

VALUING INVESTMENTS TO REDUCE THE RISK OF HYDROLOGIC FAILURES IN HEADWORKS SYSTEMS

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ABSTRACT

The paper introduces and applies a methodology to quantify the benefits of reducing water supply risks in headwork systems for municipal use, including regulated and unregulated resources, due to hydrologic failures. As risk includes both the probability of a failure and its effect (damage), the methodology combines a simulation module of the system at yearly scale coupled with 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.

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 population growth and, above all, reduction of water losses in water distribution networks.

The methodology is applied to evaluate a number of different supply-side projects aimed at increasing the reliability of the headwork system for municipal uses of over 4,000,000 inhabitants in Apulia, in southern Italy, featuring multipurpose reservoirs, unregulated surface and groundwater resources as well as a network of major transfer facilities. The projects are focused on supply augmentation by transferring additional water to the system from other systems, or producing more water in the system by building additional weirs.

The above exercise allows ranking of individual projects by their economical performances and the economic evaluation of combinations of different projects.

1 INTRODUCTION

With a wide portfolio available of different options (both on demand and supply side) 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 by explicitly including the consumer's surplus among the benefits.

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 (pipe breaks) 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 reduced supply risks. The challenge is hence to devise a procedure to assess benefits to be introduced in standard cost – benefit analysis cashflows, stemming from supply-side investments in a context where both hydrological variability and dynamic improvements to water distribution efficiency are assumed to play a significant role.

The paper introduces and applies a methodology to quantify the benefits of reducing water supply risks in headwork systems for municipal use due to hydrologic failures. As risk includes both the probability of a failure and its effect (i.e. the damage), the methodology combines a simulation module of the system at yearly scale to reproduce the probability distribution of the failures with a metric for supply failure damage provided by the price – demand relationship for municipal water.

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., 2003, 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 (Watkins and MacKinney, 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 this paper, the definition of optimal allocation rules for the system to quantify benefits is provisionally set aside; instead, simple, conservative rules are defined and simulated through a stochastic hydrologic input to determine the distribution of deficits. The value of such deficits is then quantified by the price – demand relationship for drinking water.

2 DEFINING HYDROLOGIC RISK

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

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

where $p(E)$ is the occurrence probability of event E and $D(E)$ is the associated damage (in currency/period). A synthetic indicator of the level of risk is the expected value of damage:

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

In this case, E is the occurrence of a water deficit, i.e. of a water allocation less than

target $T(t)$ and $D(E)$ is the related damage; in order to evaluate (2) one hence needs both a probability distribution of deficits and a deficit – damage relationship. It should be observed that (2) contains both the unavailability of water at the supply sources and the damage associated to a consumption level by end users lower than the target: when assessing (2) it is hence necessary to keep in mind that, while water consumption may increase from year to year due to demographic evolution and economic growth, the related withdrawals from the sources may decrease as a consequence of investments aimed at reducing water losses in distribution networks.

Damage assessed by (2) turns into a benefit when it is avoided thanks to supply – enhancing or withdrawal – reducing investments. In such a context, a yearly scale is suitable for hydrologic risk assessment; in some instances it maybe worthwhile increasing temporal resolution to seasonal or monthly scale in order to highlight some features of water demand (e.g. seasonal peaks due to tourism), but results should always be aggregated at an annual scale in order to be easily discounted via the discount rate (see eq. (6))

Water withdrawal from the supply sources corresponding to $T(t)$ is given by:

$$W(t) = T(t) / (1 - L(t)) \quad (3)$$

where $L(t)$ is the average level of losses in conveyance and distribution networks in year t , expressed as a percentage of withdrawal and t represents a year of the planning horizon, $t = 1, 2, \dots$ (e.g. year one, year 5, year 20 etc.). Water availability may also feature trends along the planning horizon due to new water treatment plants entering operation, or as the result of the enactment of environmental plans aimed at safeguarding resources (typically, reduction of withdrawals from aquifers).

