18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Simulation versus optimization in the assessment of the resource opportunity cost in complex water resources systems – the case of Agri-Sinni in southern Italy

Arena, C. [1], **A. Fortunato** [1] **and M.R. Mazzola** [1]

[1] *Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali, Palermo University, Italy*
Email: arena@idra.unipa.it

Abstract: The EU Framework Directive 60/2000 has introduced the concept of resource cost as an integral part of the decision making process in the sector of water resources exploitation and protection. Production and provision costs aside, the resource cost is associated to the idea of opportunity cost, that is, the cost of the foregone opportunities other alternative users must bear as a consequence of the choice of allocating the resource to a certain use. Marginal resource opportunity costs (MROC) represent the benefit foregone for having available one unit less of resource at a given time and location. As such, they are a function of system's configuration as well as of the relevant socio-economic water – related variables in the area.

MROC evaluation relies upon the concept of opportunity cost as second best alternative foregone for making a choice and is hence based on the idea that they must be assessed starting from some equilibrium (optimal) maximum – efficiency allocation of water resources in the system. Maximum efficiency is usually related to the idea of achieving minimum variable costs, including scarcity costs. Scarcity costs reflect the economic losses caused by water unavailability and must be assessed by appropriate loss functions for different water uses (urban, irrigation, etc.). A unit perturbation in the availability of a given resources at a certain time generates a new equilibrium condition, quantified by the selected efficiency measure (total costs). The shift in the value of the objective function (cost minimization) divided by the value of the perturbation provides an assessment of the MROC. Such assessment are directly provided by standard linear programming tools supplying shadow prices for relaxing the constraints (on maximum capacity) on a given resource.

It may be questioned, however, whether long-term maximum efficiency water allocation assessed by an optimization model is realistically achievable in real world operation of water resources systems. Given perfect input foresight and other factors, marginal opportunity costs obtained by an optimization algorithm may be a lower bound for their likely values. As an alternative, it maybe worthwhile using simulation models for a description of system's operation using current allocation criteria. The MROC is obtained by decreasing of unit quantity resources availability at a given point and time step and evaluating the response (in terms of costs) of the system, thus obtaining an approximation of the opportunity cost. The paper is provocative to some extent, in that one of its goals is to quantify the impact of inefficient management of a system on the perception of resources costs and on the subsequent decisions on infrastructures that must be built to substitute or expand them, should this become necessary.

The paper compares the outputs of a linear programming based - water allocation procedure and of a plain simulation model for the assessment of the marginal opportunity cost of groundwater resources in a real-world water resources system located in Southern Italy, where aquifer overexploitation concretely poses the problem of comparing different expansion alternatives to cope with the planned reduction of underground water withdrawals. The simulation model uses very simple operation rules (purposely oversimplistic, to some degree) to contrast results with those obtained adopting the idealized behavior of the omniscient decision maker of the optimization model. Results show that marginal opportunity costs can vary considerably with the methodology, as a consequence of the different underlying assumptions, optimization yielding an ideal maximum efficiency allocation and simulation providing an inefficient, but somehow more realistic, description of the allocation process. As the operating rule specifically employed in the simulation model pushes to the limits the contrast with those The results may be seen as upper and lower bounds for the marginal opportunity cost of resources in this specific context.

Keywords: *Resource opportunity cost, water resources system planning, optimization*

1. INTRODUCTION

The EU Framework Directive 60/2000 has introduced the concept of resource cost as an integral part of the decision making process in the sector of water resources exploitation and protection. Production and provision costs aside, the resource cost is associated to the idea of opportunity cost, that is, the cost of the foregone opportunities other alternative users must bear as a consequence of the choice of allocating the resource to a certain use. This is a well established concept in the theory of resource economics which seeks to define the conditions in which a scarce resource such as water may be allocated producing the maximum welfare for society. Such allocation is indicated as efficient.

