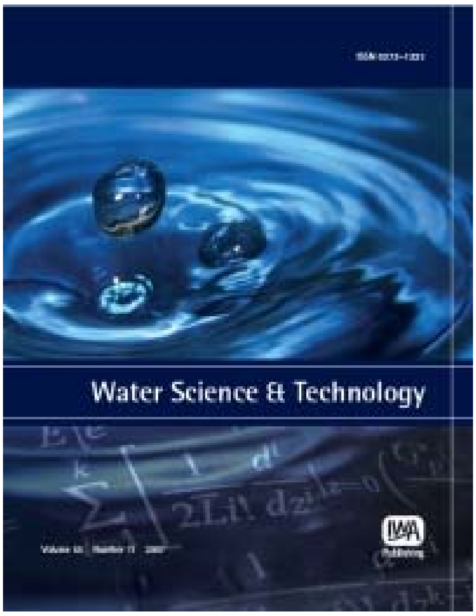
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A simulation/optimization model for selecting infrastructure alternatives in complex water resource systems

Claudio Arena, Mario Rosario Mazzola and Giuseppe Scordo

ABSTRACT

The paper introduces a simulation/optimization procedure for the assessment and the selection of infrastructure alternatives in a complex water resources system, i.e. in a multisource (reservoirs) multipurpose bulk water supply scheme. An infrastucture alternative is here a vector ***X*** of *n* decision variables describing the candidate expansions/new plants/water transfers etc. Each parameter may take on a discrete number of values, with its own investment cost attached. The procedure uses genetic algorithms for the search of the optimal vector ***X*** through operators mimicking the mechanisms of natural selection. For each ***X***, the value of the objective function (O.F.) is assessed via a simulation model. Simulation is necessary as the O.F. contains, besides investment costs, also incremental operation costs and benefits that depend on the incremental water amounts which the alternative can provide. The simulation model transforms a thirty-year hydrologic input at daily/monthly scale in water allocations, accounting for the usual nonnegativity constraints and using some simple, sytem-specific rules aimed at reducing spills and at sharing water deficits among demand centres. Different O.Fs and constraints have been tested, such as incremental financial cost/benefit minimization under various maximum water deficit constraints scenarios or cost/benefit mimization including scarcity costs. This latter approach has the advantage of implicitly allowing for the magnitude of deficits, but requires the assessment of deficit-scarcity cost relationships. The application of the procedure to a water resources system in south-western Sicily shows that the model is able to converge to results that are consistent with the planning options expressed by the selected O.Fs.

Key words | genetic algorithms, infrastructure optimization, loss functions, water resources systems

Claudio Arena (corresponding author)
Mario Rosario Mazzola
Giuseppe Scordo
Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali,
Università di Palermo,
Viale delle Scienze—Edificio 8,
90128 Palermo,
Italy
E-mail: *arena@idra.unipa.it*; *mazzola@idra.unipa.it*; *scordo@dra.unipa.it*

INTRODUCTION

Water resources systems are challenged by ever-changing boundary conditions requiring periodical upgrading of the planning assumptions. Change involves virtually all system's components, from supply, due to climate change, to demand, owing to population and economic growth (or decrease in some instances) or variations in unit demands. However, change may be simply driven by the necessity to bring to completion some older supply schemes that now operate in quite different situations (from both demand and supply side) from the assumed ones, so that it is worthwile reconsidering the proposed investments in the new context.

Capacity expansion problems have a long story in the literature on water resources planning and management. Different approaches have been proposed, ranging from linear and dynamic programming (Loucks *et al.* 1981; Loucks & van Beek 2005) to mixed-integer programming for solving timing and scheduling problems (Mays 2005).

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In general terms, a capacity expansion problem is nonlinear, (because of nonlinearities in the cost functions) with both discrete and continuous variables.

The paper explores the feasibility of Genetic Algorithms (GA in the following) as a tool to search the optimal infrastructure mix for a complex water resources system. GAs have been extensively experimented in the field of water distribution network optimization and are now the reference optimization tool for this type of problems, but have also been successfully employed in the assessment of both long-term reservoir operating rules (e.g. Oliveira & Loucks 1997; Chen *et al.* 2007; Momtahen & Dariane 2007; Dariane & Momtahen 2009) and real time drought early warning systems for multireservoir operation (Huang & Yuan 2004). Cui & Kuczera (2005) use a genetic algorithm coupled with a stochastic hydrologic input to optimize the mix of different management alternatives to respond to droughts in a complex multireservoir water resources system for urban water supply. Recent applications of GA also include optimal design of pumping networks for the production of desalinated water (Alcolea *et al.* 2008).

