Optimization methods applied for sustainable management of water-scarce basins

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ABSTRACT

This paper aims to present the information-based technologies used for water management in a test basin within the scope of the EU-sponsored SMART and OPTIMA projects. The study uses a dynamic simulation model with its associated databases and a water resources planning and optimization system, established through a web-based client–server implementation to support distributed use and easy access for multi-criteria optimization and decision support. The results clearly illustrate how a consistent and well-integrated set of advanced but practical Decision Support System (DSS) tools can be used for efficient "optimal" water management strategies and policies of use, designed for a participatory public decision-making process.

Key words | decision support, dynamic simulation, information technology, multi-criteria optimization, scenarios, sustainable water management

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INTRODUCTION

River basins in most of the Eastern and Southern Mediterranean countries suffer from water scarcity due to rapid demographic and economic development, particularly in the coastal zone, urbanization, industrialization, tourism, and an often inefficient agricultural sector as the dominant water user. Low availability of renewable water, over-exploited groundwater, pollution, inefficient infrastructure, and pronounced seasonality with unfavorable demand patterns very different from the seasonal supply aggravate the situation.

The Gediz River Basin along the Aegean coast of Turkey is a typical case where two major problems, water scarcity and pollution, need to be addressed for sustainable management of its water resources. The basin covers about 18,000 km^2 and approaches a total population of 2 million. The case demonstrates the entire range of prototypical water management problems in the region, and their potential solutions. The existing water resources are under pressure by rapid industrial development, population growth, related increases in agricultural production, and pollution. To provide water for different sectors, to maintain the sustainable development of the region and to assess the long-term impacts of water policies, domestic, industrial, irrigational and environmental water demands should be evaluated in terms of existing trends and possible future tendencies in water use. The case also reflects the importance of the institutional and regulatory framework, and the need for direct participation of major actors and stakeholders in the planning and decision-making processes.

The case is studied within the scope of two EU INCO projects: SMART (Sustainable Management of Scarce Resources in the Coastal Zone) project supported by European Commission FP5 Programme and OPTIMA (Optimization for Sustainable Water Management) sponsored by EU FP6 Programme. The presented paper aims to present the information-based methods used in the basic approaches of SMART and OPTIMA, illustrating them in the case of the Gediz River Basin. Both projects employ an annual water budget simulation model called WaterWare (provided by Environmental Software Systems–ESS, Austria) to determine the performance of the existing river

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network system in terms of available water. The analysis is mainly based on comparison of alternative water management scenarios.

The paper further presents the current status of studies on water management in the Gediz River Basin, as elaborated within the scope of the OPTIMA project, where a simulation-based water resources planning and optimization system is developed and applied to address both quantity and quality, water demand and supply, surface and groundwater, water technologies and efficiency of use, allocation strategies, costs and benefits. A web based client–server implementation supports distributed use and easy access, and a participatory approach involving local stakeholders for multi-criteria optimization and decision support. The optimization uses heuristics and concepts of genetic algorithms, based on a realistic, detailed, dynamic and distributed representation of the river basin. The underlying dynamic (daily) simulation model describes the water resources systems at the basin scale, including the groundwater system for conjunctive use. The model covers the physiographic and hydrological elements, but also aims to represents the institutional and regulatory framework, and the socio-economic driving forces. The primary optimization identifies sets of non-dominated Pareto-optimal solutions in heavily constrained scenarios; these are the basis for an interactive discrete multi-criteria selection with the participation of end users. The multi-criteria approach covers global and sectoral demand and supply balances, reliability of supply, access, cost and benefits, including environmental and social aspects. Arbitrary penalty functions can be used for the valuation of violation of standards and missing targets, both shortfalls of supply as well as excess (flooding or pollution).

In the following sections, a brief introduction to the SMART and OPTIMA projects and their basic approach and tools are presented, followed by descriptions of the WaterWare analytical tool and the case study basin, i.e. the Gediz River Basin. In the SMART project, the topology of the Gediz Basin is introduced to the WRM, all required data compiled and model runs are performed. The study was then limited only to the analysis of the irrigation system with scenarios based on changes in crop pattern and irrigation technologies. Regarding the basic management problems in the basin, Gediz was again used as the case study area in OPTIMA to elaborate on the work initiated in SMART and, in particular, to arrive at optimal solutions for water resources management.