Although fully efficient allocation of water resources may not be attained in practice and strictly economical efficiency criteria are not the only ones to be followed in resources assessment (Turner et al., 2004)., the evaluation of efficient water resources allocation scenarios is very valuable as it allows a straightforward assessment of the actual value of resources. This may be useful at least under two respects:

- it helps defining pricing strategies for water that can increase the level of efficiency of resources allocation for a given system of resources and demands;
- when applied to complex water resources systems, it provides support on decisions regarding infrastructure planning for system expansion as it allows adaptation of investment costs to the actual value of the resources demanded (N. –S. Hsu *et al*., 2008).

Other applications include the use of the marginal opportunity cost for the evaluation of the opportunity cost of environmental requirements (Andreu Alvarez et al., 2008).

The concept of opportunity cost applies to all types of externalities that may be produced by a certain resources allocation under given technology; in some instances however, namely in drought-prone areas, first-step maximum-efficiency water allocation scenarios may be obtained with reference to water quantity only, using benefit maximization or minimum variable-cost criteria. In this last case, scarcity costs play a crucial role beside production and provision costs. Scarcity costs reflect the economic losses caused by water unavailability and must be assessed by appropriate loss functions for different water uses (urban, irrigation, etc.). The evaluation of such loss functions is by no means either a standard or a trivial task, as they contain a significant amount of information on the present and/or expected level of (technological and even market) development of the sector to which water is an input factor, and are ultimately related to the price – demand relationship for water, as will be discussed in further detail later in the paper. As said, maximum-efficiency allocation scenarios are the starting point for the evaluation of the marginal cost of resources (MROC), i.e. the cost of having available one unit less of resource at a given time and location, thus contributing to define the resource's value.

In a complex water resources system, the value of each resource at a given time will hence be a function of system's configuration in terms of infrastructure and resources typology and also in terms of the relevant socio-economic water – related variables in the area, entering the demand models defining scarcity costs. Resources typology refers to both quantity and quality constraints, the first ones being related to typology of resource (roughly: surface – variable vs. underground – constant) and to the hydrological features of the catchments (seasonal and annual water resources variability) and the second ones to natural, as well as to human-induced causes of low water quality for the different uses.

Operationally, the assessment of marginal costs in a complex water resources system may be performed by an optimization algorithm of water allocations along a reasonable time span (for instance ten or twenty years) which supplies shadow prices for relaxing of one unit the constraints on the use of the resources. Such so termed hydro-economic models have recently received considerable attention from research and have found significant applications in the long-term planning of large scale water resources system (Pulido-Velazquez et al., 2004; Jenkins et al., 2004).

It may be questioned, however, whether long-term maximum efficiency water allocation assessed by an optimization model is realistically achievable in real world operation of water resources systems. Given perfect input foresight and other factors, marginal opportunity costs obtained by an optimization algorithm may be a lower bound for their likely values. In addition, standard optimization models may be incapable of providing a detailed description of the system, which may make result interpretation cumbersome. As an alternative, it maybe worthwhile using simulation models for a more detailed description of system's operation using current allocation criteria. In a simulation framework, the MROC is obtained by decreasing of one unit the availability of resources at a given point and time and evaluating the response (in terms of costs) of the system, thus obtaining an approximation of the opportunity cost value (Andreu Alvarez et al., 2008).

The paper hence seeks to compare the results of a mixed-integer linear programming based - water allocation procedure and of a plain simulation model for the assessment of the marginal opportunity cost of overexploited groundwater in a real-world water resources system located in Southern Italy, with the aim at comparing different expansion alternatives to cope with the planned reduction of underground water withdrawals.

In the case of the evaluation of over- or non-sustainable exploited water resources, beside production and opportunity costs, a third term should be considered: the so called “user cost” (Turner et al., 2004) which relates to the value of the opportunity foregone by exploiting and using the resource in the present period rather than at sometime in the future. It also incorporates increases in the costs of future resource use and exploitation that occur as a consequence of current use and exploitation, such as increases in costs of future pumping of groundwater that occur owing to the greater difficulty of extraction, but also the likely reduction of the irrigable areas due to increased soil salinity, the increased damage in aqueducts and water distribution networks because of the high saline content of water etc. While each of such costs may be assessed through sector-specific evaluations, the evaluation of the opportunity cost necessarily entails a system’s perspective. For this reason, in the paper emphasis is placed on opportunity cost.