In this model, the dynamic dimension of both supply and demand (basically trends on water availability and withdrawals) is intertwined with hydrologic variability, from which risk stems: deficit Def is defined as:

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

$$Def = 0 \quad \text{if } E_r = T(t) \quad (4b)$$

where E_r is the volume supplied to customers in a given year..

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

$$P(Def) = P(E_r \leq T(t)) \quad (5)$$

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

In order to combine hydrologic variability with the dynamic dimension of supply and demand along the planning horizon, a present expected damage value (PEDV) should be assessed:

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

where O represents the length of the time horizon (the number of years of the planning period, typically thirty years), r is the discount rate and $E[D(t)]$ is the expected

damage at year t of the planning horizon; year t has a certain target consumption level $T(t)$ and a related withdrawal from the supply sources, given by eq. (3), hence $E[D(t)]$ is given by:

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

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 $T(t)$.

To assess (7), the probability distribution of deficits $p(Def)$ must be quantified and deficits must be attributed a monetary value. In the following, this last aspect will be tackled, while the description of how to determine the distribution of deficits is given later, after illustrating the case – study, that has somehow influenced system's modelling.

2.1 Linking deficits to damage: price – demand relationship and scarcity costs

Drinking water is a commodity: assessment of the benefits associated to different levels of water availability may be performed through a demand – price relationship for drinking water. Such relationship may in principle be assessed for any type of good and is a fundamental analytical tool in the consumer's theory (Fig. 1). As is well known, it expresses the relationship between water consumption (in cubic meters and in aggregated terms over a certain group of users) and its price (in €/m³). As each point of the demand curve is actually the solution of an optimization problem (e.g. Maas – Colell et al., 1995), price in the y axis expresses the marginal cost of the amount of water indicated in the x axis, that is, the cost at which the last unit of that quantity is sold. A price – demand relationship is decreasing and the area under a certain water availability E quantifies the overall benefit associated to the consumption of quantity E .

An important notion contained in the curve is that of “consumer's surplus”: if the last cubic meter of quantity E is sold at price p , area BDAE measures the market value of water – the returns of an utility from selling that quantity (in figure 1 the assumption is that water price is constant so that marginal price coincides with average price, in the real world the structure of price typically exhibits increasing or decreasing blocks); however, consumers enjoy a further benefit as they would be willing to pay more, were water available in smaller quantities: paying quantity E at price p hence leaves them with a surplus of benefit that is not captured by water price. If E coincides with the target $T(t)$, its consumption hence produces a benefit $B(T(t))$ given by area CDAE.

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

$$D = B(T(t)) - B(Q(t)) \quad (8)$$

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

$$\eta = \frac{dQ}{dP} \times \frac{P}{Q} \quad (9)$$

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

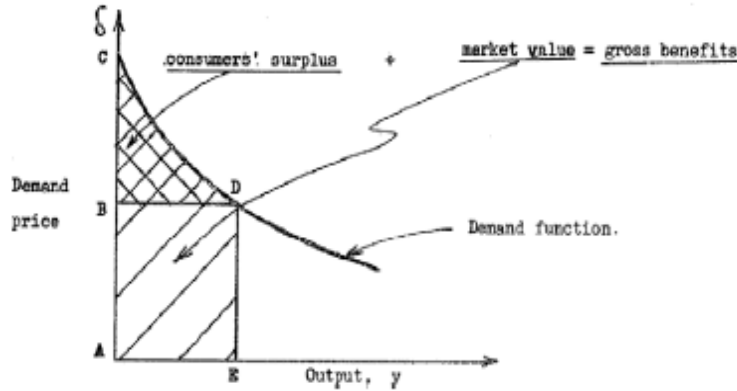


Figure 1. Price – demand relationship for water and components of benefits (from Harou et al., 2009). Output indicates here the consumed water quantity.

