An Integrated Decision Support System for the evaluation of water management strategies

by D. Assimacopoulos*

Abstract

An Integrated Decision Support System for the evaluation of water management options and regional strategic plans is presented. Water allocation between the various uses is simulated for a long time horizon using a deterministic model running on a monthly time step. The system incorporates water availability, demand, quality, and economic models all integrated in a GIS environment. The evaluation procedure of the DSS compares the effect of water management instruments or strategic plans on the basis of well-defined, comprehensive indicators expressing the three major principles of Integrated Water Resources Management underlined in the Water Framework Directive: economic efficiency, equitable allocation of resources and costs, and environmental sustainability.

1. Introduction

The decision-making processes associated with the utilization of water resources are very complex, and require thorough consideration and analysis. Sectoral approaches to water resources development and management have been and still are dominant (Lilburne et al., 1998; Salman et al., 2001) but there is need for a shift towards a holistic approach to avoid fragmented and uncoordinated policies (Rosegrant et al., 2000; Staudenrausch and Flugel, 2001). Additional challenges arise in the field of water policy from the multi-dimensional interactions between the various aspects of human activities, their impact on natural systems and the corresponding influence of natural responses upon the human domain (Simon et al. 2004; Salewicz and Nakayama, 2004).

In the context of the EU Water Framework Directive (2000/60/EC), the systematic evaluation of water management interventions should be performed for a long time horizon, simulating long-run accumulative effects and anticipating potential future changes and uncertainties. Indicators selected should assist decision-makers in identifying the appropriate policy and management instruments in relation to regional economic growth and environmental sustainability.

Complex integrated modeling can meet those objectives when based on comprehensive information systems. Multidisciplinary information is needed for the analysis of strategies and evaluation of their effects, taking into account economic, hydrologic and environmental interrelationships (McKinney et al., 1999; Bouwer, 2000; Albert et al., 2001). A variety of models and systems have been developed for water allocation and quality estimations, such as MIKE BASIN by DHI, or WEAP by the Stockholm Environment and Tellus Institutes. Systematic formulation and evaluation of alternative policies and strategies integrating the economic principles of the WFD is however missing.

* e-mail address: assim@chemeng.ntua.gr

The next paragraphs describe a prototype DSS for assisting decision making under a GIS environment for strategic planning in the context of the economic and environmental sustainability objectives, with special emphasis on the water stress problems encountered in arid and semi-arid regions. The approach is demonstrated through an application in a typical Greek island.

2. Overview of the DSS

The DSS uses the concept of a water management scheme (WMS), defined as a set of scenarios for variables that cannot be directly influenced by the decision maker (i.e. rainfall patterns constituting a water availability scenario and population growth formulating a demand scenario) and the application of one or more water management interventions.

A WMS is defined in terms of a database containing information on the water infrastructure at a certain region and reference year, at which the implementation of scenarios and strategies begins. A base case is always present, serving as input for the creation of new WMSs. User interaction with the DSS falls under three functional groups, accessed via a hierarchical navigation tree: (a) base case editing, allowing for the editing and introduction of new data for the reference year; (b) creation of WMSs, providing the capabilities for defining scenarios on water availability and demand, definition of strategies and visualization of results and for conducting a parametric economic analysis, and; (c) evaluation, which permits the comparison of different WMSs according to a predefined set of indicators (Fig. 1).