Overall, it could be said that GAs are a good choice whenever alternatives in a discrete domain must be evaluated and optimized. The motivation for selecting GA also in capacity expansion problems is similar to the one expressed by Labadie (2004) in his review on the state of the art of the optimization models for multireservoir water resources systems: commenting on the role of Genetic Algorithms in this field of research, which is different from that of infrastructure planning albeit with close connections to it, Labadie states that heuristic methods such as GA sacrifice the formal elegance of more established optimization techniques to gain flexibility and to increase the overall descriptive ability of the optimization model: this derives from the possibility of integrating virtually any type of simulation model into the optimization process. As far as the expansion problem is specifically concerned, nonlinearities in cost functions and constraints are no longer an issue with G.A. as they are evaluated by means of a simulation algorithm.

The paper is organized as follows: the first section is devoted to the description of the model. Both the simulation and optimization module are illustrated and the different objective functions used to test the model are described at length. It is necessary to highlight that the paper does not propose specific developments in Genetic Algorithm applications, rather it is aimed at assessing the response of the procedure to different objective functions. In a second section, an application to a real-world water resources system allows evaluation of the procedure.

THE MODEL

Let $\boldsymbol{X}$ be a vector containing n decision variables that describe each of the candidate projects (water transfers, treatment plants, desalination plants, etc.). The dimensions of such variables may hence be diameters or flows in m^3/s or water volumes. Each of such variables may take on a discrete number of values and has attached an investment cost and a set of parameters useful for assessing variable costs, i.e. costs associated to water flowing in the system in a given time step. Variable costs include operation and maintenance costs (O&M costs in the following) but also scarcity costs or proxies thereof. Such variable costs must be assessed via a simulation model. The model also quantifies the additional water volumes that the system is able to supply thanks to alternative $\boldsymbol{X}$. Such incremental volumes represent the basis to calculate the benefit associated to each alternative. As such, the model is static and deterministic (Loucks *et al.* 1981; Mays 2005): water demands are a "snapshot" of the situation a certain year ahead and what is analysed is the reaction of the system to the infra- and inter-annual hydrologic variability, represented by a multisite time series of flows entering the system.

The architecture of the model envisages generating randomly a first set (or population) of vectors $\boldsymbol{X}$. The impact of each of such alternatives on the system's performances may be measured through an objective function (often called a fitness function in the GA jargon) whose value is assessed through a simulation model. This first set of alternatives is hence modified, keeping the best alternatives and combining them through genetic operators (see paragraph "the optimization model") and the modified set is also evaluated. In this fashion, the model evolves towards improved solutions. Clearly, this approach is very well suited for infrastructure planning where some dozens at most of different infrastructures are commonly to be considered, each with a limited number (2/5) of candidate dimensions.

In addition, it should be highlighted that the procedure illustrated in this paper does not combine infrastructure optimization with the optimization of allocations. As will be illustrated in the paragraph "the simulation model", allocation is performed according to some prefixed rule. This is suitable when the objective is to compare benefits (increased water supply and reliability) stemming from different alternatives and it is advisable to keep the effect of increased supply separated from that of optimizing the use of the available resources among different users and periods. Approaches combining both infrastructure and optimization of allocations are proposed, among the others, by Yang *et al.* (2007), integrating a multiobjective GA for infrastructure selection with a constrained differential dynamic programming algorithm for variable cost minimization, by Sechi & Sulis (2009), who introduce a mixed optimization-simulation approach based on an advanced graphically supported network flow algorithm accounting for both fixed and variable costs, and by Watkins & McKinney (1998) who use General Bender Decomposition and Outer Approximation methods to solve the mixed-integer non linear optimization problem arising from the consideration of both infrastructure planning (with only build/don't build options) and minimization of variable costs.

THE OBJECTIVE FUNCTIONS

Different objective functions will be considered. The first one (O.F. 1) is a cost/benefit index (currency/m^3) that has been modified to account for the effectiveness of the alternative in coping with drought periods, *ceteris paribus*. For a single type of uses:

$$\text{O.F.} = \frac{\Delta C^{(\text{use})}}{\Delta B^{(\text{use})}} \times \frac{1}{\Delta M^{(\text{use})}} \tag{1}$$

where, $\Delta C^{(\text{use})}$: difference $C - C_0$ between the total cost C (investment + actualized O&M) of the system with the alternative and a reference "zero" cost C_0 (actualized variable costs in a configuration with no additional infrastructure). The superscript indicates that ΔC assessed for a given use (e.g. civil or irrigation), $\Delta B^{(\text{use})}$: difference between benefit B provided by the system with the alternative and a reference benefit B_0 in the zero situation (no additional infrastructure), $\Delta M^{(\text{use})}$: Incremental static moment around $T = 100\%$ of the area under a demand–reliability relationship. Relationships between percentages of demand target T (on the x axis) and the frequency with which such target percentages are met may be used to represent synthetically the performances of a water resources system. By definition, the area under such curves represents the average supplied volume; its static moment around the $T = 100\%$ axis measures how the alternative reacts to water shortages: let A and B be two alternatives for the water system and denote with M_A and M_B their static moment around the $T = 100\%$ line. If the two curves have the same area but $M_A > M_B$, then alternative A should be preferred, as it allows meeting more frequently lower target percentages (thus avoiding higher deficits). In reservoir management this is accomplished by defining optimized hedging rules, in expansion problems, this should encourage the selection of hydrologically reliable alternatives.