Estimation of the demand curve is typically performed on a panel of cross – sectional (space – time) data assuming a form of the relationship (widespread specifications are the loglinear one, the translog or the Stone Geary) and regressing water consumption on a number of different explanatory variables, including price, income, some climatic index, and so on (Mays, 2004). Although empirical studies produced in over forty years have yielded highly variable results in terms of demand elasticity, all agree that municipal demand, especially indoor domestic demand, making up most of the total in many instances, is inelastic ($|\eta| < 1$) and that different specifications give back similar scarcity costs, provided that deficits are not too large. 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 and the large time span covered (around thirty years, from the '60s to the '90s).

In the following, evaluations will be performed using two different specifications of the demand curve: they differ not only in the functional relationship between price and demand, but also in the estimation procedure. The first of such specifications, the log-linear one, stems from the assumption that elasticity stays constant along the whole domain of water demand: if $\eta = \text{const}$, then $dQ/Q = \eta * dP/P$, implying that $\ln Q = \eta * \ln P + C$, and finally:

$$P = \text{const}_1 * Q^{1/\eta} = a * Q^b \quad (10)$$

Constant a is found considering that when consumption equals the target, price equals P_T , the marginal cost of supply, i.e. the price of the last cubic meter of water consumed; hence $a = P_T/T^b$ with $b = 1/\eta$. This estimation methodology is termed “point expansion” because once the shape of the relationship and a constant elasticity value are assigned, only one point of the curve needs to be known. As stated above, the benefit

$B(Q)$ associated to a certain consumption level Q is found by integration of the demand curve. Damage $D(Q)$ related to a consumption Q less than the target T is given by $B(T) - B(Q)$. For the log-linear specification (also termed Cobb-Douglas) damage is given by:

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

Recalling (3), one can express the scarcity cost consequent to withdrawing a certain quantity W of water from the supply sources less than the target:

$$B(W) = a \cdot \frac{\eta}{1+\eta} \left\{ [W_T \cdot (1 - L(t))]^{\frac{1+\eta}{\eta}} - [W \cdot (1 - L(t))]^{\frac{1+\eta}{\eta}} \right\} \quad (12)$$

The second specification is a linear relationship between price and demand in a consumption dominion ranging from the target (where price is P_T , as in the previous case) to a minimum consumption $Q_{\min}$ (with the corresponding 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 (project that may 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). A linear specification results in a quadratic relationship between scarcity costs and deficits.

3 THE CASE STUDY: THE WATER RESOURCES SYSTEM SUPPLYING APULIA

The water resources system supplying domestic 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 (Figure 2). The system is multipurpose, as resources in some major reservoirs are shared with other uses, mainly irrigation. In addition, aquifers are also intensively exploited for irrigation so that they also constitute a shared resource, since the level of withdrawals for agriculture influences that of municipal uses. As the aquifers in the region are coastal ones, overextraction causes salinization of groundwater and hence already limits civil uses and is also feared to reduce irrigation benefits for agriculture.

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 extra-regional resources (spring water) to town and cities. The main canal has been then sided and reinforced by other aqueducts and resources but, to some extent, it remains the backbone of the whole system.

Overall, the system features four major reservoirs (Occhito, Locone, an off-stream reservoir supplied by water from the Ofanto river basin, Monte Cutugno and Pertusillo, the latter two outside Apulia), the Sele – Calore springs, from which the “canale

principale” originates, also outside Apulia, and a number of wells. Table 1 reports the most relevant hydrological, technical and socio-economical parameters used for the analysis.