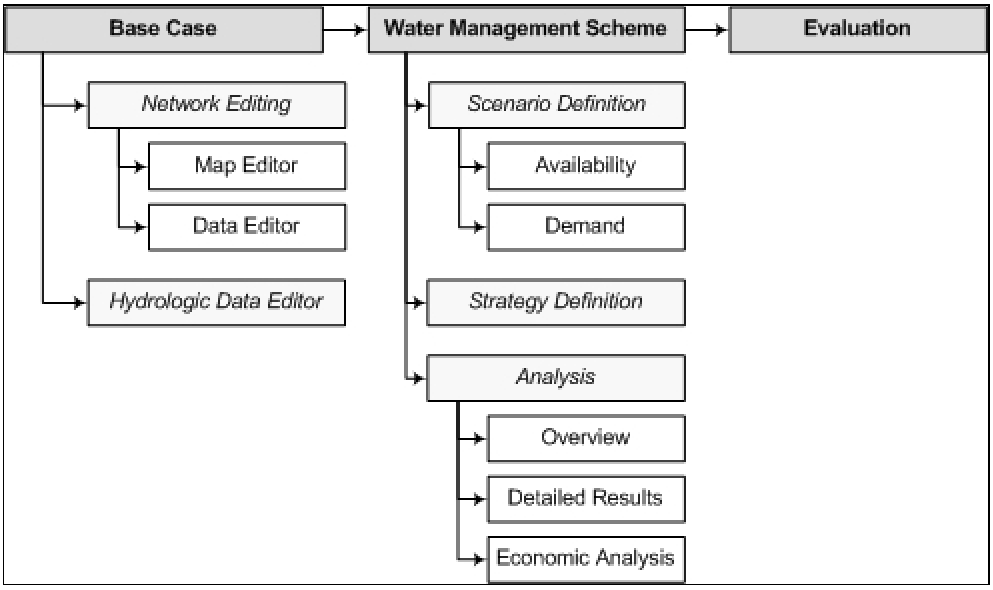

Figure 1. The DSS operational framework

The Demand Scenarios Module produces forecasted time-series of water demand for all water uses, generated by specifying appropriate growth rates to the key variables (Drivers) that govern demand pressures, such as population for domestic use, cultivable area and livestock for agricultural practices, production growth for industries and minimum required energy production from hydropower plants.

Application of water management instruments can be performed either through proper customization of abstract actions, or through modification of the properties of network objects and the introduction of new ones. As an example, supply regulation through quotas can be performed through application of the respective action, where the user defines the maximum volume of demand that can be met under a specified time period, and the geographic area of application.

The *Analysis* branch provides the visualization of results from the simulation of each water management scheme, through three functions. The *Overview* displays yearly aggregated results on water demand and shortage for the main sectors, freshwater abstractions, and costs (direct and environmental) as well as benefits from water use. The *Detailed Results* section provides the results of the allocation in terms of appropriately customized indicators aggregated either for the entire region or presented for each type of network object. An example of the interface of the DSS is presented in Fig. 2. Finally, the *Economic Analysis* branch permits the selection of appropriate models and parameters for the estimation of direct, environmental and resource costs and the definition of benefits from water uses, avoiding repetition of the entire simulation procedure.