The paper is organized as follows: first, a brief description of the methodology is provided together with a discussion on the assessment of scarcity costs and then a case study is described. Finally, a discussion on the results will highlight the basic differences between the optimization and the simulation approach.

2. OBJECTIVES AND METHODOLOGY

Methodology refers to the evaluation of over-exploited ground water resources constituting a part of the supply scheme of a system also including regulated surface water and different typologies of use (municipal and irrigation). The idea is to reduce the level of extraction and to evaluate some substitutes in terms of their economical sustainability. As stated above, besides its preservation for later use, reduction of the level of extraction from aquifers is also expected to produce benefits in terms of, *inter alia*, improved crop production due the reduced salinity and improved drinking water quality, as long as a substitute is found. The decision of withdrawing a certain amount of resource from the system to pursue the above benefits will on the other hand induce an additional cost (namely an opportunity cost) to the other users of the system.

Groundwater is modeled in the simplest possible way, i.e. as a constant withdrawal constrained not to exceed a given extraction threshold. Extraction has a unit cost that equals energy costs required for pumping from an average (assumed constant) level of the water table. Such withdrawals are integrated by surface water resources, with no quantity-related costs for irrigation and a treatment cost for municipal use. The assumption of zero cost for irrigation water from reservoirs stems from the idea that fixed costs (such as dam construction and the possible thereto related external costs) are sunk and do not affect present decisions. Under these assumptions, a maximum efficiency scenario is throne in which water resources are allocated in such a way that variable (production and scarcity) costs are minimized. A marginal departure from this optimal allocation scenario due to the tightening by one unit of the constraint on maximum extraction from aquifer produces an increase of the overall cost. Such marginal unit cost (in currency/m^3) is associated to the decision of allocating ground-water to a different use (its preservation, as above) and hence measures the marginal resource opportunity cost. As all the other costs and benefits, such cost enters feasibility analyses for the exploitation of a substitute and system expansion.

2.1. Cost assessment

Regardless of the methodology employed either optimization or simulation, for the assessment of system’s performance with different admissible extraction levels from aquifer, costs must be evaluated, as they are the measure of system’s performance. Costs must necessarily include scarcity costs, expressing economic losses due to supply less than the targeted ones. The development of loss functions for domestic, irrigation and industrial use has recently received some attention from research (Jenkins et al., 2003). The best-established procedure for deriving loss functions is to obtain them from price-demand relationships of water using two well-established principles: 1) the equivalence between loss (or damage) and the willingness to pay for avoiding it and 2) the fact that willingness to pay for an increase of the availability of a good is given by the area under the price-demand relationship for that good.

Demand curves may in turn be obtained in different ways, either parametrically as in this work or through direct (stated preference or behavioral methods - Haab and McConnell, 2002) or indirect methods, such as farm optimization models for irrigation water (e.g. Young, 1996). In this work, the demand curve for domestic use is assumed to be linear in the range of interest. The lower extreme of the demand curve corresponds to the target value of per capita daily water supply (220 l/per capita x day + losses in distribution networks) whose price is the present tariff value (1.2 €/m^3), while the upper extreme of the curve corresponds to minimum incompressible per capita use (80 l/per capita x day) for which the price of a backstop (such as tankers or desalination) can be used. In the application the price of the backstop was set at 4.0 €/m^3. A linear price-demand relationship results in a quadratic deficit – loss curve, such as the one depicted in figure 1 where the adopted time unit is one month. For irrigation, a parametric approach was used to derive a deficit – loss curve: the relationship is assumed to be shaped as a cumulate-gaussian, hence with increasing marginal losses (first derivatives) up to a certain value after which losses keep increasing but with decreasing marginal values, reflecting the fact that, albeit always increasing, losses tend to have a lesser impact for both low and very high deficit levels. The maximum loss equals the entire value added of crop production and is achieved when the entire target demand is not met. Figure 1 shows the proposed deficit – loss relationship. Both deficits and losses for irrigation are evaluated on a yearly basis (Loucks and Van Eelko, 2005).