If benefits are identified with the incremental water volume that the alternative is able to supply, (1) provides a unit resource cost (currency/m^3) multiplied by a penalty factor for alternatives which prove, *ceteris paribus*, less effective in coping with hydrologic failures.

The second objective function (O.F. 2) gives an index of the actualized net benefit:

$$\text{O.F.}^{(\text{use})} = [\Delta B^{(\text{use})} - \Delta C^{(\text{use})}] \times M^{(\text{use})} \tag{2}$$

In (2) the benefit is assessed in financial terms, by simply multiplying the incremental water volume made available by the alternative, by the average water price for that use. This will be used to analyse the impact of water price on optimal infrastructure scenarios.

Finally, the third objective function (O.F. 3) is similar to (2), but costs now also include the so called scarcity costs, born by consumers for not having available a target water quantity. They reflect the total value or utility to customers of the foregone water use, (e.g. Jenkins *et al.* 2003). Intuitively, scarcity costs cannot be linear (Loucks *et al.* 1981): classic consumer's theory provides the framework for quantifying loss functions. In an undistorted market, the marginal price of a good coincides with the marginal benefits. The economic value or benefits of a given quantity of additional water is hence the area under the price-demand relationship for that good. Such benefits turn into a cost (the scarcity cost) when, owing to water shortages (droughts), the allocated resources keep less than the target value, representing the amount of water users would take if water were priced at its current level and had unrestricted availability. We hence use a price-demand relationship for urban water use to assess benefits related to each alternative.

In this work, the basic assumption is that the demand-price relationship is linear (Del Treste & Mazzola 1991) in a range from the upper bound of non compressible demand values (corresponding to a minimum of water being supplied) to the target value, as Figure 1 shows, above which no consumer is willing to pay for an additional unit of resources, as they are fully satisfied with the target.

Minimum per capita (p.c.) consumption D_{min}, is assumed equal to 80 L/day (Al-Qunaibet & Johnston 1985); to provide D_{min} the backstop technology is in this case tankers, with an estimated unit price P_f of 4.15 €/m^3. Target demand T is quantified assuming a target per capita daily demand of 200 L plus collective uses and losses in water distribution networks kept at their economic level. Price for water at the target level is indicated as P_T in Figure 1.

Such an approach is not feasible when water is an intermediate good as is the case of agriculture. Different approaches exist for assessing the economic value of irrigation water (Young 1996) based on contingent evaluation on willingness to pay (WTP). A WTP-based approach usually includes the solution of a farmer's optimization problem where the objective is profit maximization and the unknown is the price of water resource (e.g. Bontemps & Couture 2002). Albeit theoretically straightforward, this approach is difficult to follow, when output values (prices) are distorted and input data are uncertain and incomplete. However, a reasonable a priori shape for the loss function may be assumed. We suggest a cumulate gaussian deficit-loss relationship with increasing marginal losses (first derivatives) up to a certain value after which losses keep increasing but with decreasing marginal values. Maximum loss is achieved for deficits less than 100%, as very low water availability cannot be used for irrigation of most crops.

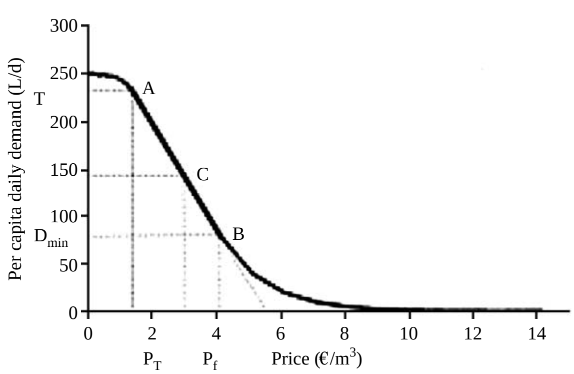

Figure 1 | Price-demand relationship for domestic water.

The basic assumption in this case is that maximum loss implies the loss of the whole annual added value of yield. Estimation procedures (Genco *et al.* 2006) have been applied using value added data from the Italian National Institute of Statistics (ISTAT) as well as information on the extent of irrigation areas and crop types.