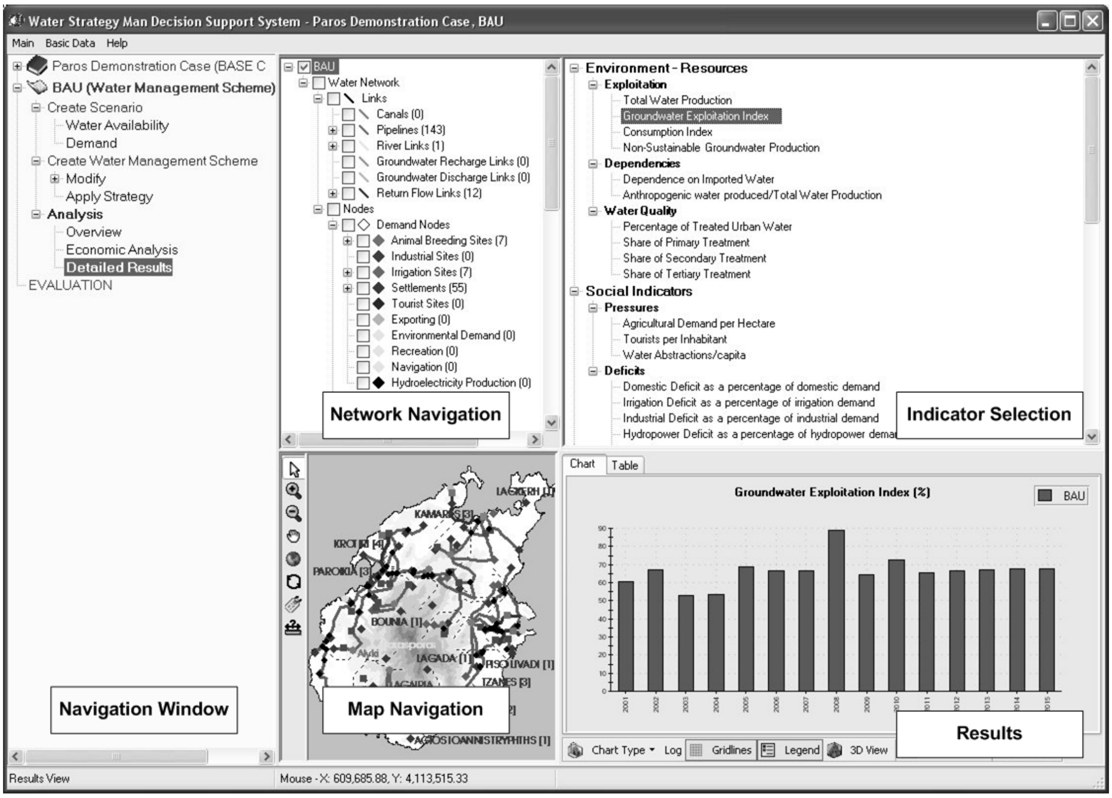

Figure 2. The Detailed Results interface

3. DSS Architecture

The Decision Support System has been implemented in Visual Basic .NET using the Arc Objects COM technology by ESRI, which is also the platform for the GIS Database. The tool was designed according to the four step schema presented in Fig. 3 that involves a) the database b) the object model linked to mathematical models for water allocation, quality and economic estimations, c) a logical coordination unit, responsible for the communication with external models and d) the user interface which allows for the definition of parameters related to the simulation and the presentation of results through customizable charts, tables and maps. Water management strategies or single interventions can be simulated under different scenarios, compared, and the decision maker or the analyst can formulate responses to mitigate water stress impacts with respect to their objectives.

