indicators were selected. The choice of the statistic and of the indicators for the MOOC was made together with the stakeholders, who, stimulated through interviews and decision support tools, choose the expected value and the following two indicators: the average annual economic return of energy production (see (2)) and average annual total deficit, defined as the sum of the indicators (11a) over the n crops. For each combination of the structural and normative actions, the efficient policies were determined by solving the resulting two-objectives MOOC problem, by means of a Stochastic

Dynamic Programming algorithm (ASA (White, 1963)). In the MOOC problem the water system model appears as a constraint and therefore, to speed up the computation, it is convenient to transform it in a Markov chain (see Castelletti and Soncini-Sessa (*this issue*). In conclusion the alternative design phase ended with a set of efficient alternatives, each one of which is constituted by a triple: a couple of structural and normative actions, and one associated efficient regulation policy.

Generally the effects that each one of these alternatives produces on the whole set of indicators would have to be estimated by simulating the global complete model over the evaluation horizon H for each alternative. Then, the values of the indicators obtained in this way would have to be arranged in an impact matrix, which finally would be the basis for the following evaluation and negotiation phases, as scheduled in the PIP procedure. However, in the case at hand all this was not necessary, because for any combination of the structural and normative actions the Pareto boundary of the associated MOOC problem turned out to be limited in a region so small that may be considered to consist of just one point.

Two examples are shown in Fig. 14: both assume the present values of the the normative actions (MIF and incentives), while differ for the value of the structural action, which corresponds to do nothing in the first (case A, circles) and to enlarge the irrigation district in the second (case B, squares). In the figure the filled shapes mark the (unique) Pareto efficient points in the two cases, while the empty shapes the performances of the alternatives that produce the optimal independent values of the two objectives (minimum deficit and maximum economic return). These latter have been inserted in order to prove that the filled shapes are the unique Pareto efficient points, because they correspond to the utopia points. The dashed lines are therefore not the Pareto boundaries, but only graphic helps for pointing out this fact. This result proves that if efficiently managed the water available in the system is sufficient to fully satisfy both the hydropower company and the farmers, not only in the present condition (case A), but also if the irrigation district would be enlarged (case B). Moreover, in the case A the efficient policy would reduce the deficit and increase the economic return of the hydropower company with respect to the historical performance (star point in Fig. 14). The deficit reduction is even more significant if one remember that the historic deficit figure is extenuated by the volumes of water bought by the farmers from the power company when they feared for deficits. To understand the reason of this significant improvement consider Fig. 15, where the trajectory of the Campotosto level in the years 1997-2001 (continuous line) is shown together with the one (dashed line) that would have been obtained in the same period if the Vomano system were managed with the efficient regulation policy of case A. It is easy to observe that the latter policy takes a larger advantage of the Campotosto active storage with respect to the historic one: it reaches higher

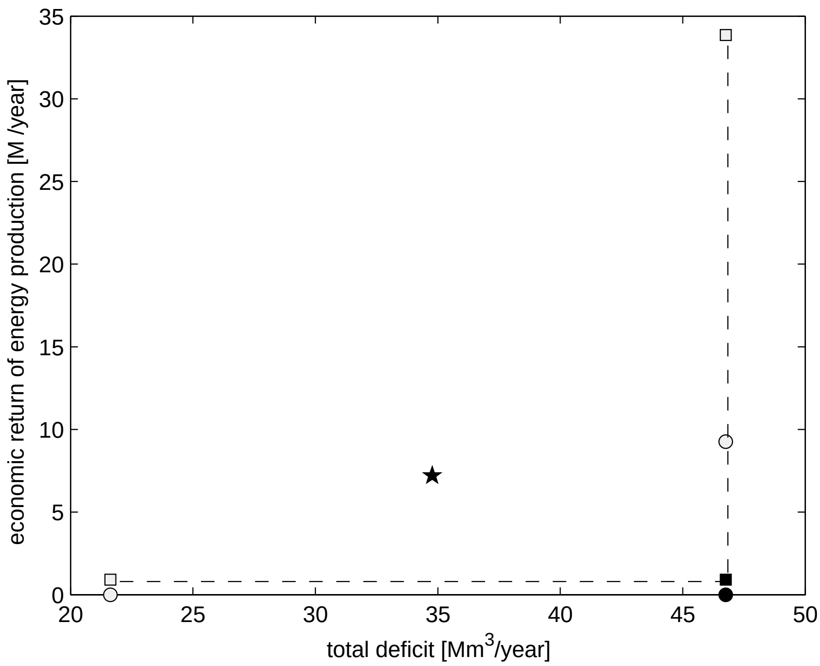

Fig. 14. The Pareto boundary in the plane of the MOOC problem objectives. The cases considered and the symbols are explained in text.

