Screening Investments to Reduce the Risk of Hydrologic Failures in the Headwork System Supplying Apulia (Italy) – Role of Economic Evaluation and Operation Hydrology

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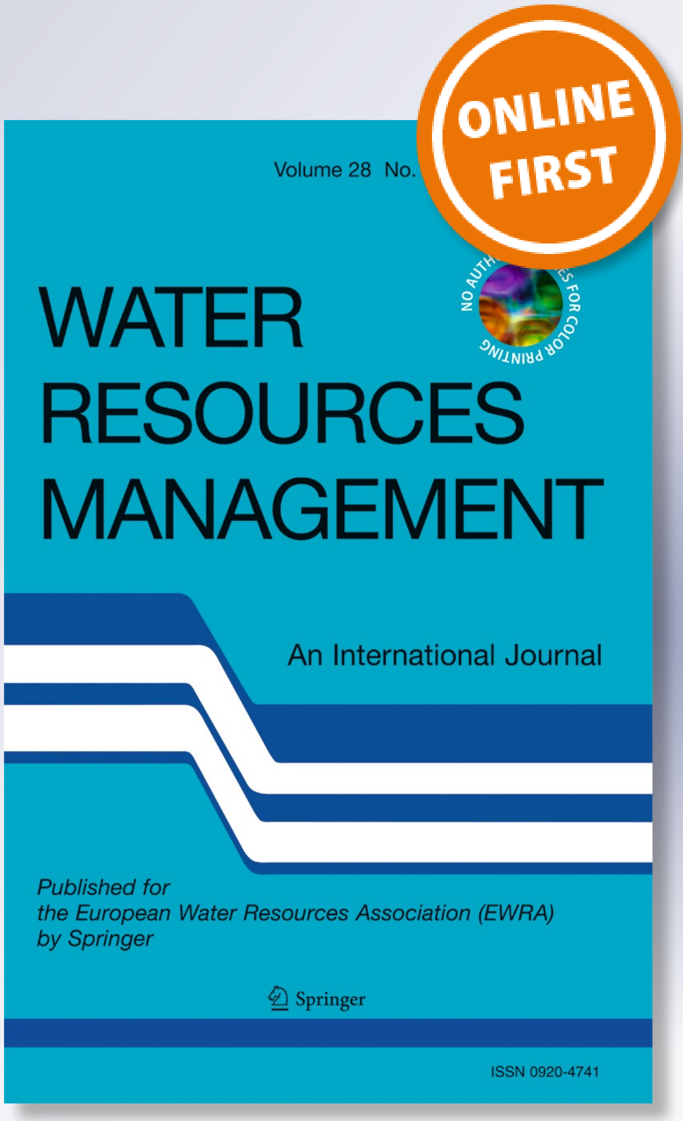

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Screening Investments to Reduce the Risk of Hydrologic Failures in the Headwork System Supplying Apulia (Italy) – Role of Economic Evaluation and Operation Hydrology

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Abstract The paper introduces and applies a methodology to screen investments aimed at reducing water supply risks due to hydrologic failures in headwork systems for municipal use, based on the principles of cost-benefit analysis. As risk includes both the probability of a failure and its effect, the methodology combines a simulation module of the system, fed by a stochastic hydrologic input to reproduce the probability distribution of the failures, with a metric for supply failure damage provided by the price – demand relationship for municipal water. Benefits are assessed as the averted damage compared to a base case without investments. This approach is then combined with the classic discounted cashflow approach of cost – benefit analysis to allow for the dynamics of both water supply and demand due to trends in population growth, individual consumption and, above all, planned reduction of losses in water distribution networks. The methodology is applied to screen a number of different supply-side projects for the headwork system supplying Apulia, in southern Italy featuring both regulated surface and groundwater resources and providing drinking water to over 4,000,000 persons. The procedure allows both ranking of single projects by their economical performances and the economic evaluation of combinations of different projects. The study also aims to assess the impact of the selected time scale, of cross-correlation among production sites, and of the specification of the demand function on projects' economic indicators. Results show that each modelling assumption has a considerable impact on the value of the economic indicators in absolute terms, but ranking of the different projects seems to be less sensitive to such modelling aspects.

Keywords Cost-benefit analysis · Water resources systems · Droughts · Water transfers · Stochastic hydrology

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1 Introduction

With a wide portfolio available of different options for managing the supply–demand balance, water planners are faced with the task of correctly understanding the actual value and usefulness of such alternatives. Cost – benefit analysis (CBA) provides a straightforward and conceptually clear approach to the issue of assessing investments for system expansion. In many mature contexts, however, where most infrastructure for water supply has been already built and consumption levels are stable, such investments must be seen as a means to reduce the risk of not supplying the demanded water, rather than as a way to close the supply – demand balance in average present, or future, conditions.

Risks in water supply mainly stem from hydrologic failures of the supply sources (droughts), from mechanic failures and from limitations in water use due to water quality. Risks are however also conditional on the present level of withdrawals from the sources that may be inflated due to high losses in both conveyance and distribution networks: reducing losses can result in less water needed and hence in mitigated supply risks.

The paper introduces a methodology to screen investments aimed at reducing water supply risks due to hydrologic failures in headwork systems for municipal use and applies it to the water resources system supplying Apulia, in Southern Italy. As risk includes both the probability of a failure and its effect, the methodology combines a simulation module of the system, fed by a stochastic hydrologic input to reproduce the probability distribution of the failures, with a metric for supply failure damage provided by the price – demand relationship for municipal water. Benefits are assessed as the averted damage compared to a base case with no investment. The paper also aims to assess the impact of different model assumptions, concerning the hydrologic input, the time scale of simulation and the specification of the demand function, on the outcomes of the screening process.

In general terms, given a certain system configuration, water allocation among different uses should be a function of both water availability and water value: optimal allocation is found at the equilibrium between marginal net benefits for the different uses (Griffin 2006). Optimal water allocation is hence a function of the operating rules for the system, which should in turn be based on some value – based criterion. This approach has been adopted in several planning studies for California (Jenkins et al. 2004; Pulido-Velazquez et al. 2004) and is basically the core of the so – called hydroeconomic models (Harou et al. 2009). The issue of assessing optimal system configurations minimizing both fixed and variable costs, (e.g. Watkins and McKinney 1998, Yang et al. 2007) clearly also revolves around this theme, as well as that of determining the optimal mix of infrastructure for a water resources system (Arena et al. 2010). In the paper, simple intertemporal and intersectorial allocation rules are employed, as will be shown in the next sections.

It should also be highlighted that, although water resources planning often makes use of risk and hazard concepts (e.g. Preziosi et al. 2013, Wenquan et al. 2012), explicit assessment of the value of risk reduction is seldom placed as a basis for investment evaluation (Razavi Toosi and Samani 2012); cost-effectiveness criteria are preferred instead (Rosenberg and Lund 2009, Matrosov et al. 2013).

2 Defining Hydrologic Risk

The classic definition of risk related to some event E is given by:

$$R = p(E) * D(E) \quad (1)$$

where p(E) is the occurrence probability of E and D(E) is the associated damage (in currency/period). In a given year t within the planning horizon, a synthetic indicator of the level of risk is the expected value of damage E[D]:

$$E[D(t)] = \int_0^{\infty} p(E)D(E)dE \tag{2}$$

In a water resources system designed to supply water for different purposes, event E is the occurrence of a water deficit, i.e. of a water allocation less than target demand T(t), and D(E) is the related damage; T(t) is the water volume demanded (and consumed) by end users when water is not scarce. In order to evaluate (2) both a probability distribution of deficits and a deficit – damage relationship are hence necessary. Damage assessed by (2) turns into a benefit when it is avoided thanks to supply – enhancing or withdrawal – reducing investments.