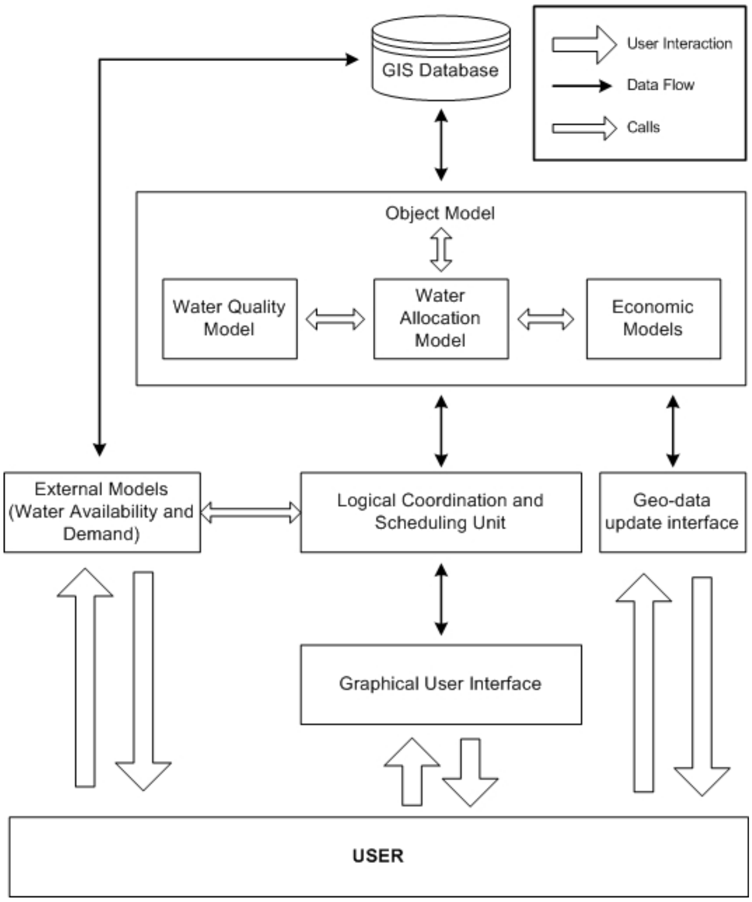

Figure 3. The DSS architecture

The system, which is currently being applied to river basins and administrative regions in Greece, Italy, Cyprus, Portugal, Israel and Spain, can easily be extended to work with other regions (WaterStrategyMan project, 2003). All specific regional data are stored in an ESRI GIS Database (geodatabase). Special attention has been given to the portability of the DSS. The developed object model with the inter-linked mathematical models can easily be transported to other GIS environments since most GIS functions are implemented outside the modeling procedures and algorithms.

GIS Database, Data and Object Model

The GIS Database, as well as the Object Model of the DSS, is formulated around the concept of an ESRI geometric network. A geometric network is described as a set of junctions (points) and edges (polylines) that are topologically connected to each other. In the Object Model junction elements are conceptualized as water nodes while the connections between them are the water links. Water nodes are classified into three categories, (a) supply nodes standing for alternative water supply sources and characterized by the monthly available supply; (b) demand nodes modeling water uses and flow requirements and, (c) transshipment nodes standing for treatment plants and generic network junctions. Water link objects are classified in four categories according to the connectivity rules of the network and the particular modeling requirements of the DSS: supply links (pipelines and canals) conveying water from supply sources to demand nodes, groundwater interaction links (recharge and discharge), representing the natural interaction between surface and groundwater bodies, return flow links, conveying return flows from consumptive demand uses to receptor bodies (surface or groundwater) or wastewater treatment plants, and river links, representing the natural course of a river water body. An overview of the object model for water nodes is presented in Fig. 4.