2.2. Optimization

The procedure for water allocation is driven by a minimum variable cost criterion. Variable costs are those related to the amount of water allocated and as such they include scarcity costs (losses, as in figure 1), treatment and pumping costs. The model is linear, in that constraints are linear and non-linear cost functions are linearized. This is obtained through integer decision variables turning the problem into a mixed-integer linear programming (MIP) model. The model minimizes variable costs subject to:

- storage constraints (storage at each reservoir at time t must equal storage at time t-1plus inflow minus releases, including a fixed minimum ecological flow, and losses);
- Capacity constraints (for reservoirs, treatment plants, aquifer and pipelines);
- Demand constraints (releases must not exceed target levels);

2.3. Simulation

As stated in the introduction, efficient allocation of water resources unfortunately constitutes the exception rather than the rule: reasons for this must be sought, among other things, in the failure of institutions involvement with the allocation and management of water. Sources of institutional failure include markets, policies, and political and administrative factors. The different sources of institutional failure are reviewed in Turner et al. (2004). For such reasons, although maximum-efficiency allocation is an important benchmark for the actual level of efficiency of the system, it may be worthwhile assessing marginal resources opportunity cost using rational, albeit suboptimal, system's operation rules, also given that perfect foresight of future water availability is an abstraction. In this work we use a "base-line" or "standard" allocation policy (Loucks and Van Beek, 2005, p. 65), consisting of routing system's reservoirs with the objective of meeting the whole demand at time t if water resource is available, leaving the reservoir empty otherwise, with a repartition rule for deficits between irrigation and domestic demand constraining the volumes allocated to irrigation to be percentually always less than those allocated to

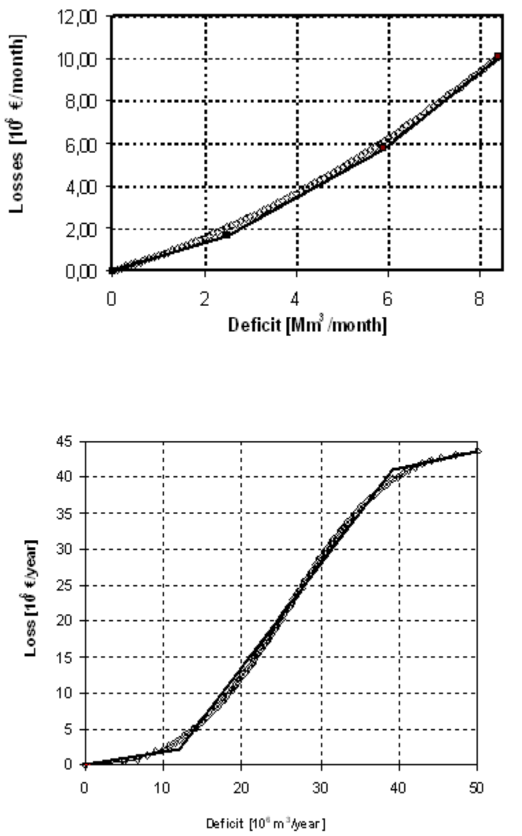

Figure 1. Deficit –loss relationships for domestic use (above) and irrigation (below) and piecewise linearization.

municipal demand by at least 30%. Municipal demand is assumed to be constant over the year and irrigation demand varies along the year according to a certain pattern that remains constant over the years. Wells are modeled as the "no show" person of the model, as they constitute a resource balancing a certain part of the demand. Scenarios of progressive reduction of the maximum admissible extraction level are performed by turning the no longer available groundwater resources into demands to the reservoirs. The latter are managed separately as each of them is assigned an *a priori* rate of the municipal demand. Admittedly, this is quite a rough representation of the management of the system, but it can highlight, by contrast with the optimal allocation scheme supplied by the programming model, the impact of inefficient management of resources on their opportunity cost. The simulation model has been implemented via two electronic spreadsheets, one for each reservoir of the system. It simply routes monthly inflows using mass balance between stored volumes at time t and t+1, releases at time t and evaporation losses; when release is less than demand a deficit occurs, when stored volumes exceed reservoir capacity, a spill occur. Deficits are shared between municipalities and irrigation areas through the above-described policy and are the basis for the evaluation of scarcity costs. Well-established models such as Mike Basin, RiverWare, REALM, WARGI and AQUATOOL (Andreu et al., 1996) and many others may be used to this end. Using this simple, "standard" policy, however, the outputs of such models is likely to be similar to those supplied by a simple mass balance with a fixed policy for sharing deficits as the one used in this work.