For a multipurpose water resources system with N different uses, Equations (1) and (2) can be extended as follows:

$$\text{O.F.}^{(\text{system})} = \sum_{i=1}^{N} w_i \times \text{O.F.}_{\cdot i} \qquad (3)$$

Equation (3) states that the O.F. for the whole system is the weighted sum of the O.F.s for different uses. The weights may be set equal to the ratio between the average annual demanded volume for a given use and total annual demand or may be proportional to the unit value (or price) of water for that use.

Equation (3) represents the simplest way to aggregate multiple and conflicting objectives of an optimization problem in a single function. As this paper is mainly focused on evaluating the response of the model to different objective functions, it was not deemed essential to include explicitly in the test cases also a function such as (3). Owing to the existence of different types of use and different districts, the problem illustrated in the application is, however, basically multiobjective in its nature.

THE SIMULATION MODEL

The model is implemented in Matlab® and simulates both water transfers through the infrastructure options to be optimized and the allocation on a monthly basis of the hydrologic input (30 years from 1971 to 2000) to the various demand centres. The model can work at different time scales. For the application illustrated in the next section, water transfers from a river to treatment plants were simulated at daily scale, while reservoir routing was performed at monthly scale. To calculate costs and benefits both daily and monthly values must be aggregated to an annual scale.

Starting from month one, the routine for reservoirs develops for each reservoir a volume balance among inflows, evaporation and demanded volumes (including ecological demand downstream). Non-negativity constraints on stored volumes applied to a "standard" (i.e. non-hedging) operation rule (Loucks & Van Beek 2005, pp. 65–66) provide deficit values, and capacity constraints provide spills from reservoirs. Deficit is shared among users proportionally to their target demand level. The model allows for "demand-driven" inflows to reservoirs, that is for those water flowing to reservoirs through pumping or water transfers. Whenever possible, such volumes are reduced to limit spills through the introduction of simple, system-specific, operation rules that favour the reduction of withdrawals from the costliest resources.

THE OPTIMIZATION MODEL

As well known, genetic algorithms are heuristic optimization models in which the search process of a maximum/-minimum in the solution space is driven by a number of different operators mimicking the mechanism of natural selection. They act iteratively on the components (also known as individuals) of a population: each population consists of a given number of individuals and each individual is a combination of the decision variables and as such is a feasible solution for the problem. The individuals of the starting population are generated at random and are encoded in strings. Subsequently, simple manipulation of such strings through genetic operators such as selection (deletion of the less fit individuals according to the value of the O.F. they yield), crossover (recombination of strings to form new individuals) and mutation (involving random change in some part of some individual) lead to a new population whose individuals should have overall "evolved" compared to those of the previous population, although they do keep some features (hopefully the most promising ones) of it.

In this work, a population is constituted by 200 individuals; each individual of the starting population is generated at random and is routed through the simulation model to assess its fitness, that is, the value of the Objective Function.

After generation of the first population of alternatives, natural selection is performed by eliminating the 100 alternatives with the worst fitness. The creation of the new 100 alternatives to restore the original set of 200 is based on the principle of the correlation among the fittest solutions: modules for probabilistic/crossover, mutation and elitism (an additional operator allowing to transfer a few of the best individuals to the next population unchanged) have been used in this work.

The effect of the new alternatives is then assessed via the simulation model and the process continues until a stopping criterion is met. In this case, the algorithm stops after 20 generations, corresponding to $(1 \times 200 + 19 \times 100) = 2{,}100$ simulations.

A scheme of model architecture, showing interactions between the simulation and optimization model is reported in Figure 2.

MODEL APPLICATION

The system

The model has been applied to a multipurpose (urban, irrigation, hydropower) water resources system in south-western Sicily (Figure 3) supplied by surface (reservoirs and weirs) and underground (springs) sources. At the selected time horizon (2032), urban water demand is estimated in $56.0 \times 10^6\,m^3$, around $37.0 \times 10^6\,m^3$ of which may be met by local resources, whereas irrigation demand is assessed in around $55.0 \times 10^6\,m^3$, to be entirely met by surface water resources. Presently, both urban and irrigation service is considerably irregular, with an alternation of "normal" years when no relevant issues in water supply are recorded, and dry years with reduced water availability resulting into