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

HYDROLOGICAL PARAMETERS		
Average yearly streamflow of Sinni river at M.te Cutugno dam	279,1	Mm ³
Standard deviation of yearly streamflow of Sinni river at M.te Cutugno dam	110,9	Mm ³
Average yearly streamflow of Agri river at Pertusillo dam	212,9	Mm ³
Standard deviation of yearly streamflow of Agri river at Pertusillo dam	59,9	Mm ³
Lag 1 serial correlation coefficient of yearly streamflow of Agri river at Pertusillo dam	0,44	
Average yearly streamflow of Fortore river at Occhito dam	159,4	Mm ³
Standard deviation of yearly streamflow of Fortore river at Occhito dam	93,5	Mm ³
Lag 1 serial correlation coefficient of yearly streamflow of Fortore river at Occhito dam	0,36	
Average yearly flow of Caposele and Cassano Irpino springs (for Apulia)	159,9	Mm ³
Standard deviation of yearly flow of Caposele and Cassano Irpino springs (for Apulia)	22,9	Mm ³
Lag 1 serial correlation coefficient of yearly flow of Caposele and Cassano Irpino springs (for Apulia)	0,63	
Average yearly diversion from Santa Venere weir for Locone reservoir	36,3	Mm ³
Standard deviation of yearly diversion from Santa Venere weir for Locone reservoir	16,7	Mm ³
Average yearly streamflow of Locone creek at Locone dam	11,8	Mm ³
Standard deviation of yearly streamflow of Locone creek at Locone dam	1,06	Mm ³
Losses from M.te Cutugno reservoir (evaporation and environmental downstream requirements)	n.d.	
Losses from Pertusillo reservoir (evaporation and environmental downstream requirements)	13,1	Mm ³
Losses from Locone reservoir (evaporation and environmental downstream requirements)	10%	Yearly streamflow
Losses from Occhito reservoir (evaporation and environmental downstream requirements)	15%	Yearly streamflow
TECHNICAL PARAMETERS		
Maximum withdrawal for municipal uses from Pertusillo reservoir	113	Mm ³
Maximum withdrawal for municipal uses from M.te Cutugno reservoir	140	Mm ³
Withdrawal for irrigation from M.te Cutugno reservoir	164	Mm ³
Maximum withdrawal for municipal uses from Locone reservoir	47	Mm ³
Withdrawal for irrigation from Pertusillo reservoir	51,5	Mm ³
Withdrawal for irrigation from Occhito reservoir	92	Mm ³
Withdrawal for irrigation from Locone reservoir	5	Mm ³
Active capacity of Pertusillo reservoir	118,5	Mm ³
Active capacity of Monte Cotugno reservoir	256	Mm ³
Active capacity of Locone reservoir	35	Mm ³
Active capacity of Occhito reservoir	133	Mm ³
SOCIO – ECONOMICAL PARAMETERS		
Marginal price of water supply and distribution in target conditions	1,65	€/m ³
Unit cost of back stop technology	2,0	€/m ³
Minimum incompressible water consumption	80	l/ab. x day
Price – demand elasticity in the Cobb-Douglas specification	-0,4	
Discount rate	5%	

The supply-enhancing investments (in dotted red line in figure 3) are considered as additional to those contained in the medium-term (2009 – 2018) master plan of the utility providing municipal water service for the whole region (Piano d'Ambito, PdA in the following). The plan formulates forecasts for future water demand in the next ten years both at the delivery point to customers and at the sources; in doing this, it accounts for demographic 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 ten years thanks to an extensive programme of pipe maintenance and substitution. Such reduction, if it actually takes place, will result in a dramatic increase of water availability for the system and may hence jeopardize the role and meaning of the additional resources.

Although most of the additional resources will be made available in a medium-term perspective, it was decided to include in the analyses also the transient deriving from such planned loss reductions in the next ten years or so. The supply-enhancing investments are summarized in table 2. It should be noted that the quali-quantitative description of benefits follows estimations of the authorities that have prepared the projects which are not based on an overall picture of the system as a whole. Investment and operating costs have also been provided by the same authorities; they include the financial costs of the inputs for the investments and energy costs as operating expenses. Water treatment cost of the additional water (0,05 €/m³, based on operational data of similar plants) as well as maintenance costs (1%/year of the investment cost) have been included in the analysis reported in section 5.

3.1 Modelling allocations for the Apulian water resources system

The allocation model consists of mass-balance equations, turning a hydrological input on a yearly basis (streamflow at the different dams and yield of Sele-Calore springs) into allocations to municipal uses; in doing this, 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 and subsequently being sided by other sources and infrastructures, makes this assumption reasonable.