The current status of the case study presented includes the simulation model runs for two baseline scenarios relating to a wet and a dry year. The annual water budget for the scenarios is then elaborated with an economic assessment procedure to determine the economic parameters for the business-as-usual case. This initial phase of the optimization procedure comprises the statement of objectives, criteria and instruments for basin management. The next step focuses on the development of future scenarios based on the “instruments” or “water technologies” specified by Gediz stakeholders. Assessment of economic parameters for each scenario allows for the selection of the “optimum” management plan among a number of alternatives.

GENERAL DESCRIPTION OF SMART AND OPTIMA PROJECTS

SMART project

The SMART project, which was executed between 2002 and 2005, developed methods and tools for long-term policy analysis and strategic decision support for integrated coastal development with special emphasis on water resources and land use and the resource balance between the coastal region and inland areas (http://www.ess.co.at/SMART). The SMART approach is based on a multi-sectoral integration of quantitative and qualitative analyses, combining advanced tools of quantitative systems engineering, based on numerical simulation models. It comprises methods of environmental, socio-economic and policy impact assessment, using rule-based expert systems technology and interactive decision support methods. Water resources modeling, including both quantitative and qualitative aspects, has provided the framework for policy scenarios, exploring different development strategies, the consequences and implications of demographic, socio-economic and technological development, and the interaction of these driving forces towards long-term sustainability of the coastal regions and their hinterland.

Aiming to support a participatory approach to policy-making and impact assessment, the SMART approach also foresaw the extensive use of the Internet to facilitate broad participation and a shared information basis to empower the various actors and stakeholders in the decision-making process. The integration of advanced quantitative methods and models with qualitative assessment, aggregated into policy-relevant indicators of sustainable development, have added scientific rigor to the interactive and participatory political process. This has made it possible to focus the debate on policy issues, objectives and values, rather than on the underlying physical based data and information, describing better quantifiable constraints and dependences of the physical world.

Within the framework of SMART, a common methodology for policy design, evaluation and decision-making was developed and tested in a set of parallel case studies in each of the participating Mediterranean countries, and the results were compared with the corresponding EU policies. Lessons from the comparative analysis of these case studies helped to ensure a generic and generally applicable methodology, and at the same time help to foster inter-regional contacts and the exchange of experience.

OPTIMA project

The OPTIMA project is funded, in part, by the EU INCO-MPC Programme for a project period of 3 years between 2004 and 2007. The overall aim of OPTIMA is to develop, implement, test, critically evaluate and exploit an innovative, scientifically rigorous yet practical approach to water resources management intended to increase efficiencies and to reconcile conflicting demands. It essentially derives its basic approach in dynamic simulation and scenario development for decision-making from the SMART project and extends the methodology to cover multi-criteria optimization in basin management. Based on the European Water Framework Directive (2000/60/EC), the OPTIMA approach equally considers economic efficiency, environmental compatibility and social equity as the pillars of sustainable development (http://www.ess.co.at/OPTIMA).

The project also aims at building a wide dissemination network of expertise and knowledge exchange, sharing its findings, generic data and best practice examples. OPTIMA extends the classical optimization and mathematical programming methodology in several respects, by:

- Using a full-featured dynamic and distributed simulation model and genetic algorithm as the core to generate feasible and non-dominated alternatives. Water technology alternatives, including their cost structure, and up-to-date remote-sensing-derived land use information are the primary inputs.
- Extending the set of objectives, criteria and constraints through expert systems technology to include difficult-to-quantify environmental and social dimensions.
- Putting specific emphasis on local acceptance and implementation through the inclusion of stakeholders in an interactive, participatory decision-making process, carefully embedded in institutional structures, using a discrete multi-criteria reference point methodology.
- Comparative evaluation and benchmarking across the set of local and regional case studies in 7 locations, namely Cyprus, Turkey, Lebanon, Jordan, Palestine/Israel, Tunisia and Morocco.