Target water withdrawal $W_T(t)$ from the supply sources, corresponding to target demand T(t), is given by:

$$W_T(t) = T(t)/(1 - L(t)) \tag{3}$$

where L(t) is the average level of losses in conveyance and distribution networks in year t, in percentage of withdrawal, and t represents a year in the planning horizon. Water availability may feature a trend along the planning horizon due to new water treatment plants entering operation, or as the result of environmental measures for freshwater protection.

Deficit Def is defined as:

$$\mathrm{Def} = \mathrm{T(t)} - \mathrm{Q} \quad \text{if } \mathrm{Q} < \mathrm{T(t)} \tag{4a}$$

$$\mathrm{Def} = 0 \qquad \text{if } \mathrm{Q} = \mathrm{T(t)} \tag{4b}$$

where Q is the volume supplied to customers in a given year, coinciding with water consumption.

The cumulative probability of the occurrence of a deficit in a certain year is given by:

$$\mathrm{P(Def)} = \mathrm{Pr}\,[\mathrm{T(t)} - \mathrm{Q} \leq \mathrm{Def}] \tag{5}$$

Whence p(Def), the probability density of deficits, is given by dP/dDef.

In this model, the dynamic dimension of both supply and demand (trends on water availability and withdrawals) is intertwined with hydrologic variability: in order to combine them, a present expected damage value (PEDV) is assessed:

$$PEDV = \sum_{t=1}^{O} \frac{E[D(t)]}{(1+r)^t} \tag{6}$$

where O represents the length of the time horizon (typically 30 years), r is the discount rate and E[D(t)] is the expected damage at year t of the planning horizon; E[D(t)] is given by:

$$E[D(t)] = \int_0^{T(t)} p(Def)D(Def)dDef \tag{7}$$

where D(Def) is the damage (in M€) associated to a given deficit. The integral is between 0 and T(t) because deficits must be positive and can be no larger than T(t).

It should be noted that according to other authors (Tsakiris 2007), Eq. (7) measures the expected *hazard* to the adverse phenomenon, while risk should also include the vulnerability, a dimensionless function with values from 0 to 1, expressing the potential degree of protection of the system thanks to the mitigation measures.

Figure 1 schematically represents the basic concepts of the methodology adopted in this work: during the planning horizon, target withdrawals from supply sources $W_T(t)$ and consumption for municipal purpose follow a trend dictated by economic and demographic growth as well as loss reduction programmes. In every year of the planning horizon, hydrologic variability determines a probability distribution of water availability, summarized in the figure as a single probability density function (pdf, in blue). Dashed area indicates the non-exceedance probability of the target, i.e. the probability of a deficit, and is hence associated to a certain level of risk. Such risk level decreases along the planning horizon. A supply-enhancing investment modifies the pdf of water availability (in red), thereby further reducing risk.

2.1 Linking Deficits to Damage: Price – Demand Relationship and Scarcity Costs

In developed countries and at standard consumption levels, drinking water can be considered a commodity: assessment of the benefits associated to different levels of water availability should hence be performed through a demand function. It is a fundamental analytical tool in the consumer's theory (Fig. 2) and expresses the relationship between water consumption and its price. Price in the y axis equals the marginal cost of water indicated in the x axis, i.e. the price at which the last unit of that quantity is sold.

An important notion contained in the curve is that of consumer's surplus: if the last cubic meter of quantity Z is sold at price p, area OPYZ measures the market value of water – the returns of a water company from selling that quantity; however, consumers enjoy further benefits as they would be willing to pay more, if less water were available: paying quantity Z

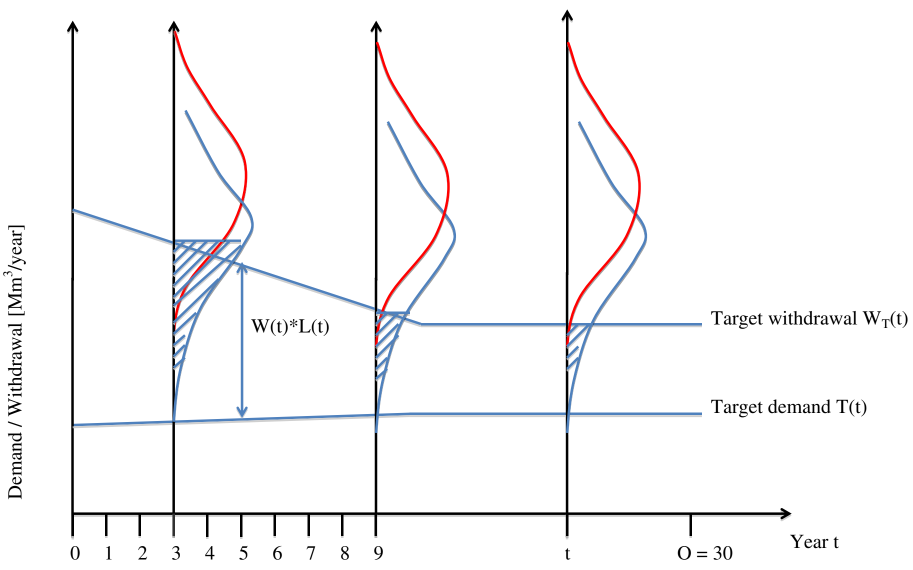

Fig. 1 Schematic of the risk assessment procedure

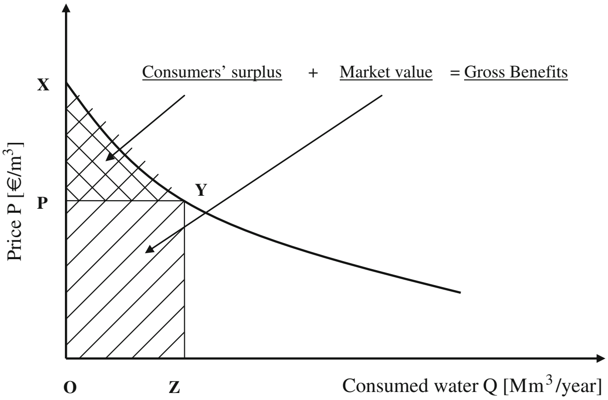

Fig. 2 Demand function for water and components of benefits

at price p hence leaves them with a surplus of benefit that is not captured by water price. If Z coincides with target T(t), its consumption produces a benefit B(T(t)) given by area OXYZ.

Supplying a quantity Q less than the target turns into a damage D (or scarcity cost – Jenkins et al. 2003) given by:

$$D = B(T(t)) - B(Q(t)) \tag{8}$$

A parameter measuring how much the amounts of water demanded Q depends on its price P is the elasticity :

$$\eta = \frac{dQ}{dP} * \frac{P}{Q} \tag{9}$$

expressing the percent variation of Q for a unit shift of price.

Although empirical studies produced in over 40 years have yielded highly variable results in terms of demand elasticity, all agree that municipal demand, and especially its indoor component, is inelastic ($|\eta|<1$): studies by Espey et al. (1997) and Dalhuisen et al. (2003) contain rich databases of water demand elasticities assessed in many tenths of empirical studies. According to Dalhuisen et al., the average elasticity of drinking water is -0.38, whilst the average from the studies reported by Espey et al. is -0.51, two quite similar values considering the methodological differences among the studies: the time span covered and the different environmental and socio-economical contexts examined.