1,500 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 from the early '80s to 2006. When yearly data exhibited statistically significant serial correlation, data were generated using auto-regressive models of order 1. Cross correlation among yearly flows at the different sources have been simulated in a simple way, using at each site the same random value for streamflow generation: this actually results in higher cross correlations than those observed, and the generated series are likely to exhibit low-availability periods that are probably longer and more intense than the observed ones.

The intertemporal allocation rule adopted is the standard one (Loucks and Van Beek, 2005), 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. Two different intersectorial allocation rules are employed, giving rise to two different risk scenarios: in the first one (scenario A), competition for resources is ignored in Locone and Occhito reservoirs and releases for municipal use from these

reservoirs are assumed constant and equal to those targeted in the PdA; in this scenario irrigation and industrial demand is considered only in the reservoirs of the southern part of the system (Pertusillo and Monte Cotugno): the rule is to try meeting all non-municipal demand first and municipal demand second. In the second scenario (scenario B), priority is given to all non-municipal uses in all reservoirs. It is expected that both the high cross correlations among flows and these conservatives allocation rules will tend to overestimate hydrological risk for municipal use in scenario B.

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

Description	Effects	Short description of the expected benefits	Investment costs [€]	Operating costs [€/year or €/m ³]
Dismantling of Castrocucco hydropower station – water presently diverted offstream for hydropower generation is released downstream and stored in Monte Cotugno reservoir	Increase of water availability in the downstream Monte Cotugno reservoir	Increases of up to 100 Mm ³ /year from Monte Cotugno reservoir by reducing hydropower production from the upstream Cogliandrino reservoir; possibility to reduce withdrawals from high-salinity groundwater	0	0,085 €/m ³
Completion of Sauro and Sarmento weirs	Increase of water availability from Monte Cotugno reservoir	Approximately additional 75 Mm ³ from Monte Cotugno reservoir	13.500.000* (Sauro weir only)	-
Use of water resources from San Giuliano reservoir for municipal purposes	Additional volumes for the Sinni water treatment plant	Approximately additional 40 Mm ³ /year to be treated in the Sinni treatment plant	11.200.000	2.400.000 €/year
Water transfers from Ponte Liscione reservoir (not in fig. 2) to Occhito reservoir	Increase of water availability from Occhito reservoir	Approximately additional 20 Mm ³ from Occhito reservoir	90.000.000	2.200.000 €/year
Interconnection between Rendina reservoir (not in fig. 2) and Locone reservoir	Increase of water availability from Locone reservoir	Approximately additional 24 Mm ³ from Occhito reservoir	5.150.000	770.000 €/year
Interconnection between Marascione tank (not in fig. 2) and Locone reservoir	Increase of water availability from Locone reservoir	Approximately additional 23 Mm ³ from Occhito reservoir	29.880.000	-

The allocation procedure may be hence summarized as follows:

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

$$S_i^j = S_{i-1}^j + I_i^j - Mun_rel_i^j - Irr_rel_j^j - L_i^j \quad (13)$$

Where S_i and S_{i+1} are stored volumes in years i and $i+1$, Mun_rel_i and Irr_rel_i are releases for municipal and irrigation purposes respectively, and L are losses for evaporation and environmental downstream requirements. J stands for reservoir ($j = 1$ for Occhito and $j = 2$ for Locone) and $i = 1, 2, \dots, 1,500$. Releases can be less than the target, according to water availability. Allocation between irrigation and municipal use follows the previously introduced rules.

For each time step, municipal releases from Occhito and Locone reservoir are summed to water availability from springs and from other hydrology-independent sources (wells, for instance), to obtain an overall demand to the two reservoirs in the southern part of the system, Pertusillo and Monte Cotugno; this approach makes sense because active capacity of these two reservoirs (around 560 Mm^3) is approximately twice the capacity of Occhito + Locone (around 280 Mm^3). In assessing allocations for municipal uses from Monte Cotugno and Pertusillo, also capacities of the two treatment plants downstream are allowed for.