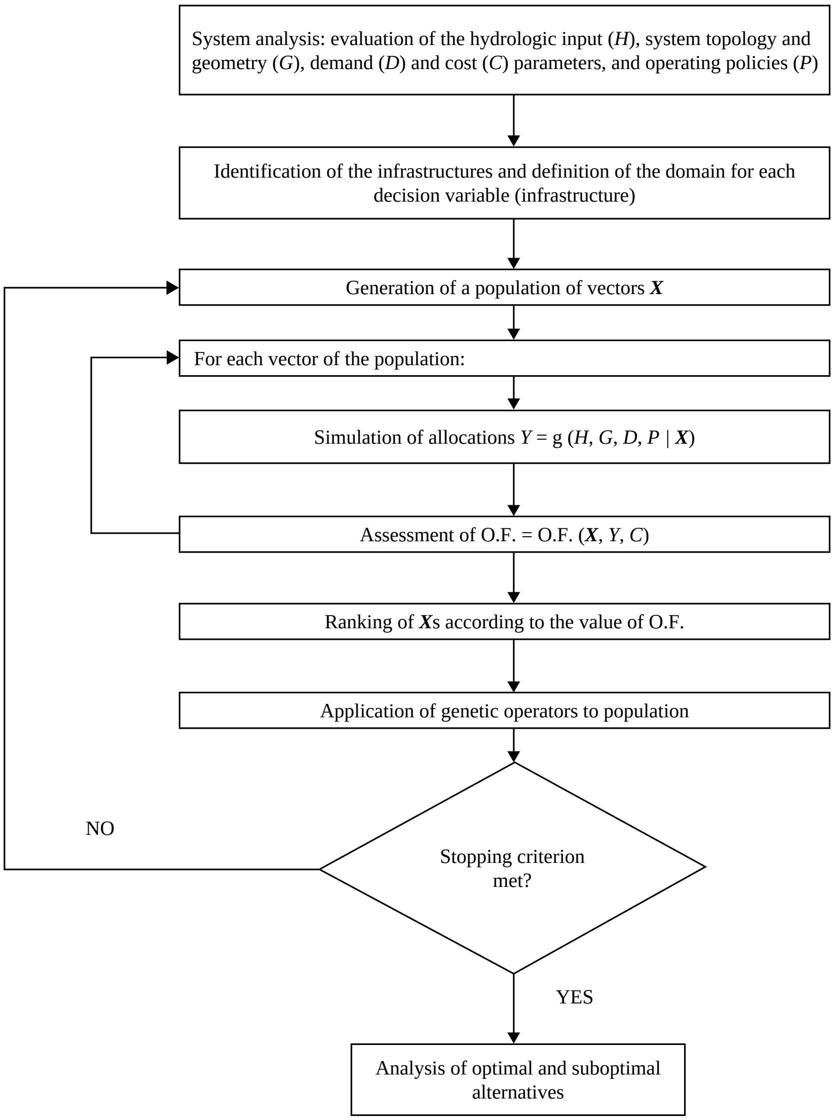

Figure 2 | Model architecture—for a given infrastructure alternative ***X***, allocations provided by the simulation model are a function of hydrologic input, demand characteristics and other features of the system, including allocation policy.

rationing and conflicts. On the one hand, this is certainly due to the natural variability of surface water availability that features coefficient of variations of around 0.5 on a yearly basis which can lead to yearly streamflow less than 60% of the average once every five years and to multiyear droughts with up to six consecutive years with total streamflow below the annual long term mean. On the other hand, this occurs in a context with high losses in water distribution networks (both irrigation and urban).

Demand analysis for irrigation and urban usages shows however that, even when losses will be reduced to their economic level through extraordinary maintenance/renovation of distribution networks, the supply-demand balance cannot be closed with regularity. In order to normalize service, the idea is hence to use additional surface water resources from Verdura river (blue line on the right in Figure 3) which are presently exploited upstream almost exclusively for hydropower generation. As a former plan of a new off-line reservoir has been abandoned given the long and uncertain duration of construction, it becomes attractive to analyze the feasibility of using residual capacities of the two main reservoirs of the system, Garcia (60 Mm^3, S02