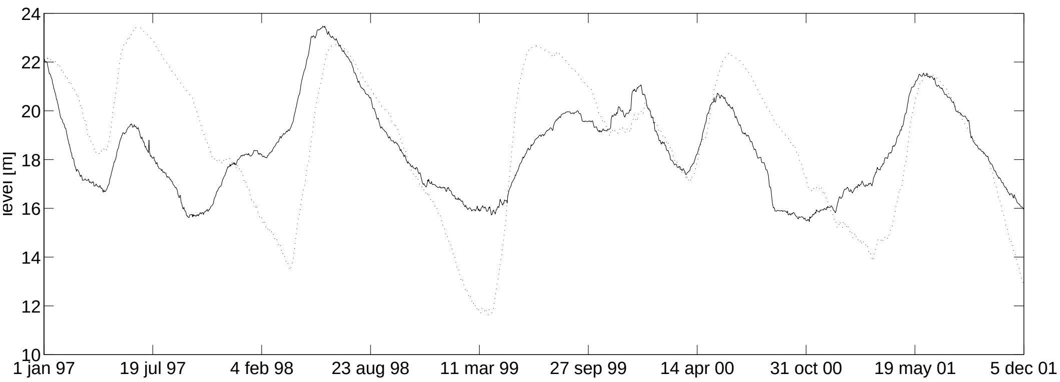

Fig. 15. The trajectory of the Campotosto level in the years 1997-2001 (continuous line) and the one (dashed line) that would have been obtained in the same period by managing the Vomano system with the efficient regulation policy of case A.

peaks and lower minima. The first are obtained by making a more intensive use of the pumping potential of the system, while the latter by the reduced risk aversion of the efficient policy with respect to the human (unassisted) regulator. The fact that the Pareto boundary be reduced to just one point means that the present conflict between the power company and the farmers is due to an inefficient management of the system, but can be completely removed by adopting an efficient policy. Once the two parts realized this fact it was evident that the evaluation and negotiation phases were useless for them.

Table 7
The percentage variation, with respect to case A and the history, of the power company and aqueduct indicators induced by applying the maximum considered value (30%) of the three MIF, one at a time.

	variations [%] of					
	i_{hp1} with respect to		i_{hp2} with respect to		i_{aq} with respect to	
MIF	case A	history	case A	history	case A	history
Fucino	-0.2	13.0	-0.6	34.0	0.0	0.0
1100 interceptor	-3.0	8.0	-5.0	30.0	0.0	0.0
400 interceptors	-3.0	8.0	-5.0	30.0	40.0	40.0

As far as other actions and stakeholders are concerned, with respect to case A the introduction of MIF does not affect the farmers, has a minor negative effect on the hydropower indicators, while strongly affects the one of the Ruzzo aqueduct, as it is shown in Tab 7. However, when measured with respect to the historical performance, the variations of the power company indicators are positive, because the advantages produced by an efficient policy are so strong that can not be canceled by the introduction of the MIF.

8 Conclusions

A participatory modelling approach was presented in this paper that integrates Bns with the other types of models commonly used in river basin modelling to build up the global model of a water system. The approach was embedded within a Participatory Integrated Planning (PIP) procedure (see Castelletti and Soncini-Sessa, 2005) to address the planning of the Vomano water system, in Italy. The application clearly shows that Bns are a powerful and flexible modelling tool to quantitatively describe the social aspects that Decision Makers have to face with in the planning of a water system and to improve participation in the model building process through the inclusion of issues that are usually neglected in the water system modelling practice. It is however important to stress that they have not to be considered as a comprehensive modelling tool to be generally applied to all the components of a water system, because, as suggested in Castelletti and Soncini-Sessa (*this issue*), other types of models could be more suitable for that scope, depending on the characteristic of the component at hand. To prove this fact in the Vomano case study we tried to model the entire irrigation district by means of a Bn network. However, when the farmers were asked to provide the conditional probabilities required to populate the CPTs describing the Potential evapotranspiration and the Growth blocks in Fig. 7, they suggested to compute these figures by means of the models they were using. Then it was evident that it would be more rational to directly embed these latter in the Vomano water system model.

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