Within the above general framework, OPTIMA foresees a number of specific scientific and technological objectives:

- To build and test, in a number of parallel comparative case studies, a consistent and well-integrated set of advanced but practical Decision Support System (DSS) tools for efficient "optimal" water management strategies and policies of use, designed for a participatory public decision-making process.
- To extend the classical techno-economic approach by explicit consideration and inclusion in the two-phase optimization methodology of acceptance and implementation criteria, where the method not only helps to generate optimal solutions, but facilitates the process of agreeing on what exactly "optimal" means in any particular case;
- To develop a generic approach to combine engineering analysis and formal optimization with socio-economic considerations in a unifying and consistent multi-criteria multi-objective framework.
- To integrate expert systems technology and heuristics with complex simulation and optimization models to improve their usability in data-poor and data-constrained application situations.

- To develop appropriate tools and methods for the communication of complex technical information to a broad range of stakeholders in the policy-making process, based on classical workshops and Internet technology, and in particular, the easy and efficient elicitation of preferences and trade-offs in an interactive, reference point approach.
- To adapt and further develop formal methods of optimization for highly complex, non-linear, dynamic and spatially distributed systems that are non-differentiable by applying heuristics, genetic algorithms combined with local stochastic gradient methods and post-optimal analysis for large scale discrete multi-criteria problems.

The starting point for the project is, on the one hand, the obvious water scarcity and constraint to development experienced in the Mediterranean countries. Recognizing the severity of this limitation to sustainable development, the objective is to build efficient yet appropriate tools for optimal and generally acceptable solutions that exploit all factors likely to reduce pressure on water resources and to avoid irreversible damage within the local socio-political and institutional systems. On the other hand, and despite the progress made over the last two decades, classical optimization methods, when applied to complex, non-linear, dynamic, spatially distributed systems and models, face serious limitations in that effective optimization usually involves considerable simplifications. At the same time, optimization is usually performed, considering one or very few dimensions, usually water and economic efficiency, and fails to take economic, technological, environmental and social considerations into account simultaneously. Furthermore, the complexity of the classical mathematical programming methodologies makes it difficult to involve actors and stakeholders directly and interactively, so that the actual acceptance and implementation of what is designed as optimal but with insufficient participation by stakeholders often fails.

OPTIMA addresses all these shortcomings and restrictions with a novel, multi-step and iterative approach to optimization that extends classical approaches by:

- Deriving preference structures, water issues, criteria, objectives and constraints in an interactive process with active participation with stakeholders and major actors.
- Basing the first step of optimization on the full detail and resolution of a dynamic water resources simulation model embedded in a programming framework, made possible by the exploitation of more and more powerful yet affordable computer hardware.
- Extending the set of dimensions considered in the optimization by socio-economic and environmental objectives, criteria and constraints into a comprehensive multi-criteria representation.
- By adding a second, participatory and interactive phase that defines the trade-offs to select an optimal solution from the set of feasible, non-dominated alternatives generated in the first step by a discrete, multi-criteria reference point methodology that facilitates finding trade-offs and compromise solutions and thus defines the concept of optimality for broad acceptance.

ANALYTICAL TOOLS OF SMART AND OPTIMA

General features

SMART builds on a number of interactive tools and models for natural resources analysis. These tools are applied in five parallel case studies of partner countries, simulating that *status quo* as well as selected scenarios of future development. The basic analytical tool is the WaterWare system, a river basin scale water resources management information and decision support system. WaterWare describes a dynamic water budget for a given catchment in terms of water demand and supply, allocation policies, efficiency of use, water quality and the economics of demand and supply. The main elements, which are operational in a web environment accessible with a standard web browser and the associated online manual, include the Land Use Change Model (LUC), the Rainfall–Runoff Model (RRM) and its automatic calibration tool (RRMCAL), and the Water Resources Model (WRM) (http://www.ess.co.at/SMART).