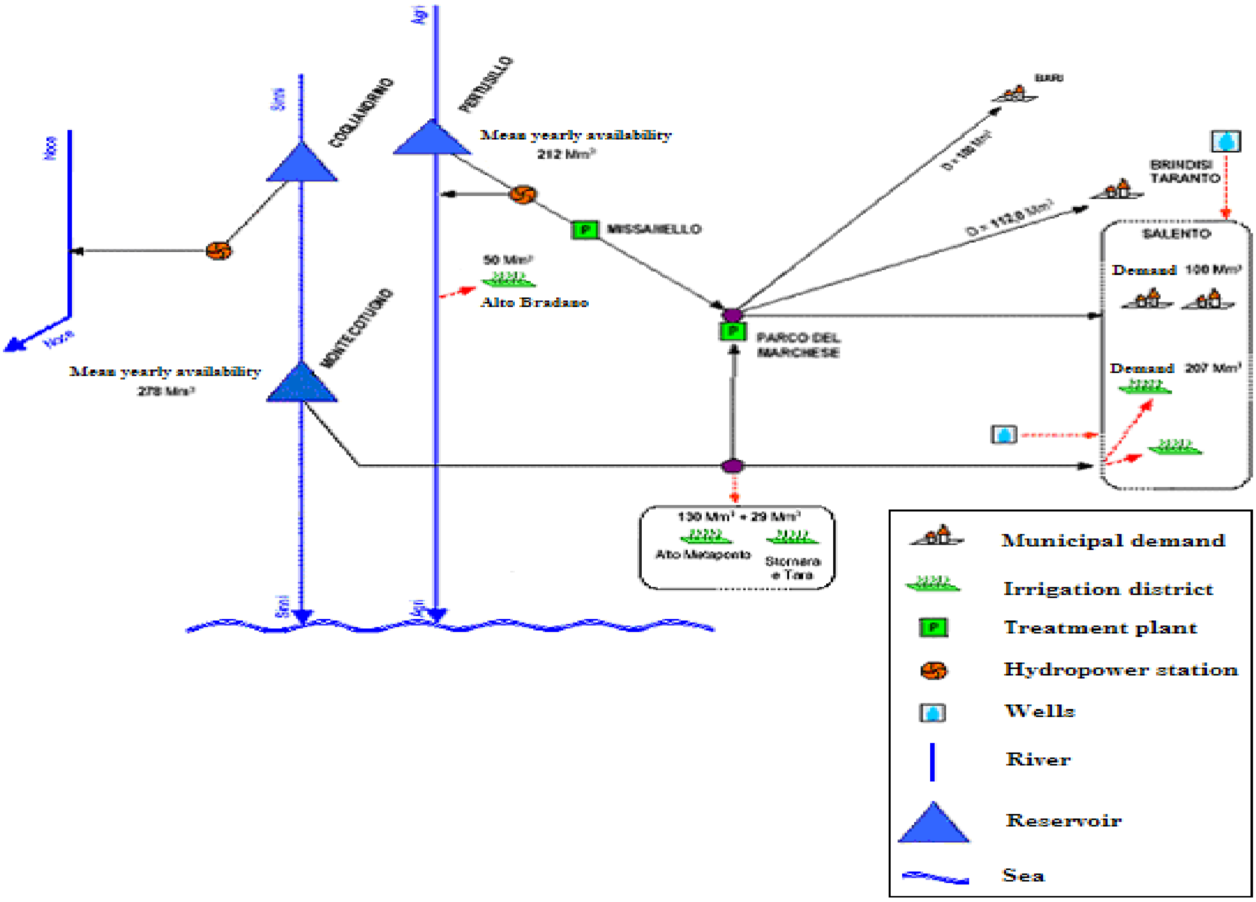

Figure 2. A scheme of the Agri-Sinni water resources system – All demands are on yearly basis