In the following, two different specifications of the demand curve will be used: the first one, (termed log-linear or Cobb-Douglas), stems from the assumption that elasticity stays constant along the whole domain of water demand: if η=const, then $dQ/Q=\eta*dP/P$, implying that $\ln Q=\eta*\ln P+C$, and finally:

$$P = const_1 * Q^{1/\eta} = a * Q^b \tag{10}$$

Constant a is found considering that, when consumption equals the target, price equals P_T, the price of the last cubic meter of water consumed; hence $a=P_T/T^b$ with $b=1/\eta$. Benefit B(Q) is found by integration of the demand curve: recalling (8), damage D(Q) related to a consumption Q less than the target T is given by:

$$D(Q) = a * \frac{\eta}{1+\eta} * \left(T^{\frac{1+\eta}{\eta}} - Q^{\frac{1+\eta}{\eta}}\right) \tag{11}$$

Following (3) and (11), scarcity costs may be expressed as a function of W, the withdrawal from the supply sources:

$$D(Q) = a * \frac{\eta}{1+\eta} * \left\{ [W_T * (1-L(t))]^{\frac{1+\eta}{\eta}} - [W * (1-L(t))]^{\frac{1+\eta}{\eta}} \right\} \tag{12}$$

The second specification is a linear relationship between price and demand (Fig. 3) in a consumption dominion ranging from target T (where price is P_T and the corresponding withdrawal from the source is W_T) to a minimum consumption Q_{min} (with a withdrawal W_{min}), corresponding to uncompressible needs where the price corresponds to the cost P_{max} of the least costly backstop technology that is able to provide that amount of water (Del Treste and Mazzola 1991).

The estimation procedure is hence based on the concept of alternative cost, which is likely to yield underestimates of customer's willingness to pay (customers may be willing to pay more than the alternative cost of supply) and may hence prove conservative from the standpoint of investment evaluation: projects that exhibit benefits exceeding costs with a Cobb-Douglas specification may fail to do so if a linear specification based on this estimation criterion is adopted.

The expression of a linear price – demand relationship is the following:

$$\mathrm{P} = a - b * \mathrm{Q} \tag{13}$$

Coefficients a and b are greater than zero and given by:

$$a = \mathrm{P_{max}} \text{and } b = (\mathrm{P_{max}} - \mathrm{P_T})/(\mathrm{W_T} - \mathrm{W_{min}}) \tag{14}$$

A linear specification results in a quadratic relationship between scarcity costs and deficits: Equation (15) provides the expression of damage as a function of water withdrawal from the supply sources.

$$\mathrm{D(W)} = -\mathrm{A} * \mathrm{W}^2 + \mathrm{B} * \mathrm{W} - \mathrm{C} \tag{15}$$

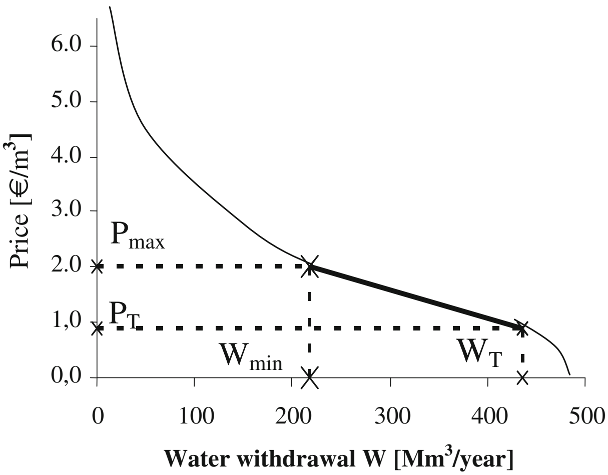

Fig. 3 Linear specification of the price – demand relationship of municipal water: amounts supplied less than W_{min} are considered outside the range of applicability of the linear relationship

Where

$$A = \frac{1}{2}\frac{P_{max}-P_T}{W_T-W_{min}}[1-L(t)]$$

$$B = \frac{1}{2}(P_{max}-P_T)\frac{W_T+W_{min}}{W_T-W_{min}} + \frac{1}{2}(P_{max}+P_T)[1-L(t)]$$

and $C = \frac{(P_{max}+P_T)[1-L(t)]W_{min}}{2} + \frac{1}{2}(P_{max}-P_T)\frac{W_T W_{min}}{W_T-W_{min}}[1-L(t)]$

Figure 4 depicts the two scarcity cost – deficit relationships based on the two different specifications of the demand function. It shows that for annual deficits less than 20 % of the target, the two specifications provide approximately the same level of damage, while for larger deficits damages diverge.

3 The Case Study: The Water Resources System Supplying Apulia

The water resources system supplying municipal uses of Apulia, a region of over 4,000,000 inhabitants in Southern Italy, features both regulated and unregulated surface resources as well as aquifers (Fig. 5). The system is multipurpose, as resources in the major reservoirs are shared with other uses, mainly irrigation.

The system has been developing since one century by successive additions to a long canal, the "canale principale" crossing from North to South the whole region and conveying spring water to town and cities. Overall, the system now features four major reservoirs: Occhito (R_1), Locone (R_2), Monte Cotugno (R_3) and Pertusillo (R_4), as well as the Sele – Calore springs and a number of wells. Table 1 reports the most relevant hydrological, technical and socio-economical parameters used for the analysis, together with a list of symbols to be used throughout the paper.

The supply-enhancing investments (in dotted red line in Fig. 5) are meant to increase water availability in the reservoirs of the system. In its master plan, AQP, the utility managing water supply in Apulia, formulates forecasts for future water demand in the next 10 years both at the delivery point to customers and at the sources; in doing this, it accounts for demographic

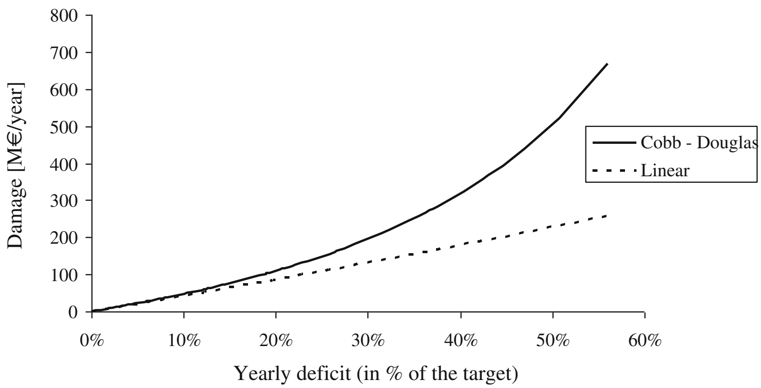

Fig. 4 Comparison of damage – deficit relationships obtained from a log-linear (Cobb-Douglas) and from a linear demand function for municipal water. Deficit is expressed in percentage of the yearly target demand

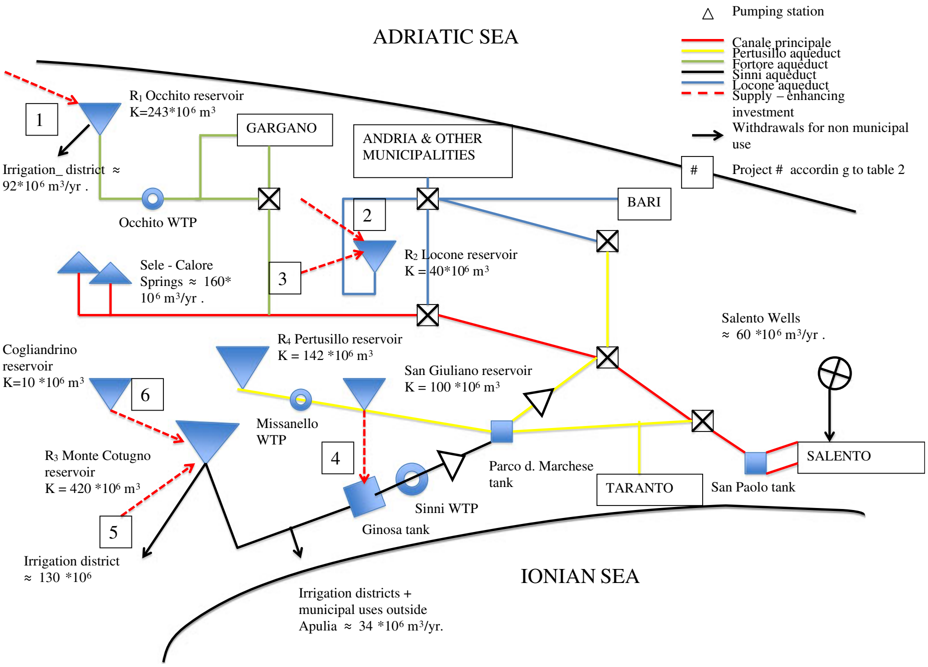

Fig. 5 Schematic representation of the water resources system supplying municipal uses in Apulia. The numbers inside the boxes refer to supply-enhancing projects # (see Table 2)

dynamics but first and foremost for the reduction of conveyance and distribution losses from the present 52 % of the volumes withdrawn from the supply sources to 40 % in 10 years. Such reduction, if it actually takes place, will result in a dramatic increase of water availability for the end-users and would hence have implications for the timing and need for additional resources. AQP and the regional government of Apulia have invested over 150 M€ in this large-scale water distribution network rehabilitation and metering project, over 90 M€ of which have already been spent in the last 6 years or so. Loss reduction is, overall, in line with the plans and this has already led to a partial reduction of withdrawals from wells in the overexploited Salento aquifer, in the southern part of the region.