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

4 RESULTS

Deficits are then given a value according to the equations of section 2 and a trend of $E[D(t)]$ (in $\text{M€}/\text{year}$) may be obtained for $t = 1, 2, \dots, 30$ years. Such flow is then discounted using a 5% interest rate (UE REGIO, 2008). In the “business as usual” (BAU) configuration, the $PEDV_{\text{without}}$ (eq. 6) measures the level of expected damage for the system in its present condition, i.e. without any of the supply-enhancing investments and subject to the efficiency improvements scheduled in the PdA. Adding one of the supply-enhancing investments to the system results in a decreased value of PEDV. The difference $PEDV_{\text{without}} - PEDV$ between the present expected damage without and with the investment provides a measure of the discounted benefit generated by the project during the planning horizon. It may be added to other benefits and manipulated to obtain the typical performance indicators (Net Present Value, Internal Rate of Return, Benefit - Cost ratio) used in standard cost-benefit analysis (UE REGIO, 2008).

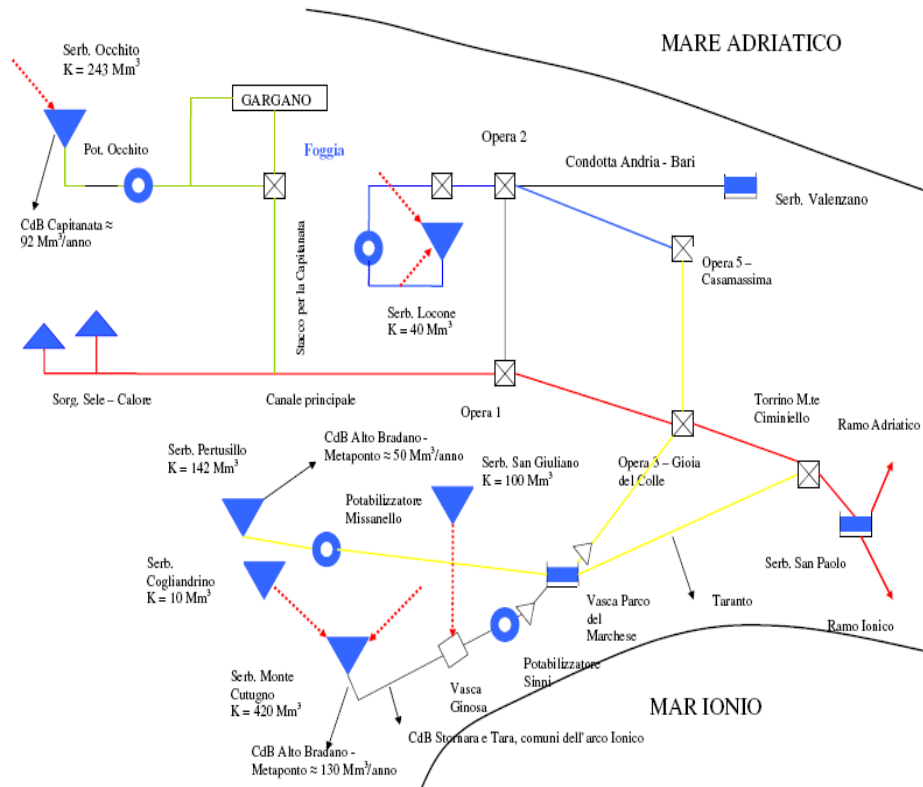


Figure 2. Schematic representation of the water resources system supplying municipal uses in Apulia. Down-pointing blue triangles indicate reservoirs, upward-pointing blue triangles indicate springs. Empty blue circles represent water treatment plants; crossed squares represent interconnections between aqueducts. Empty triangles indicate pumping stations, while blue rectangles denote tanks. Aqueducts are indicated with different colours: red line indicates the “canale prinvipale”, green line represents the Fortore aqueduct, yellow line the Pertusillo aqueduct, and blue line the Locone aqueduct. Back arrows indicate withdrawals for non-municipal uses (CdB stands for Consorzio di Bonifica – reclamation consortia, managing irrigation projects). Dotted red lines indicate the planned supply-enhancing projects.