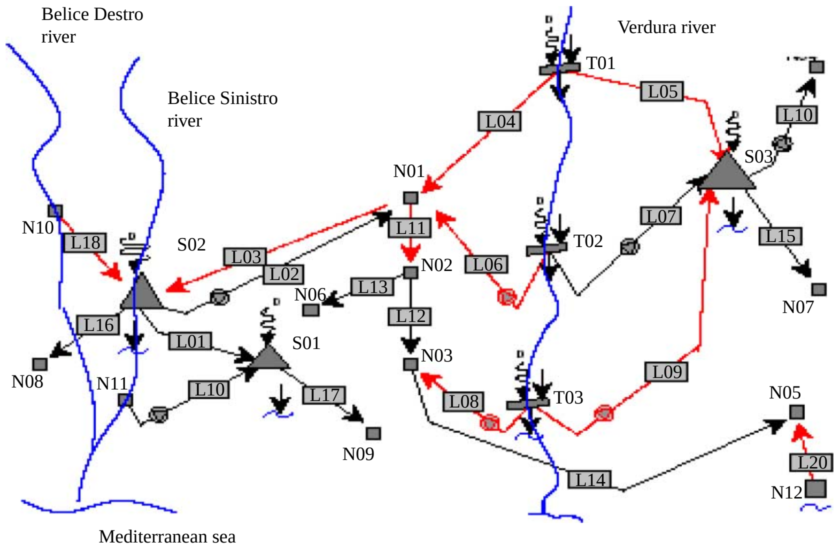

Figure 3 | The Sosio Verdura water resources system and its connections with neighbouring schemes: Belice on the left and Castello (S03) on the right. Existing transfers are in black, planned candidate connections are in red (grey). Straight arrows indicate direction of flow towards uses or plants. Bent curves indicate natural inflow to reservoirs and weirs. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst

in Figure 3) and Castello (18 Mm^3, S03 in Figure 3) to store water from Verdura river. In addition, Garcia reservoir can transfer water to Arancio reservoir (S01) which is used only for irrigation purposes. In order to reduce investment costs, it is suggested to use the existing hydroelectric infrastructure on the river (pressure pipes and canals) to create intakes to the reservoirs. Intakes may be built 1) upstream, using pressure pipes from San Carlo generation plant (T01, actually the small reservoir supplying the generation plant) to take water westward directly to Sambuca treatment plant (arc L04) and eventually to Garcia reservoir (L03) and eastward to Castello reservoir (arc L05) or to either of the two, 2) downstream from a canal connecting Favara weir (T02) to Poggiodiana generation plant (T03) to Sambuca plant (L06) or downstream all hydropower generation plants (T03).

Irrigation uses (orchard and citrus): although withdrawal for urban use is now increasing. Water is treated in plant N03. The decision maker is hence confronted by a set of different objectives: (i) increase water availability and the reliability of the allocated volumes, (ii) reduce investment and operation costs, (iii) share resources equally between the two subsystems, and (iv) minimize interference with hydropower generation. All this must comply with environmental constraints expressed by minimum ecological flow from reservoirs.

In such a scheme, where the alternatives are mainly based on withdrawals from a river (featuring flashy hydrological response) with direct connection to treatment plants, the trade-off between additional costs and gained volumes can be appreciated only at a finer time scale than the month, a scale where withdrawn volumes are comparable with the capacities of treatment plants: for such reason, simulation of withdrawals from Verdura river has been simulated at a daily scale. Simulation of reservoirs has been carried out at monthly scale, as customary in this kind of applications. Table 1 reports the set of infrastructure and their design values.

RESULTS

Table 2 reports the optimal long-term infrastructure configurations for the three different tested Objective Functions with various constraint typologies and levels. Nine decision variables x_i, $i = 1, \ldots, 9$ were selected to form a candidate alternative $\boldsymbol{X}$. The meaning of each variable has been illustrated in Table 1, but will be restated throughout the discussion.

The decision variables are expressed in terms of the maximum capacity of the infrastructure they represent. Considering the domain of variability of the nine decision

Table 1 | Decision variables, their role in the system and design values

Decision variable	Arc/node	Explanation	Design values ($m^3 s^{-1}$)				
x_1	L03	Expansion of transfers from Garcia reservoir to Sambuca treatment plant	0.0	0.5	0.9	1.2	
x_2	L04	Construction of upstream transfer from S.Carlo generation plant to Cozzo Agghiastro disconnection tank (N01)	0.0	0.6	0.9	1.0	1.2
x_3	L05	Construction of upstream transfer from San Carlo generation plant to Castello reservoir	0.0	0.6	0.8	1.0	1.2
x_4	L06	Construction of a pumping plant from Favara weir to Cozzo Agghiastro disconnection tank (N01)	0.0	0.6	0.9	1.0	1.2
x_5	L08	Construction of a treatment plant at Ribera and of a pumping plant from Verdura river (downstream Poggiodiana generation plant) to the treatment plant	0.0	0.1	0.2		
x_6	L09	Construction of a pumping plant from Verdura river (downstream Poggiodiana generation plant) to Castello reservoir	0.0	0.5	0.8	1.0	1.2
x_7	L11	Expansion of Sambuca treatment plant	0.0	0.5	0.9		
x_8	L18	Construction of a diversion from Belice destro river basin to Garcia reservoir	Yes/no (the investment will increase inflows to Garcia reservoir by an average of $4.0 \times 10^6 m^3/yr$.)				
x_9	L20	Construction of a desalination plant to supply Agrigento city (N05)	0	0.1	0.2		

variables (4 variables with 5 different possible maximum capacities including the zero option, 3 variables with 3 different possible maximum capacities, 1 variable with 4 different possible maximum capacities and one variable with a yes/no option), the decision set is constituted by 135,000 alternatives. As the algorithm converges well before the stopping criterion of 20 generations, it seems actually capable of determining optimal solutions by exploring less than the 2% of the space of the feasible solutions.