The supply-enhancing investments are summarized in Table 2. The benefits described by projects' proponents (AQP itself and the River Basin Authority for Apulia) are not based on an overall picture of the system as an integrated whole, but rather on mere hydrological assessments. Investment and operating costs, also provided by the same organisations, include the financial costs of the inputs for the investments and energy costs. Treatment cost of the additional water (0.05 €/m^3), as well as maintenance costs (1 %/yr. of the investment cost) have been also included in the analysis.

3.1 Modelling Allocations for the Apulian Water Resources System

An allocation model turns a hydrological input into allocations to the different demand centres. In simulation models, routing of the hydrological input is performed according to certain operating policies that define how water resources should be allocated among different uses at a given time step (intersectorial rules) and how water resources should be managed along

Table 1 Most relevant hydrological, technical and socio-economical parameters used in the model

Hydrological parameters			
μ_3	Average yearly streamflow of Sinni river at M.te Cotugno dam	279.1	$10^6 m^3$
σ_3	Standard deviation (SD) of yearly streamflow of Sinni river at M.te Cotugno dam	110.9	$10^6 m^3$
μ_4	Average yearly streamflow of Agri river at Pertusillo dam	212.9	$10^6 m^3$
σ_4	SD of yearly streamflow of Agri river at Pertusillo dam	59.9	$10^6 m^3$
ρ_4	Lag 1 serial correlation coefficient of yearly streamflow of Agri river at Pertusillo dam	0.44	
μ_1	Average yearly streamflow of Fortore river at Occhito dam	159.4	$10^6 m^3$
σ_1	yearly streamflow SD of Fortore river at Occhito dam	93.5	$10^6 m^3$
ρ_1	Lag 1 serial correlation coefficient of yearly streamflow of Fortore river at Occhito dam	0.36	
$\mu_{springs}$	Average yearly flow of Caposele and Cassano Irpino springs	159.9	$10^6 m^3$
$\sigma_{springs}$	Yearly flow SD of Caposele and Cassano Irpino springs (for Apulia)	22.9	$10^6 m^3$
$\rho_{springs}$	Lag 1 serial correlation of yearly flow of Caposele and Cassano Irpino springs (for Apulia)	0.63	
$\mu_{S.Venere\text{-}Locone}$	Average yearly diversion from Santa Venere weir for Locone reservoir	36.3	$10^6 m^3$
$\sigma_{S.Venere\text{-}Locone}$	SD of yearly diversion from Santa Venere weir for Locone reservoir	16.7	$10^6 m^3$
μ_2	Average yearly streamflow of Locone creek at Locone dam	11.8	$10^6 m^3$
σ_2	SD of yearly streamflow of Locone creek at Locone dam	1.06	$10^6 m^3$
L_3	Losses from M.te Cotugno reservoir (evaporation and environmental downstream requirements)	10	% yearly streamflow
L_4	Losses from Pertusillo reservoir	13.1	$10^6 m^3$
L_2	Losses from Locone reservoir	10 %	% yearly streamflow
L1	Losses from Occhito reservoir	15 %	% yearly streamflow
Technical parameters			
$Max_{Missanello}$	Maximum withdrawal for municipal uses from Pertusillo reservoir (capacity of Missanello WTP)	113	$10^6 m^3$
Max_{Sinni}	Maximum withdrawal for municipal uses from M.te Cotugno reservoir (capacity of Sinni WTP)	140	$10^6 m^3$
T_Irr^3	Target withdrawal for irrigation from M.te Cotugno	164	$10^6 m^3$
T_Irr^4	Target withdrawal for irrigation from Pertusillo	51.5	$10^6 m^3$
T_Irr^1	Target withdrawal for irrigation from Occhito	92	$10^6 m^3$
T_Irr^2	Target withdrawal for irrigation from Locone	5	$10^6 m^3$
K_1*	Active capacity of Occhito reservoir	133	$10^6 m^3$
K_2*	Active capacity of Locone reservoir	35	$10^6 m^3$
K_3*	Active capacity of Monte Cotugno reservoir	256	$10^6 m^3$
K_4*	Active capacity of Pertusillo reservoir	118.5	$10^6 m^3$

Table 1 (continued)

Socio – Economical parameters			
P_T	Marginal price of water supply and distribution in ordinary conditions	1.65	€/m^3
P_{max}	Unit cost of the backstop technology	2.0	€/m^3
Q_{min}	Minimum incompressible per capita water consumption	80	l/day
η	Price – demand elasticity in the Cobb-Douglas specification	-0.4	
r	Discount rate	5	%

future time steps (intertemporal rules). Intertemporal rules may be defined by experience or by appropriate optimization algorithms (e.g. Oliveira and Loucks 1997, Chen et al. 2007; Huang et al. 2002; Labadie 2004; Momtahen and Dariane 2009; Koutsoyiannis and Economou 2003). The theory of intersectorial allocation rules is based on the concept of net benefit maximization

Table 2 A list of the supply-enhancing investments evaluated in this study

Project #	Description	Effects	Short description of the expected benefits	Investment costs [€]	Operating costs
1	Water transfers from Ponte Liscione reservoir (not in Fig. 5) to Occhito reservoir	Increase of water availability from Occhito reservoir	Approximately additional 20 10^6m^3/yr from Occhito reservoir	74,300,000	–
2	Interconnection between Marascione tank (not in Fig. 5) and Locone reservoir	Increase of water availability from Locone reservoir	Approximately additional 23 10^6m^3/yr from Occhito reservoir	29,880,000	–
3	Interconnection between Rendina reservoir (not in Fig. 5) and Locone reservoir	Increase of water availability from Locone reservoir	Approximately additional 24 10^6m^3/yr from Occhito reservoir	5,150,000	770,000 €/year
4	Use of water resources from San Giuliano reservoir for municipal purposes	Additional volumes for the Sinni water treatment plant	Approximately additional 10^6m^3/yr for the Sinni treatment plant	13,350,000	2,400,000 €/year
5	Completion of Sauro and Sarmento weirs	Increase of water availability from Monte Cotugno reservoir	Approximately additional 10^6m^3/yr from Monte Cotugno reservoir	13,500,000 (Sauro weir only)	-
6	Water from Cogliandrino reservoir presently diverted offstream for hydropower generation to be released downstream and stored in Monte Cotugno reservoir through dismantling of Castrocucco hydropower station	Increase of water availability in the downstream Monte Cotugno reservoir	Increases of up to 100 10^6m^3/yr from Monte Cotugno reservoir; possibility to reduce withdrawals from high-salinity groundwater	0	0.085 €/m^3

subject to availability constraints: it leads to recognizing that at the optimum, marginal net benefits for all uses are the same and equal the opportunity cost of resources (Griffin 2006).