Table 3 reports the economic performance indicators associated to the various individual projects, together with the associated average value of the incremental water availability for municipal uses and the residual expected damage, as a % of the damage in the BAU configuration. Residual expected damage represents the expected damage for the system after the investment has been completed and has entered operation.

Table 3 shows in the first place that not all investments are able to generate benefits

that outweigh costs. In the second place, steady-state incremental water availability 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 actual required volumes; this also means that “on demand” water transfers (as that from San Giuliano reservoir, requiring pumping, or from Cogliandrino reservoir, implying downstream releases against payment of the lost hydropower production) will not occur every year, and in many years transfers will not be activated. This partly explains why investments such as these are among the most profitable: the investment producing the highest NPV is actually the one of substituting hydropower generation (at the cost of 0.085 €/m³) from Cogliandrino reservoir with releases to the downstream reservoir (Monte Cotugno) and subsequent treatment for municipal purposes. Clearly, investment performance depends on the transfer rule assumed: for “on demand” transfers additional water to the system is assumed to be withdrawn only in years when a shortage occurs and this additional water is used for civil purposes only; while this is certainly a reasonable assumption, other rules may be devised, such as withdrawing in “normal” small amounts of water in order to have them available in dry years. For transfers independent of demand (such as those deriving from building weirs), the assumption was to allocate these additional volumes (assumed constant over the 1,500 time steps) to irrigation first and to municipal uses second, as previously illustrated.

Finally, table 3 shows that benefit estimates obtained 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

Clearly, combinations of different investments may also be analyzed through this procedure. Ignoring residual damage as an additional criterion for plan selection and basing decision on NPV only would lead to decide that releases from Cogliandrino reservoir alone are the best option. Adding to the NPV the residual expected damage gives back combinations whose NPV dominate that of the Cogliandrino investment alone. The combination of Cogliandrino + the two weirs transferring water to the southern system and in particular to Monte Cotugno reservoir (the largest of the system) seems to be the most promising one.

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. 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 at a yearly scale 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 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 such as the Net Present Value or the Benefit/Cost ratio.

Table III. Economic performance indicators of the supply-enhancing investments, expected residual damage and incremental water availability for municipal use. Values refer to B scenario. Medium term incremental availability is assessed with reference to years 10 and later, when the planned efficiency recovery should already be completed

Investment	Net Present Value [M€]		Internal Rate of Return		Benefit – Cost ratio		Expected residual damage		Medium – term incremental water availability for municipal use [Mm ³ /year]
	Cobb-Douglas	Linear	Cobb-Douglas	Linear	Cobb-Douglas	Linear	Cobb-Douglas	Linear	
Water transfers from Ponte Liscione reservoir to Occhito reservoir	-27.7	-37.6	-	-	0.6	0.4	82%	81%	0.8
Interconnection between Marascione tank and Locone reservoir	13.1	11.3	9%	8%	1.5	1.4	66%	68%	1.9
Interconnection between Rendina reservoir and Locone reservoir	38.4	20.8	51%	35%	7.2	5.2	64%	67%	1.10
Use of water resources from San Giuliano reservoir for municipal purposes	28.5	12.0	22%	13%	3.2	1.9	52%	56%	0.7
Sauro weir	39.8	22.2	25%	17%	3.8	2.5	41%	40%	2.8
Sarmiento weir	61.0	39.8	-	-	8.2	5.5	29%	30%	1.3
Sauro + Sarmiento weirs	65.7	38.2	34%	24%	4.8	3.1	12%	15%	4.0
Releases from Coghandrino reservoir	75.5	42.8	-	-	10.3	6.3	29%	34%	3.00

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