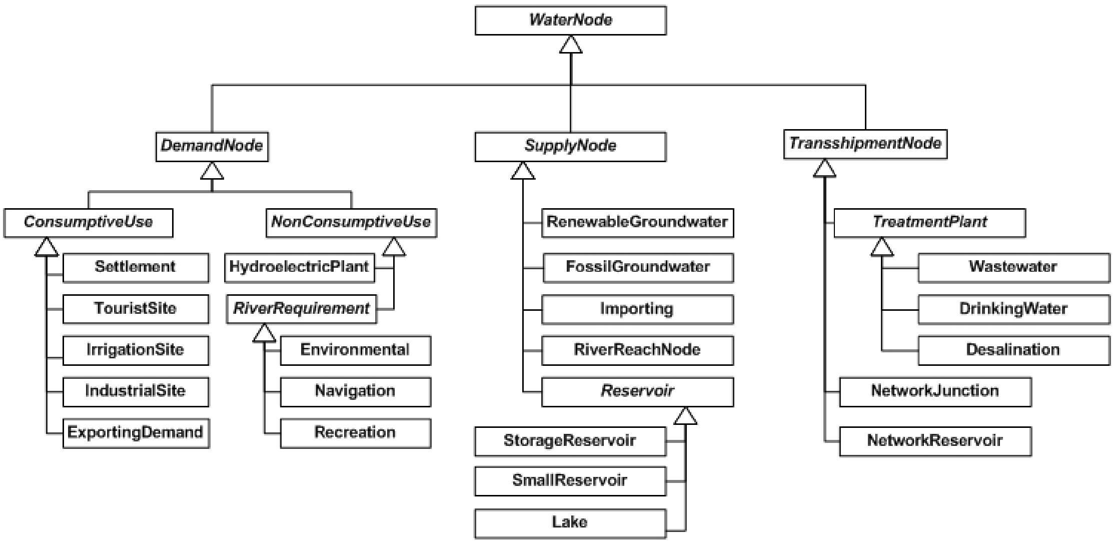

Figure 4. Overview of the object model for water nodes

Water Allocation

Economic optimization models, aiming to maximize the social water surplus require the monetary valuation of environmental impacts, societal objectives, developmental priorities and property rights, which in most cases is subject to many constraints and limits the applicability of a tool. The DSS water allocation model minimizes water shortage under limited water supplies (Manoli et al., 2001). In situations of water shortage, distributing the water available from the various supply sources to the connected uses creates conflicts. The allocation model can solve this problem using two user-defined priority rules. First, competing demand sites are treated according to specified priorities. Those can express social preference or constraints, economic preference (prioritization to activities with highest economic values), or a system of water rights. In case that a particular use can be supplied by more than one resource, supply priorities are used to rank the choices for obtaining water. Supply priorities in this case express: (a) cost preference (b) quality preference of uses (e.g. domestic or industrial use) for supply sources with high water quality; (c) need for the protection of resources and the formation of strategic reserves.

Economic Analysis

The primary aim of the economic analysis is the estimation, according to the results of the allocation algorithm, of financial, environmental and resource costs. A full water services cost recovery strategy (WATECO, 2002) can be used as an indication of pricing structures that could meet the desired cost recovery levels.

Estimation of financial costs associated with the provision of water supply is rather straightforward and depends on the depreciation of capital construction costs and specific energy, operation and maintenance costs associated with each part of the infrastructure. Two types of environmental costs have been incorporated, one for the abstraction and consumptive use of freshwater resources (surface and groundwater) and one for the disposal of polluting effluents from demand activities. Resource costs are associated with the scarcity rent of freshwater resources, defined as a surplus, the difference between the opportunity cost of water and the per unit costs of turning that natural resource into products (agricultural crops for farmers, water services for the residence of an urban centre, industrial production etc).

Strategy Formulation

A characteristic of the DSS is that it predefines a number of “abstract” water management instruments (actions) and incorporates them as methods into the system. Those methods modify accordingly the properties of the network objects or introduce new ones, related to water infrastructure development. An “abstract” action becomes “application specific” by the user-definition of its magnitude, time horizon and geographic domain. An initial set of actions that can be taken into consideration is presented in Table 1. Actions incorporated are mainly focused on instruments to deal with the frequent water shortages occurring in arid regions. The main aim is to either enhance supply, promoting the protection of vulnerable resources through structural interventions, or to regulate demand through the promotion of conservation measures, technological adjustments for promoting efficiency of water use, and pricing incentives.

Table 1. Summary Table of Policy Options and related Actions

Policy Options	Actions
Supply Enhancement	o Unconventional/untapped resources o Surface Waters and precipitation (direct abstraction, dams, reservoirs) o Groundwater o Desalination o Importing o Water Reuse
Demand Management	o Quotas, Regulated supply o Irrigation method improvements o Conservation measures in the home o Recycling in industry and domestic use o Improved infrastructure to reduce losses (networks, storage facilities) o Raw material substitution and process changes in industry
Social-Developmental Policy	o Change in agricultural practices o Change of regional development policy
Institutional Policies	o Economic Policies (Water pricing, Cost recovery, Incentives)

Evaluation

Evaluation of alternative schemes takes into account the entire simulation horizon. As a first step, time series of indicators are computed, describing the behavior of the water system in terms of environmental, efficiency, and economic objectives (Table 2).