Once rules have been defined, simulation of water resources system's performances may be performed either through dedicated software packages or by building a specific model. Dedicated software includes both academic, open-access and commercial packages (Rani and Moreira 2010 provide a complete overview): although they are all endowed with attractive and user-friendly graphic interfaces to build customized schemes of water resources systems, their use requires training, skill and experience. In addition, they provide different results depending on their specific features: Sulis and Sechi (2013) compare different generic software packages for water resources system simulation, contrasting simulation-only models with simulation models aided by optimization modules, and find that each model has its own way to reproduce operating rules in the reservoirs.

In this paper, a simple model has been developed using Microsoft Excel® spreadsheets – such models can meet the requirement of being easily accessible and customizable by skilled technical staff of administrations that do not have time and resources to invest in buying specific software and/or training staff to test and use them.

In building a model for the specific case of the Apulian water resources system, the assumption is that the system be completely interconnected, i.e. each demand centre may be supplied by any resource. Although this does not completely hold true in the actual system, its structure, with the "canale principale" previously supplying the whole region, makes this assumption reasonable.

3.1.1 Hydrologic Input

One thousand five hundred years of water availability values at each supply source have been generated by simple, at-site probabilistic models (normal or lognormal distributions) calibrated on yearly streamflow data (water year October – September) from 1984 to 2006 or using auto-regressive models of order 1 (e.g. Salas 1993) when yearly streamflow exhibited statistically significant serial correlation. Correlation among yearly flows at the different sources has been simulated in a simple way, using at each site the same random value for streamflow generation: this results in higher cross correlations than those observed, and the generated series are likely to exhibit low-availability periods longer and more intense than the observed ones. This assumption will be removed later in the paper in order to assess the impact of cross correlation on economic indicators.

3.1.2 Intertemporal Allocation

The intertemporal allocation rule adopted is the standard operating policy (SOP, Loucks and Van Beek 2005; Jain and Singh 2003), consisting of releasing in the present time step all the available volume, if this is less than the target demand, and storing only when water availability exceeds the target. Although in drought-prone areas this rule is seldom applied as is, being it preferred to perform some kind of hedging to save stored water for future dry periods (Tu et al. 2008; You and Cai 2008), the SOP does have some significant properties: Klemeš (1977) has shown it to be the optimal rule as either hydrologic or economic uncertainties grow beyond limits; in addition, it is able to minimize any linear function of deficit (Hashimoto et al. 1982). It is hence the rule of choice in seasons of abundant water availability and/or whenever uncertainty on the future grows high.

Definition of hedging-based operating rules in a system with considerable carry-over capacity and persisting dry periods, such as the one under study, may be valuable to reduce the magnitude of damages associated to droughts (Draper and Lund 2004) and should hence be considered as preliminary to the consideration of supply-enhancing investments. This type of analysis has not been performed in this chapter, but the impact of effective hedging rules on the value of damage is likely to be large in contexts like the one examined and may hence further reduce the value of the supply – enhancing investments.

3.1.3 Intersectorial Allocation

As mentioned above, intersectorial allocations in dry years should recognize the opportunity cost of resources, which is associated to the value of each use. However, in planning exercises as the one in this paper, governmental or local agencies require that planners stick to simple rules or formulate different allocation scenarios. For the purpose of this study, it was agreed that, from the standpoint of risk assessment for the municipal sector, a conservative allocation rule could be that of supplying first all non-municipal uses and trying to meet municipal demand second.

The allocation procedure may be summarized as follows:

1) Mass balances for Occhito and Locone reservoirs are performed separately in each of the 1,500 time steps, in order to assess the actual releases:

$$S_i^j = min\left[S_{i-1}^j + I_i^j - Mun\_rel_i^j - Irr\_rel_i^j - L_i^j; K_j^*\right] \quad (16)$$

Where S_i and S_{i+1} are stored volumes in time step i and i+1, I_i and I_{i+1} are the inflows into reservoir in time step i and i+1, Mun_rel_i and Irr_rel_i are releases from the reservoir for municipal and irrigation purposes respectively, L_i are losses for evaporation and environmental downstream requirements, and K^* is the reservoir's active capacity. J stands for reservoir and i=1, 2…1,500. Releases can be less than the target withdrawal, according to water availability.

The difference should be noted between index "t" (Eqs. 2 – 7) that indicates the passing of time in the planning period, where "dynamic" processes such as trends in supply and demand take place, and index "i" that reflects the "static" essence of hydrologic variability impacting all years of type "t" in the same way, if no trend in water availability due to climate or land-use change is assumed, as is the case in this study.

It is also important to point out that using one year as time unit forces to consider a smaller active capacity for reservoirs (K_j* in Eq. (16)) in order to obtain realistic estimates of the available storage: releases for irrigation are concentrated in the dry season, but in a yearly model they are lumped together with continuous releases for municipal use. If reservoirs' actual capacity were used, reservoirs could happen to be full at the beginning of the next time step, which is impossible because reservoirs may well be full at the beginning of the drawdown season, but releases for irrigation and municipal supply as well as evaporation will unavoidably reduce the volume stored in the reservoir. In this study, reservoir capacity has been decreased by the average value of releases for the different uses and evaporation losses during the drawdown season.

2) For each time step, municipal releases from Occhito and Locone reservoirs are summed to water availability from springs and from sources that may be considered insensitive to hydrologic variability, to obtain an overall demand to reservoirs 3 and 4 in the southern part of the system, Pertusillo and Monte Cotugno, indicated as $Dem_i^{(3+4)}$.
3) Releases from the Monte Cotugno and Pertusillo reservoirs are obtained through the following steps:

3.1 It is checked that:

$$S^4_{i-1} + S^3_{i-1} + I_i^4 + I_i^3 - Irr\_rel^3_i - Irr\_rel^3 - L^3_i - L^4_i >= Dem_i^{(3+4)};$$

3.2 If 3.1 holds true, and if the capacity of the two treatment plants downstream the two reservoirs is enough to treat half of the demand each, then each reservoir is to release half of the volume demanded to both reservoirs: $Mun\_rel^4_i = Mun\_rel^3_i = Dem_i^{(3+4)}/2$; otherwise, release is constrained by treatment plant's capacity;

3.3 If 3.1 does not hold true, then the water balance of each reservoir is evaluated separately, and reservoirs are emptied, if necessary;

3.4 Once $Mun\_rel^4_i$ and $Mun\_rel^3_i$ for the i-th time step are known, S^4_i and S^3_i are evaluated through (16);

4) For a given year t of the plan, in each of the 1,500 time steps, a deficit is recorded if the aggregated release W(t) from all sources is less than target withdrawal $W_T(t)$, otherwise deficit is zero.

4 Results

Deficits are then given a value according to (12) (Cobb-Douglas specification of the demand function) or (15) (linear specification of the demand function) and a trend of E[D(t)], in M€/ year, may be obtained for t=1, 2…30. Such flow is then discounted using a 5 % interest rate (EU REGIO 2008). In the base case, or "business as usual" (BAU) configuration, the $PEDV_{BAU}$ (Eq. 6) measures the level of expected damage for the system in its present condition. Adding one of the supply-enhancing investments to the system results in a $PEDV_{with} < PEDV_{BAU}$. The difference $PEDV_{BAU} - PEDV_{with}$ provides a measure of the discounted benefit generated by the project during the planning horizon. It may be used to obtain the typical performance indicators (Net Present Value NPV, Internal Rate of Return IRR, Benefit - Cost ratio B/C) used in standard cost-benefit analysis (EU REGIO 2008). Each project is added individually as a constant incremental water volume for each of the 1,500 time steps of simulation. The assessment also includes the residual value of the investment in the last year of the planning horizon.