3. CASE STUDY

The above ideas have been applied to the Agri-Sinni water resources system (fig 2), a part of a larger system supplying Apulia as well as cities and irrigation districts in the Taranto Gulf, in Southern Italy. The system presently features two reservoirs, Monte Cutugno on river Sinni with a capacity of 430 Mm^3 and Pertusillo on river Agri with a capacity of 170 Mm^3 as well as a third, smaller reservoir, Cogliandrino, upstream Monte Cutugno reservoir which is presently used for hydropower generation. Releases from hydropower generation are discharged outside the basin so that they presently cannot be further used for other purposes, although the hydropower producer occasionally allows the use of resources from the upstream Sinni basin for transfer into the Monte Cutugno reservoir for civil and irrigation purposes against payment for lost hydropower production. Both reservoirs can supply municipal demand centers all along Apulia, from the south (Salento) to the north (Bari) and they also supply local irrigation districts. In particular, Monte Cutugno will supply irrigation in Salento through extensive (and already completed) irrigation projects, while irrigation in Salento presently heavily relies on groundwater resources, which are also exploited for municipal uses. Due to heavy exploitation for a long time, the quality of groundwater resources in Apulia has diminished considerably in the last decade and dramatically in Salento where it now seems to constitute the true limiting factor for the expansion of irrigation districts. To remedy this situation, it is planned that a large fraction of wells will be closed with a switch to surface water resources. Nonetheless, there is a strong resistance to abandoning the old (and probably costlier) groundwater resource in favor of the new irrigation projects. To mitigate the reduction of water availability induced by well dismiss ion, different alternatives are under study, including the diversion of streamflow upstream Monte Cutugno into the reservoir against payment to the hydropower producer of lost production, water reuse for agriculture and reverse osmosis plant to treat both brackish and sea water.

4. APPLICATION AND RESULTS

The above described optimization and simulation model have been applied to the Agri-Sinni system with the aim at assessing the marginal opportunity cost of groundwater resources for varying level of maximum extraction. The hydrologic input is the twenty-year (1983/84 – 2002/2003) monthly series of inflow to the reservoirs as reconstructed from operation data. The optimization model has been solved through the CPLEX solver of the GAMS software. GAMS or similar software (LINGO for instance) is the customary tool for implementing demand-supply models (DS) such as this (Griffin, 2007). Ilich (2008) has recently raised a number of critical issues related to the application of Network Flow Algorithms, a class of wide-spread models in the field of water resources system programming and simulation. Although directed towards linear models in general, Ilich’s concerns are mainly focused on NFA rather than on MIP techniques as those used in our work. Another point raised by Ilich is the choice of the appropriate time scale for water resources system simulation/optimization that may lead to spill underestimation. This is not the case, however for this application, as the capacity of Monte Cutugno reservoir, the largest in the system, is around 1.5 times the mean annual flow. In addition, the selected twenty-year period is probably the driest in the century and spills, if any, have been occasional.

Marginal costs at a certain time step have been obtained by imposing a unit decrease of available groundwater resources (which turns into an additional unit demand to the reservoirs) on at a time and evaluating the difference in the total cost. Such difference, divided by the amount of water resource subtracted, is a proxy of the marginal cost of groundwater at that time (Andreu Alvarez et al., 2008). As the simulation model requires demands to reservoirs, the values obtained actually represent the opportunity cost of increasing demand at a certain time to a certain reservoir of the system and as such they also include the opportunity cost of increasing demand at that specific time step instead than at a later one.