Table 2. Indicators in the DSS evaluation procedure

Category	Indicator
Environment Resources	Dependence on Inter-basin water transfer
	Desalination and reuse percentage
	Groundwater exploitation index
	Non-sustainable water production index
	Share of treated urban water

Category	Indicator
Efficiency	Coverage of Animal breeding, Domestic, Environmental, Hydropower, Industrial and Irrigation demands
Economics	Direct Costs
	Benefits
	Environmental Cost
	Rate of cost recovery

The comparison is performed through a multi-criteria analysis based on the computation of statistical criteria for reliability, resilience and vulnerability (Bogardi and Verhoef, 1995; ASCE, 1998). The statistical criteria express the behavior of the monthly or yearly time series of each indicator with respect to the predefined range of satisfactory values that the indicator can assume. *Reliability* is defined as the probability that any particular indicator value will be within the range of values considered satisfactory. *Resilience* describes the speed of recovery from an unsatisfactory condition. *Vulnerability* statistical criteria measure the extent and the duration of unsatisfactory values. Performance for each indicator is computed as the product of the above criteria, and the relative sustainability index of each WMS is the weighted sum of the performance of the selected indicators, and can be used to rank alternative strategies or instruments according to the objectives of the undertaken analysis.

4. Case Study

Paros, with an area of 196 km^2 is one of the most popular tourist destinations in the Cycladic Complex, Greece. During the summer months the seasonal population is almost three times greater than the permanent population (from 10,000 to 35,000). Water demand growth in the last decades was faced with the construction of extensive water drillings, both public and private, to supply the domestic and agricultural sectors. Since 2002 a brackish desalination unit with a capacity of 1,450 m^3/d supplies the northern tourist part of the island, accounting currently for 11% percent of domestic water supplies. Domestic needs in year 2004 are estimated at approximately 1.96 hm^3. Irrigation demand is estimated at approximately 2.5 hm^3. In a “business as usual” scenario (BAU) domestic demand is estimated at 2.5 hm^3 in 2020 and 2.9 hm^3 in 2030, resulting in a total deficit (under normal hydrology conditions) of 1.36 million m^3.

Intervention 1: Network Unifications

Water distribution networks throughout the island are fragmented since up to the year 1999 each municipal department was responsible for the management and development of its own water resources. Network unifications, where feasible, can allow for the transfer of water from relatively rich water areas to areas under water stress.

Intervention 2: Desalination

Desalination units can be used to supply areas with strong seasonal demand and limited access to groundwater resources. Plants are designed to meet at least 95% of domestic water needs in the supplied areas, act as a primary source of supply, and normally operate in full capacity during the peak month of August. Units are replaced after the 15th year of operation, in 2021. Currently required capacity is estimated at 2700 m^3/d under a normal shortage scenario.

Intervention 3: Conservation measures in the domestic sector

The intervention is related to the subsidization of low flow tap installation in households and hotels in order to decrease consumption rates for tourists and residents by 8%. An initial penetration of 40% is assumed while stronger incentives should be introduced in order to achieve further demand reduction.

Results

Simulation results for the domestic deficit are presented in Fig. 5.