Before analysing the economic indicators of the various projects, it is worthwhile highlighting the impact of the distribution networks rehabilitation programme alone on the reduction of hydrologic risk. This impact can be assessed from the base case by comparing the value of E[D(1)], the expected value of damage in year 1, at the onset of the rehabilitation programme, with E[D(7)], the expected damage in year 7, when loss reduction targets are expected to be met. The difference E[D(1)] – E[D(7)] equals 10.7 M €. If the rehabilitation programme were not undertaken, E[D(1)] would provide a lower bound of the annual damage value for each year of the planning horizon (actually, if the rehabilitation programme is not undertaken, losses may even increase due to networks obsolescence and so could risk), hence E[D(1)] – E[D(7)] provides the annual value of the benefit from reducing losses from the present level to the expected one. Overall, this benefit value entails a reasonable pay-back period of the investment (around 20 years), considering that annual capital expenses should also be included in the analysis to keep the target level of losses and that the rehabilitation programme also generates benefits other than the mere reduction of hydrologic risk of water supply.

Table 3 reports the economic performance indicators of the various individual projects, together with the associated average value of the incremental water availability for municipal

Table 3 Economic performance indicators of the supply-enhancing investments, expected residual damage and incremental water availability for municipal use. "N.d." stays for "non defined" – IRR is not defined for cashflows with no negative value

Project #	Net Present Value [M€]		IRR [%]		B/C		Expected residual damage [% on the BAU scenario]		Medium - term average incremental water availability for municipal use [$10^6 m^3$/year]
	Cobb-Douglas	Linear	Cobb-Douglas	Linear	Cobb-Douglas	Linear	Cobb-Douglas	Linear	
1	−55.3	−59.8	−3	−3	0.2	0.16	81	80	0.8
2	14.1	−1.6	9	4	1.6	0.93	64	68	1.8
3	34.1	21.9	47	37	6.4	5.4	62	66	1.9
4	28.2	10.3	20	11	2.9	1.7	53	57	1.9
5a (Sauro weir alone)	41.5	22.5	25	17	3.9	2.6	43	42	2.8
5b (Sarmento weir alone)	63.5	40.2	n.d.	n.d.	8.5	5.6	30	30	3.3
5c (Sauro + Sarmento weirs)	70.5	39.8	36	25	5.0	3.2	11	14	4.2
6	78.9	43.3	n.d.	n.d.	10.6	6.3	30	35	3.0

uses and the residual expected damage, as a percentage of the damage in the BAU configuration. Residual expected damage represents the expected damage for the system after the project has entered operation.

Table 3 shows in the first place that not all investments are able to produce benefits that outweigh costs. In the second place, steady-state incremental water availability (last column) is always considerably less than that estimated by mere hydrological assessments, as those reported in Table 2: capacity limitations and, above all, saturation of demand greatly reduce the volumes actually required; this also means that "on demand" water transfers will not occur every year, and in many years transfers will not be activated, and partly explains why investments such as these are among the most profitable: the investment producing the highest NPV is the one that substitutes hydropower generation from Cogliandrino reservoir with releases to the downstream reservoir, Monte Cotugno.

Finally, Table 3 also shows that benefits estimated via a linear demand relationship are always less than those obtained by a Cobb-Douglas demand function, as was expected. Differences in absolute terms can be relevant, especially for the NPV, less for the other indicators.

Combinations of different investments may also be analysed through this procedure. In this case, residual damage becomes an important additional criterion for plan selection. Table 4 reports economic indicators for different combinations of projects. It shows that basing decision only on NPV would lead to decide that project 6 (Cogliandrino) is, alone, the best option. Considering the residual expected damage as a further cost, and hence subtracting it from the NPV, gives back a more realistic picture and provides combinations whose NPV dominate that of project 6 alone. There are combinations that dominate others in that they have higher values of the difference NPV – Residual Damage and provide an optimal capacity expansion, because adding further water availability to the system does not improve the economic indicators. In this specific case, combination 6+5c seems to be the best, as it features the highest value of the difference NPV – Residual Damage.

Table 4 Economic indicators of combinations of different projects and NPV less residual damage, evaluated using a Cobb-Douglas (a) and a linear (b) specification of the demand function for municipal water

Combination	NPV [M€]	IRR [%]	B/C	Residual Damage [M€]	NPV – Residual Damage [M€]
a)					
6	78.9	n.d.	10.6	43.7	35.2
6+5a	61.0	31	4.5	21.9	39.1
6+3	64.6	56	7.1	30.5	34.1
6+5c	72.1	35	5.3	3.3	68.8
6+3+5a	64.5	27	4.2	11.8	52.7
6+3+5c	69.4	28	4.5	1.6	67.8
b)					
6	43.3	n.d.	6.3	32.0	11.3
6+5a	32.5	20	2.9	15.3	17.2
6+3	36.3	38	4.4	23.0	13.3
6+5c	40.9	24	3.5	2.6	38.3
6+3+5a	34.2	17	2.7	8.7	25.5
6+3+5c	38.0	19	2.9	1.3	36.7

Table 5 Comparison of at-site statistics of observed and generated time series at the four main sources of the system

Supply source	Mean [Mm^3/year]		Standard deviation [Mm^3/year]		Lag 1 correlation	
	Observed	Generated	Observed	Generated	Observed	Generated
Sele - Calore springs	156.0	155.6	23.3	23.9	0.62	0.59
Monte Cotugno	273.4	275.2	109.0	113.8	0.15	0.14
Pertusillo	212.2	211.0	59.0	61.6	0.47	0.42
Occhito	171.9	176.7	89.2	112.5	0.60	0.51

4.1 Assessing the Impact of Intersite Correlation on the Evaluation of Water Transfer Benefits

So far, intersite correlation has been treated simplistically, as the hydrologic input has been generated by conservatively assuming a single innovation value for all sites at a given time step. This approach may be justified by the lack of simultaneous data or by the low level of confidence in the estimates of cross-correlation when augmented streamflow series are employed. Thus, it may be of interest to understand the impact of different modelling assumptions concerning cross-correlation on the final economic indicators. To this end, a simple, popular, intersite model for the generation of yearly streamflow at n sites has been employed (Matalas and Wallis 1976):

$$\mathbf{Z}_{i+1} = \mathbf{A}\mathbf{Z}_i + \mathbf{B}\mathbf{V}_i \tag{17}$$

Where $\mathbf{Z}_{i+1}$ and $\mathbf{Z}_i$ are column vectors (n×1) of zero-mean annual streamflow totals at the n sites in year i+1 and i, **A** and **B** are (n×n) matrices that are able to reproduce the lag 0 and lag 1 of the flows at each site, and $\mathbf{V}_i$ is a column vector of independent innovations, i.e. standard-normal random variables that are independent in space and time.

Tables 5 and 6 report a comparison of the main statistics of observed and generated series. It shows a good agreement between observed and generated values. The generated series are routed into the simulation model and the three performance indices are evaluated. To make results fully comparable, the series generated with model (17) are rescaled by the mean of the

Table 6 Comparison of observed and generated lag 0 intersite correlation among yearly streamflows at the four main sources of the system

	Pertusillo	M.te Cotugno	Springs	Occhito
Observed				
Pertusillo	1.00	0.56	0.75	0.80
M.te Cotugno	0.56	1.00	0.52	0.52
Springs	0.75	0.52	1.00	0.71
Occhito	0.80	0.52	0.71	1.00
Generated				
Pertusillo	1.00	0.61	0.76	0.77
M.te Cotugno	0.61	1.00	0.58	0.50
Springs	0.76	0.58	1.00	0.67
Occhito	0.77	0.50	0.67	1.00

series generated with the naïve method: although differences are small, this helps isolating the role of cross-correlation on results.