In Table 2, the first column indicates the type of O.F. tested (see section devoted to model description). Overall, the model provides optimal configurations that are consistent with the objectives described by the different O.F.s and by the constraints.

Table 2 | Optimal solutions for different objective functions and constraint levels

		Water price (€/m^3)		Decision variables (m^3/s)								
O.F.	Constraints	Urban	Irrigation	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
1	Unconstrained	–	–	–	–	–	–	0.2	–	–	–	–
1	Yearly deficit	–	–	1.2	0.6	0.8	–	–	0.5	–	Yes	0.2
2	Unconstrained	0.60	0.15	–	0.9	–	–	0.2	–	0.9	–	0.2
2	Unconstrained	0.45	0.10	–	0.9	–	–	–	–	–	–	0.2
2	Unconstrained	0.30	0.05	–	0.6	–	–	–	–	–	–	0.2
2	Yearly deficit	0.60	0.15	–	0.9	0.6	–	–	0.5	0.9	Yes	0.2
3	Unconstrained	–	–	–	0.9	–	–	–	0.8	–	–	0.2

Starting from the simplest combination, i.e. unconstrained O.F. 1 (financial cost/benefit minimization) the model includes in the optimal alternative only the least-cost project: the construction of Ribera treatment plant (x_5, arc L08 in Figure 3). It certainly is an effective intervention, so that it had actually been built and operated for some year but was abandoned because of urban customers' mistrust to using treated river water. Incidentally, although water quality aspects are not included in such a quantity-oriented model, they could be also built as constraints in the simulation procedure to model situations such as the one described above.

The choice of such a parsimonious infrastructure configuration is clearly consistent with the objective of cost minimization that would have even led to a zero option (do nothing), had it not been for the need to account for non-zero benefits at the denominator of O.F. 1.

A likelier description of the type of system's configuration O.F. 1 can lead to is obtained by setting a constraint on the maximum percentage deficit on an annual basis: max $(T_j - R_{ij})/T_j < a_j$, with $i = 1, 2, \ldots, N_{\text{years}}$, $j = 1, \ldots, N_{\text{usages}}$, T_j = Yearly Target Demand for the j-th use and R_{ij} total release for the j-th use in year. Too tight constraints on yearly deficits ($a_{\text{Urban}} < 0.20$) cannot be respected for the given hydrologic input; the solution allowing respect of constraint levels $a_{\text{Urban}} = 0.20$ and $a_{\text{Irrigation}} = 0.40$ requires both the construction of x_2 (arc L04 in Figure 3), i.e. the connection from S. Carlo generation plant (supplied by Gammauta reservoir T01) to Sambuca treatment plant, and of the expansion of connection of Garcia reservoir to Sambuca treatment plant (arc L03, variable x_1). This last option has the only effect to increase the stored volumes at Garcia reservoir, given that no expansion of the treatment plant is suggested as optimal. The optimal solution also includes the construction of the river intake from Belice Destro to Garcia reservoir (variable x_8, L18 in Figure 3) and building the desalination plant (x_9). As far the Castello (eastern) subsystem is concerned, the model suggests realizing all the available investments to withdraw water from Verdura river, both by gravity (x_3, arc L05 in Figure 3) and by pumping (x_6, arc L09 in Figure 3). It is worthwhile noticing how the model does not include now its unconstrained best choice (Ribera treatment plant, x_5, arc L08 in Figure 3) probably because the model contains the policy to share the residual available volumes instream (net of minimum ecologic flows) according to demand levels whenever water availability from the river is not enough to meet x_5 and x_6. This would penalize the smaller withdrawals from Verdura to the western subsystem compared to those eastwards and make them financially unsustainable. Clearly, a different policy, corresponding to possible future agreements among managing bodies, may lead to different results.

In O.F. 2 the objective is to maximize net benefits, where benefits are here the sum of the products of the volume supplied for a given use by its unit price. Different levels of unit prices have been considered (columns 3 and 4 of Table 2) for irrigation and civil water and sensitivity of results in terms of infrastructure is analyzed in the following.