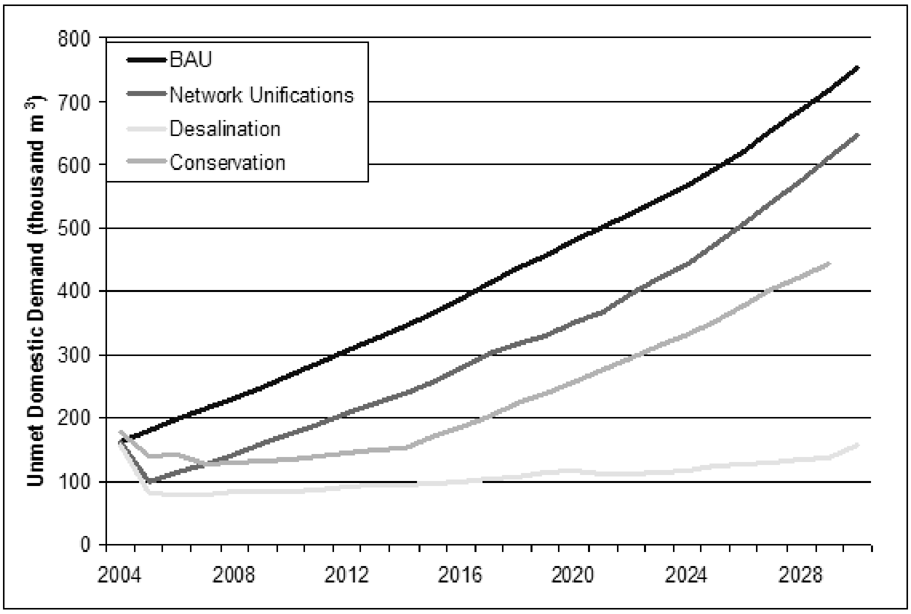

Figure 5. Domestic deficit for the normal shortage scenario

For the evaluation procedure, environmental performance is based on the groundwater exploitation index, which should not exceed the upper limit of 75%. The target for domestic demand coverage is set at 95%. Evaluation results are presented in Fig. 6, which combines the total score with the net present value computed for direct and environmental costs from groundwater abstraction (weights are set at 0.2 and 0.8 respectively).

Desalination is the intervention that can be considered the more efficient in meeting the particular environmental objective and the efficiency goal set. However, high direct costs imply that a strategic approach should also integrate non-structural interventions, such as conservation, in an effort to reduce the required installed capacity. Similar results are obtained from the analysis of the high dry scenario. In this case direct costs are increased by 55 % with respect to the business as usual scenario. Network unifications seem to have little or no effect in the performance of the system, especially under high shortage conditions. Additionally, the intervention leads to augmentation in groundwater abstractions with respect to the business as usual scenario due to the transfer of additional resources between the municipal departments.

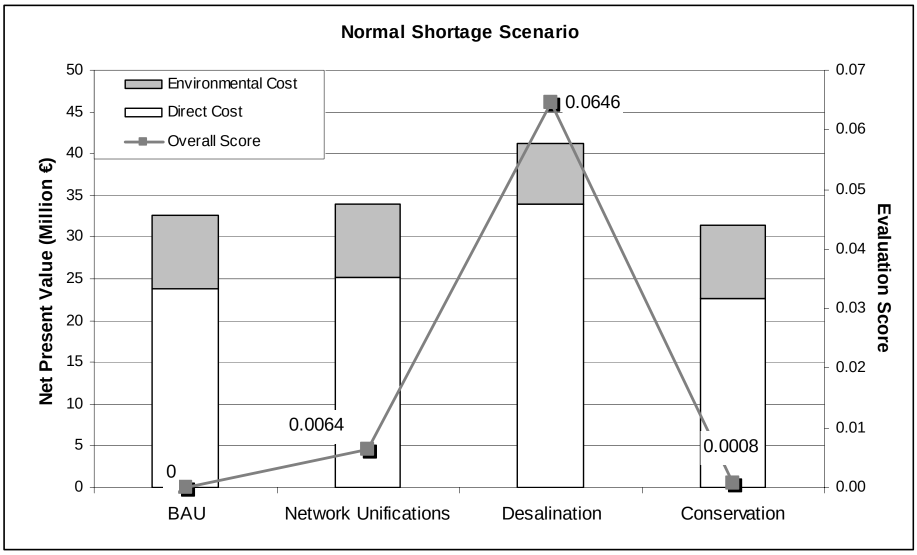

Figure 6. Overall evaluation score, direct and environmental costs for the three interventions under the normal shortage scenario

5. Conclusions

The application of the Water Framework Directive requires the interpretation of the goals of equity and financial and environmental sustainability in a set of comprehensive indicators, which can facilitate the actions of the authorities involved. Those indicators should serve as a basis for the selection and scheduling of appropriate measures under different hydrology and socio-economic conditions. Although an analysis of this type can only be subjective and requires many assumptions for costs, benefits, ecological responses and environmental costs, the approach implemented in the presented DSS is simple enough and can easily be extended to other cases.

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