Table **1**. Average resource costs and average marginal groundwater resource opportunity costs

Maximum admissible extraction rate [% of Target demand]	Average resource cost [€/m^3]		Average optimal groundwater allocation [Mm^3/year]	Mean marginal groundwater resource opportunity cost [€/m^3]			
				Optimization		Simulation	
	Optimization	Simulation		Civil	Irrigation	Civil	Irrigation
100	0.039	0.095	168.4	0.005	0	0.287	0.050
80	0.040	0.100	166.7	0.026	0	0.308	0.103
60	0.043	0.108	157.8	0.163	0.000	0.506	0.105
40	0.083	0.141	106.1	0.360	0.193	0.515	0.151
20	0.136	0.212	56.60	0.419	0.195	0.813	0.224
0	0.182	0.306	0.00	0.527	0.088	0.827	0.204

Table 1 reports results in terms of average resource cost and average marginal opportunity cost as a function of the maximum admissible extraction rate from groundwater. A level of 100% indicates the status quo, with groundwater resources in charge to supply around 300 Mm^3/year for both municipal (around one third) and irrigation uses. Whereas average resource cost is simply the ratio between total costs and total allocated volumes (including surface water) over the twenty year period, mean groundwater opportunity cost has been obtained by taking the mean of the marginal costs of groundwater for each time step, as supplied by the optimization or simulation model.

Overall, results are consistent with objectives and limitations of both the optimization and the simulation models. As expected, simulation yields in all cases larger unit costs, both average and opportunity. As groundwater availability decreases, results tend to converge, as a consequence of the lesser scope for resource optimization. After increasing until the admissible extraction rate is 20% of the target, the mean opportunity cost sinks in the case of irrigation when the extraction rate is zero, as a consequence of the assumed shape of the loss curve for irrigation in its upper tail (figure 1); a similar behaviour, albeit softer in its extent, can be observed for outputs of the simulation procedure. On the other hand, the difference between the two methodologies is particularly striking for the marginal opportunity costs when relatively large groundwater amounts are available. In such instances, the optimal amount of groundwater to be used, under the above assumptions of zero cost of irrigation water from reservoirs, is quite lower than the admissible one (168.4 Mm^3 against the admissible 300 Mm^3), pointing out the opportunity to implement all the measures needed to foster the effective operation of the large irrigation projects in Salento. To make results comparable, in the simulation model, for each scenario of maximum extraction (100%, 80% etc.), the volumes extracted have been set equal to those suggested by the optimization model. Nevertheless, marginal opportunity costs obtained from rough, but realistic operation rules are still always quite higher than those corresponding to maximum efficiency resource allocation. This may justify the feeling for further investments to substitute groundwater resources; a feeling that could be explained by the overall inefficient present management of the system and that must hence be contrasted with all the measures aimed at increasing the level of efficiency of the system before resorting to new infrastructure.

The opportunity cost of resources enters cost-benefit analysis together with the other potential sources of benefits and costs a project can generate. However, values such as those in table 1 may help identifying interventions appropriate to the intensity of the likely water deficits generated by the close-down of wells. Water from Cogliandrino reservoir, for instance, has been evaluated 0.05 €/m^3 (the price applied by the hydropower producer for missed hydropower production) and is hence a substitute compatible with the range of marginal opportunity costs indicated for a moderate reduction of water availability from aquifers. On the other hand, imagining desalinated water as a suitable substitute for groundwater is, given the state of the art of desalination technology, possible only in the perspective of an integral closedown of wells. Even in this case, however, other lower-cost alternatives should be implemented first, thus reducing the opportunity cost of decreasing groundwater extraction.