Figure 6 reports the PEDVs in the base case plotted against the general level of intersite correlation in the tree models. Such level is simply the average of the off-diagonal intersite correlations in the correlation matrix: it varies from 0.006 when series are generated independently (i.e. intersite correlation is ignored and simultaneous streamflows are generated using different independent innovations at each site) to 0.9 when intersite correlation is modelled naively by using a single random value for all the time series in a given year. The intermediate value of 0.64 is the one obtained by modelling cross-correlation via (17). The relationship appears to be non linear, with the impact of cross correlation growing with the level of intersite correlation: this is consistent with the non linear metric of damage employed to evaluate benefits.

Table 7 reports a comparison of NPV and B/C ratio for the supply-enhancing projects when cross-correlation is modelled with (17), when cross-correlation is modelled naively and when intersite correlation is ignored. This modelling situation is certainly extreme, but can represent the case where, due to inadequate reconstruction or augmentation of individual series, the resulting level of intersite correlation is considerably lower than the actual one.

The table shows that intersite correlation has a dramatic impact on the economic indicators in absolute terms, with some of the projects exhibiting a positive NPV turning into projects with a negative one, as in the case of project 3. However, when it comes to ranking the different projects in order to give them a priority, all modelling options tend to yield the same priority order, with some exception: in the “naïve” modelling, interconnection of Rendina reservoir to Locone, a project with comparatively low investment and operation costs, seems to be preferable to a project aimed at increasing resources in the southern system (San Giuliano), while with the other type of modelling the ranking is inverted – once again the consequence of the fact that more severe simultaneous droughts (as in the naïve model) impact more on reservoirs with limited carryover storage capacity.

4.2 The Impact of Time Scale – Seasonal vs. Yearly Model

When modelling water resources systems, another relevant aspect is the time scale employed. While there exists a general agreement that in planning studies, such as the one in this chapter, a monthly scale fits the purpose of suitably representing the dynamics of allocations at both

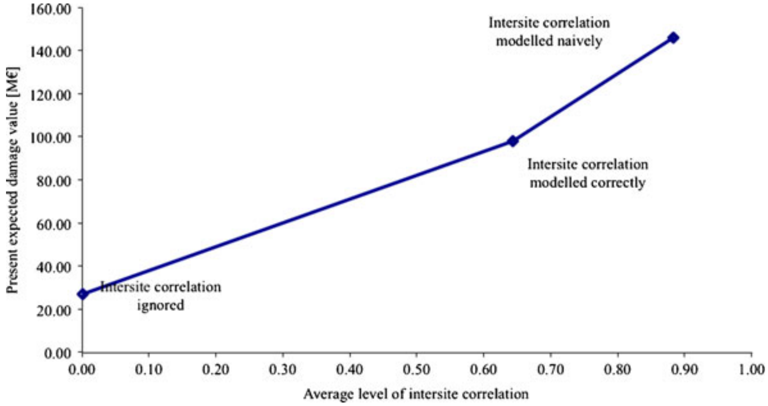

Fig. 6 Present expected damage in the BAU case as a function of the average level of intersite correlation among supply sources

Table 7 Economic indicators of the projects when inter-site correlation is ignored, when is modelled naively, and when is modelled through (17). Assessments are performed using a Cobb-Douglas specification for the demand function of municipal water

Project #	NPV [M€]			B/C		
	Cross correlation ignored	Cross correlation modelled	Cross correlation modelled naively	Cross correlation ignored	Cross correlation modelled	Cross correlation modelled naively
1	−69.7	−58.1	−55.3	0.0	0.2	0.2
2	−23.1	−6.9	14.1	0.1	0.7	1.6
3	−2.4	13.2	34.1	0.7	2.9	6.4
4	−5.7	20.4	28.2	0.6	2.6	2.9
5a (Sauro weir alone)	−6.4	23.6	41.5	0.6	2.6	3.9
5c (Sauro + Sarmento weirs)	−6.2	38.6	70.5	0.5	3.2	5.0
6	14.4	58.3	78.9	6.9	8.3	10.6

within and over – year time scales, larger time scales such as one year or one season may still be appropriate, while allowing to reduce considerably the modelling efforts. In this section, a comparison will be attempted between a yearly model and a two-season model, with a wet season, lasting from October to May, and a dry season from June to September. To this end, flows generated through (17) have been disaggregated into seasonal values Fwet and Fdry as follows:

$$\mathrm{Fwet}_{ik} = a_k * F_{ik} + b_k \tag{18}$$

where Fwet_{ik} is the streamflow total in the wet season of time step (year) i at site k, F_{ik} is the streamflow total at time step i, and a_k and b_k are ordinary-least-squares regression coefficients at site k. Clearly, $\mathrm{Fdry}_{ik}=F_{ik} - \mathrm{Fwet}_{ik}$.

Comparison between observed at-site and intersite statistics (Tables 8 and 9) show a good agreement between the observed and generated time series.

For the purpose of system's simulation, both intertemporal and intersectorial allocation rules are the same as before; in the seasonal model, demands for irrigation are split in the two seasons according to the historical seasonal values, while municipal demand is kept constant along the year.

In the base case, the difference of the present value of expected damage between the seasonal and the yearly model is dramatic, with a PEDV of 37.7 M€ in the seasonal model and 97.8 M€ in the yearly one, if a Cobb-Douglas specification is used, and a smaller difference for a linear specification of the demand function (33.1 M€ against 72.5 M€). The way storage is treated in the two options plays a crucial role in determining releases from the reservoirs. Table 10 reports average reservoir levels in the two modelling options: in the seasonal model they are always higher than those of the annual model. Clearly, the use of a seasonal scale allows a more realistic description of the evolution of storage.

The difference between the outputs of the two different modelling options (seasonal and yearly) is magnified by the non linearity of the damage function: although the difference between total yields is not very relevant in average terms (419 Mm^3/year of the seasonal model against 417.2 Mm^3/year of the annual model; target value is 420.4 Mm^3/year), the difference in the average yearly damages are heavier.

Table 8 Comparison of at-site statistics of observed and generated seasonal time series at the four main sources of the system. $\rho_{dry\text{-}wet}$ indicates the correlation coefficient between flows in dry and wet season, $\rho_{wet-year}$ indicates the correlation coefficient between flows in the wet season and yearly streamflow totals

Observed	Pertusillo		Monte Cotugno		Springs		Occhito	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Mean [Mm^3]	191.2	21.0	255.7	21.9	107.7	56.2	166.0	5.9
SD [Mm^3]	55.1	7.5	97.5	23.3	14.6	9.2	88.0	6.2
Lag 1 corr. Coefficient (year)	0.41	0.33	0.16	−0.11	0.72	0.56	0.55	−0.01
ρ dry-wet (seasonal)	0.48		0.41		0.86		0.17	
ρ wet - year (seasonal)	0.99		0.98		0.98		0.99	
Generated	Pertusillo		Monte Cotugno		Springs		Occhito	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Mean [Mm^3]	190.4	20.9	251.2	23.5	102.6	52.8	171.8	6.7
SD [Mm^3]	58.1	7.5	103.9	20.7	15.4	9.5	117.4	5.4
Lag 1 corr. Coefficient (year)	0.42	0.12	0.13	0.07	0.56	0.51	0.51	0.01
ρ dry-wet (seasonal)	0.49		0.49		0.87		0.25	
ρ wet - year (seasonal)	1.00		0.99		0.98		0.99	

Table 9 Comparison of observed and generated lag 0 intersite correlation among seasonal streamflows at the four main sources of the system