In the first place, unconstrained maximization of O.F. 2 leads to realizing investments only in the western subsystem and only for the urban sector. This choice is consistent with the objective of maximizing revenues from bulk water, as in this excercise urban water has unit prices by four to six times greater than irrigation water. The model suggests building the upstream connection between Verdura basin and Sambuca treatment plant (x_2, arc L04) with the expansion of the latter (x_7), as well as building Ribera treatment plant (x_5) and the desalination plant (x_9). Clearly, in the spirit summarized by O.F. 2, the perspective of reduced revenues due to decreasing unit prices also reduces the inclination to build, as evidenced by the progressive reduction of the number of investments when unit water price for domestic use shifts to lower values (for a reduction of 25% of the unit water from 0.60 €/m^3 a 0.45 €/m^3 the model deletes options x_7 and x_5). It may be interesting to notice how the model confirms the need for a disalination plant, albeit its higher unit costs, as it is able to supply water also in the dry season when withdrawals from the river stop.

Introducing a constraint on maximum admissible water deficits modifies the optimal configuration that now seems more balanced as far as different uses and subsystems are concerned. The Castello subsystem, previously neglected due to its prevailing agricultural purpose, now receives additional water from Verdura river by pumping (x_6, arc L09 in Figure 3). In the western subsystem, the suggested

Table 3 | Some suboptimal solutions using model with O.F. 3

		Decision variables (m^3/s)								
Rank	**O.F. values.**	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
1	1,154.3	–	0.9	–	–	–	**0.8**	–	–	**0.2**
9	1,147.9	–	0.9	–	–	**0.1**	1	–	–	0.2
14	1,146.1	**0.9**	1.2	–	–	–	1	–	–	0.2
40	1,136.4	–	1.2	–	–	–	0.8	**0.9**	–	0.2
56	1,129.5	–	1.2	**0.6**	–	–	0.8	–	–	0.2
59	1,125.9	–	1.2	–	**0.6**	–	0.8	–	–	0.2
65	1,105.8	0.9	1.2	–	–	0.2	–	0.9	**Yes**	0.2

investments are similar as for O.F. 1 with the same type of constraints, except that the model indicates expanding Sambuca treatment plant (x_7), rather than increasing tranfer capacity from and towards Garcia reservoir.

Finally, using O.F. 3 leads to recognising as optimal a long-term system configuration with the desalination plant (x_9), withdrawal from Verdura river upstream by gravity to Sambuca tratment plant (x_2), and downstream by pumping to Castello reservoir (x_6). Introducing constraints on deficits is not necessary in this case, as their impact is already incorporated in the model implicitly, through deficit-loss relationships. Although conceptually the most straightforward approach, it suffers from the uncertainties related to the form of the demand model underlying the deficit-loss relationships and its parameters. This could be overcome by extensive sensitivity analyses aimed at understanding the impact of such uncertainties on infrastructure options. While this aspect is not tackled in this paper, it is worthwile observing how the optimal configuration suggested under O.F. 3 features a smaller infrastructure set than that resulting from use of the constraints on deficits and also automatically satisfies the (desiderable) equity requirement between subsystems.

With reference to O.F. 3 scenarios, we also provide a picture of some suboptimal solutions among the first hundred best. They are summarized in Table 3, with the corresponding O.F. value and their rank.

Table 3 only includes alternatives in which a different infrastructure appears from those included in the former (higher rank) alternatives, leaving out solutions in which the model suggests the same type of expansion, albeit with different sizes. It shows how the optimal solution is rather robust, in that there are not completely different combinations of new infrastructures yielding O.F. values similar to the optimal ones. The optimal solution is also the one that minimizes investment costs.

CONCLUSIONS

A GA based simulation/optimization procedure for complex water resources system expansion has been introduced and evaluated. The model is static and deterministic in that target demands are considered fixed at some time in the future and hydrologic variability is analysed using a multisite historic record of streamflows. The procedure seems interesting because it allows optimization of system expansion without giving up a detailed description and simulation of the system. The simulation model developed for the application allows, for instance, the use of different time scales according to the different components that need to be modelled. This model is well suited for discrete combinatorial optimization problems such is the search for the optimal infrastructure configuration of a system where the search domain is constituted by a set of candidate infrastructures, each with a discrete number of different possible dimensions. In order to test the procedure, it has been applied to the problem of assessing optimal long-term system expansion for a multireservoir, multipurpose water resource system in south-western Sicily using different objective functions subject to various constraint typologies and levels. In all cases the model has shown its ability to provide responses that are consistent with the objectives expressed by the objective functions and constraints and seems to explore the solution space quite efficiently, in that it converges to a consistent solution after exploring less than the 2% of the feasible solutions.

An analysis of the suboptimal solutions with reference to the infrastructure scenarios driven by objective function 3 shows that the optimal solution is rather robust and is also the one that minimizes investment cost. The work also emphasizes the role of deficit–loss relationships in providing well-balanced solutions, although work must be done to gain deeper insights on both their theoretical foundations and their pratical application.

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