5. CONCLUSIONS

The paper has compared simulation and optimization procedures for the assessment of the marginal opportunity cost of groundwater resources in a complex water resources system, a key variable for evaluating a suitable substitute in the case aquifer withdrawals must be reduced or stopped because of overexploitation. Evaluation is provided in terms of resources quantity only, leaving aside quality-related costs and benefits and is based on production, treatment and scarcity costs under hydrologic variability expressed by a twenty – year monthly historical time-series. To facilitate comparison, results are reported in average terms, although examination of the time-pattern of the opportunity cost may be useful for understanding how the value of resources varies along with hydrological conditions. Both procedures have disadvantages as they are both based on assumptions that are unrealistic to some extent, such as perfect foresight (and perfectly working allocation mechanisms) in the case of optimization and maximization of releases with no hedging in the case of simulation (with, in addition, fixed demands to reservoirs and constant extraction rates from aquifers). However, rather than as competing, both methodologies should be seen as complementary: whereas optimization models provide in this context an (idealized) benchmark for the marginal opportunity cost of resources, simulation can be useful to evaluate the impact of different allocation policies on resources value. Such policies may be designed using rules of thumb or optimized hedging rules for which literature now abounds (e.g. Oliveira and Loucks, 1997). Using multiple hydrological scenarios via, for instance, operational hydrology would broaden the scope of the analysis and would also allow incorporating uncertainty in basic hydrologic parameters. Finally, the optimization model used thus far in this application adopts a non linear objective function that is linearized to make the problem manageable with mixed-integer programming techniques. A full non-linear optimization model could be then contrasted with the one used in this work to assess the impact of different modeling options on marginal costs.

ACKNOWLEDGMENTS

This research has been partially funded by the Research Project of National Relevance (PRIN 2005): “Decision support systems in the management of water systems with conflictual uses during droughts”.

REFERENCES

Andreu, J., Capilla, J., and E. Sancìz (1996), AQUATOOL, a generalized decision support system for water resources planning and management, *Journal of Hydrology*, 177, 269-291.

Andreu Alvarez, J., Pulido Velazquez, and G. Collazos (2008), Methodology and tools for integrated assessment of resources and environmental requirement costs. *Second International Workshop on Implementing Economic Analysis in the Water Framework Directive*, Paris, France,17-18 February 2008, Conference CD.

Griffin, R.C. (2006), *Water Resources Economics – The analysis of scarcity, policies, and projects*, MIT press, Cambridge, Massachusetts.

Haab, T.C., and K. Mc Connell (2002), Valuing Environmental and Natural Resources, Edwar Elgar Publishing, 324 pp., Cheltenham UK.

Ilich, N. (2008), Shortcomings of linear programming in optimizing river basin allocation, *Water Resources Research*, 44, W02426, doi: 10.1029/2007WR006192.

Jenkins, M.W., Lund, J.R., and R.E. Howitt (2003), Using economic loss functions to value urban water scarcity in California, *Journal AWWA*, 95(2), 58-70.

Jenkins, M.W., Lund,J.R., Howitt, R.E., Draper, A.J., Msangi, S.M., Tanaka, S.K., Ritzema, R.S., and G.F. Marques (2004), Optimization of California’s water supply system: results and insights, *Journal of Water Resources Planning and Management*, 130(4), 271 – 280.

Loucks, D.P., and E. Van Beek (2005), *Water Resources Systems Planning and Management –An Introduction to Methods, Models and Applications*, Studies and Reports in Hydrology, UNESCO Publishing.

Hsu, N.-S., Cheng, W.-C., Cheng, W.-M., Wei, C.-C., and W. W.-G Yeh (2008), Optimization and capacity expansion of a water distribution system, *Advances in Water Resources*, 31, 776–786.

Oliveira, R., and D. P. Loucks, (1997), Operating rules for multireservoir systems, *Water Resources Research*, 33(4), 839 – 852.

Pulido-Velazquez, M., Jenkins, M. W., and J.R. Lund (2004), *Economic values for conjunctive use and water banking in southern California, Water Resources Research*, 40, W03401, doi: 10.1029/2003WR002626.

Tsur, Y., and A. Dinar. (1997), On the relative efficiency of alternative methods for pricing irrigation water and their implementation, *World Bank Econ. Rev*., 11, 243-262.

Turner, K., Stavros, G., Clark, R., Brouwer, R., and J. Burke (2004), *Economic valuation of water resources in agriculture*, FAO, Rome.

Young, R.A. (1996),. *Measuring economic benefits for water investments and policies*. World Bank Technical Paper No. 338.