Observed					Generated				
Intersite correlation wet season					Intersite correlation wet season				
	M.te Cotugno	Pertusillo	Springs	Occhito		M.te Cotugno	Pertusillo	Springs	Occhito
M.te Cotugno	1	0.6	0.26	0.57	M.te Cotugno	1	0.61	0.57	0.48
Pertusillo	0.60	1	0.61	0.79	Pertusillo	0.61	1	0.74	0.76
Springs	0.26	0.61	1	0.59	Springs	0.57	0.74	1	0.65
Occhito	0.57	0.79	0.59	1	Occhito	0.48	0.76	0.65	1
Intersite correlation dry season					Intersite correlation dry season				
	M.te Cotugno	Pertusillo	Springs	Occhito		M.te Cotugno	Pertusillo	Springs	Occhito
M.te Cotugno	1	−0.13	0.13	0.02	M.te Cotugno	1	0.24	0.35	0.11
Pertusillo	−0.13	1	0.25	0.59	Pertusillo	0.24	1	0.42	0.12
Springs	0.13	0.25	1	0.68	Springs	0.35	0.42	1	0.19
Occhito	0.02	0.59	0.68	1	Occhito	0.11	0.12	0.19	1

Table 10 Comparison of average storage levels in the four reservoirs of the system with the seasonal and the yearly model

Reservoir	Average storage level [Mm^3]	
	Yearly model	Seasonal model
Occhito	56.4	95.2
Locone	34.8	33.3
Pertusillo	85.7	117.9
Monte Cotugno	184.2	294.1

Finally, Table 11 contains a comparison of the performance indicators with the seasonal and the annual model for a selection of projects; it shows that moving from an annual to a seasonal model has dramatic impacts on the performance indicators of the individual projects. It is worthwhile observing that with a seasonal model, the benefit of reducing losses decreases to 5.1 M€/year, less than one half the value estimated using a yearly time step.

4.3 Why Include Risk in a Screening Process?

In various contexts, simple screening methodologies that ignore risk and concentrate on average improvements produced by the investments are considered suitable to screen alternative measures. The European Water Framework Directive, for instance, recommends cost-effectiveness analysis (CEA) as the tool of choice to classify measures for the protection of water bodies. Admittedly, CEA is a simpler analysis tool than the risk-based methodology presented in this paper, as it gives up monetizing risk-related benefits and summarizes the positive impacts of the project in a single average effect. In an analysis such as the one presented here, where the only effect considered is an increase in water supply, CEA could be considered as a suitable, simpler tool for screening investments. An appropriate cost-effectiveness index (CEI) could be built in this case by dividing the actualized financial cost of the investment over the whole planning period (30 years) by the average incremental water volume supplied over the same period, thus obtaining a cost-effectiveness index in €/m^3. The question is now whether a simpler index as this is able to provide a ranking of projects similar to that obtained by the risk-based methodology presented here. In order to show differences between the two approaches, Table 12 reports for each of the six projects: the actualized total cost over the planning horizon, the average

Table 11 Economic indicators with an annual and a seasonal model. Streamflows are generated through Eq. (17) and benefits are evaluated through a Cobb – Douglas specification of the demand function for municipal water

Project #	Net Present Value [M€]		Internal rate of return [%]		Benefit/Cost ratio	
	Annual	Seasonal	Annual	Seasonal	Annual	Seasonal
1	−58.1	−64.7	−3	−4	0.19	0.09
2	−6.9	−19.5	−3	−3	0.72	0.2
5	38.6	2.4	25	7	3.6	1.03

Table 12 Actualized total cost over the planning horizon, average yearly incremental water withdrawn for the system and cost – effectiveness index for the six investments considered

Project #	Actualized total cost [M€]	Average annual incremental water for municipal use [Mm^3]	Cost-Effectiveness Index [€/m^3]	Project Ranking according to CEA	Project Ranking according to the risk-based methodology
1	69.9	1.5	1.57	7	7
2	23.9	1.6	0.51	6	6
3	6.3	1.8	0.12	2	4
4	15.1	1.7	0.30	5	5
5a (Sauro weir alone)	14.4	2.5	0.19	4	3
5c (Sauro + Sarmento weirs)	15.3	3.7	0.14	3	2
6	8.20	3.1	0.09	1	1

annual incremental volume supplied and the cost-effectiveness index, while Table 13 contains the same information for the combinations of projects of Table 4. It can be easily verified that project ranking according to the CEI is 6, 3, 5c, 5a, 4, 2,1, while according to the methodology introduced in this paper the ranking is 6, 5c, 5a, 3, 4, 2, 1. For the single projects, a simple CEI is hence able to identify the best and the worst project as well as the worst three, while there is a difference in the identification of the second and third best.

However, the value added of using a risk-based methodology becomes clearer when comparing different combinations of projects. In this case, CEA cannot provide an adequate idea of how much capacity should be added: like the NPV criterion of CBA without consideration of a residual damage, CEA would identify project 6 as the only one to carry out; the methodology presented here allows instead to evaluate combinations of projects also under the standpoint of the residual expected risk they leave in the system. The best capacity expansion is hence the one that is able to compromise between a high NPV of the combination of projects and a low residual expected damage.

Table 13 Actualized total cost over the planning horizon, average yearly incremental water withdrawn for the system, cost – effectiveness index for the combinations of investments of Table 4 and ranking of combinations according to the risk-based methodology presented in this study and CEA

Combination	Actualized total cost [M€]	Average annual incremental water for municipal use [Mm^3]	Cost-Effectiveness Index [€/m^3]	Ranking according to CEA	Ranking according to the risk-based methodology of this study
6	8.2	3.1	0.09	1	5
6+5a	17.4	3.5	0.16	4	4
6+3	10.7	3.5	0.10	2	6
6+5c	16.6	4.01	0.14	3	1
6+3+5a	20.2	3.8	0.18	6	3
6+3+5c	19.9	4.0	0.17	5	2

5 Conclusions

The paper has presented a methodology to assess benefits associated to investments aimed at increasing water availability for a water resources system, to be introduced in standard cost-benefit analysis templates for screening different investment alternatives. The methodology quantifies benefits as the expected averted damage from reducing the magnitude of deficits stemming from drought events. It is based on an allocation model of the water resources system fed by a stochastic hydrologic input for the assessment of the distribution of deficits, and on a price – demand relationship for domestic water to monetize the deficit-induced damage.

The methodology has been applied to screen a number of supply–enhancing investments in Apulia, in southern Italy, and has allowed a ranking of the individual investments and groupings thereof based on standard cost-benefit analysis indexes.

Besides the general methodology presented, the role of intersite correlation, time scale of simulation and specification of the demand function on the economic indicators has been evaluated. Results have shown that the economic indicators of the projects are individually quite sensitive to each of these modelling assumptions: damage evaluated through a Cobb-Douglas specification of the demand function for municipal water will in general lead to more conservative estimations of damage than a linear specification will. Likewise, an annual model tends to yield systematically more conservative estimates of damage than a seasonal model, due to an oversimplification in the representation of the refill-drawdown sequence. Also modelling of intersite correlation among water availabilities at the various supply sources influences considerably the economic indicators of the projects. Albeit each of these elements has significant impacts on the value of the single project, ranking of the projects is influenced much less by these modelling assumptions; this should reassure about the possibility to use the methodology as a robust planning tool to screen projects and determine intervention priorities.

Finally, the paper has also compared the presented approach with a simpler cost-effectiveness methodology where risk is ignored and projects' impacts are captured by a single indicator such as the incremental expected water volume supplied. The comparison of results shows that the main differences between the two approaches rely in how combinations of projects are assessed: in this case the cost-effectiveness analysis is not able to identify the optimal amount of investments, as it cannot capture the idea of the residual risk in the system after the alternative has been completed.

Being an application of risk and hazard principles as outlined, e.g. by Tsakiris (2007), the methodology is quite general and may be applied to a variety of water resources systems. As far as the generalization of results of the sensitivity analysis on the different modelling assumptions is concerned, it is certainly difficult to claim that results may be transferred "as is" to other systems – a general lesson, however, coming from this study is that adding complexity to modelling leads to less conservative scenarios of hydrologic risk and hence supports a critical analysis of supply-enhancing projects. Further work is needed to assess the sensitivity of the economic performance indicators to the simulation platform and to hedging rules for reservoir management.

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