The SMART project has provided the smooth integration of advanced quantitative tools based on applied systems analysis and information technology, such as the state-of-the art simulation and optimization models and expert systems technology, into the socio-political and economic framework of regional development planning and public policy with its uncertainties, qualitative criteria and conflicting objectives.

For the modeling approach in OPTIMA, one possible solution to represent complexity at different scales is to build sets or cascades on linked models, rather than using one model to encompass all representations, and to switch from a classical optimization paradigm that minimizes or maximizes an objective function to a concept of satisfying (Fedra & Harmancioglu, 2005), i.e. finding one or more feasible solutions for a set of interactively defined, and increasingly tightened, constraints. The interactive involvement of stakeholders requires easy access to tools that may need substantial computing power: a web-based solution can offer a powerful set of servers organized in a cluster to end users that only need a standard PC and web browser.

In OPTIMA, a set of linked models is used for the simulation and optimization of water resources management problems:

- A sub-basin scale dynamic rainfall–runoff model that feeds the water resources model with flow inputs for ungaged basins, primarily reacting to changes in land use.
- An irrigation water demand model, estimating supplementary irrigation water demand, driven by crop patterns and irrigation technology.
- System operating on a topological network of nodes and reaches and linked to aquifers for conjunctive use scenarios (Fedra, 2002; Fedra & Harmancioglu, 2005; http://www.ess.co.at/WATERWARE).
- A dynamic basin-wide water quality model for DO/BOD and conservative or first-order decaying pollutants, linked to the water resources model, using its flow results as inputs.

The models of OPTIMA are linked to databases that describe a river basin in terms of GIS layers, monitoring time series of climatic and hydrometeorological data, and the main components of the water resources system like major demand nodes, configured in a topological network. Linkage between the models is by means of time series of flow or water demand that summarize the output from one model as boundary conditions and dynamic inputs for another. The data and related analysis tools are accessible through the Internet to facilitate the dissemination of project results, but also to make it easier for the various actors and stakeholders in each of the regional cases to share a common information basis.

Water resources modeling

Basic features

The central model of both SMART and OPTIMA projects is a dynamic, basin-wide water resources model (WRM), which is one of the core components of the WaterWare system that is compliant with the EU Water Framework Directive 2000/60/EC (Fedra & Jamieson 1996; Jamieson & Fedra 1996; Fedra 2002, 2004*a*, *b*). It describes the water flow and availability, demand and supply balance on a daily basis across the basin and its elements, based on conservation and continuity laws.

WRM uses a topological network representation of a river basin, which consists of various node types and the river reaches and canals connecting them (ESS 2006*a*). Nodes represent objects such as sub-catchments, reservoirs, wells, diversions and confluences, and areas of water demand, such as cities, tourist resorts, irrigation districts and large industries. The surface water network can be coupled to one or more aquifers to represent conjunctive use scenarios. Control nodes keep track of flows versus targets or constraints and can represent both minimum flow requirements and environmental water demands, such as for the nourishment of wetlands, as well as flooding conditions with arbitrary penalty functions.

The basic model paradigm is dynamic mass budget simulation as a straightforward implementation of the conservation laws of classical physics. As part of the mass budget approach, the model calculates a cumulative mass budget error over all nodes and time steps – the mass budget error results from the simplified river channel routing, and the mixed use of difference and differential equation and their numerical integration, respectively.

Basic outputs of the water resources model

The model operates on a daily time step; its primary state variables are the content and flow of water between the different elements. Performance of the system is expressed in terms of criteria and indicators (any one of which can be used in the optimization) such as:

- **Overall water budget**, balancing all inputs, losses, uses, outflows including export and inter-basin transfer, and change in storage including reservoirs and the groundwater system; additional information relates to the storage/extraction relationships and thus the sustainability of the overall system in a long-term perspective.

- **Technical efficiency** of the system: this describes the ratio of useful demand satisfied to the losses through evaporation from reservoirs and seepage losses through the various conveyance systems.
- **Supply/demand ratio**, globally, for any and all individual demand nodes, or any functional/sectoral grouping; this also includes any environmental water demands, low flow constraints, wetland nourishing, etc.
- **Reliability of supply**, measured at any or all demand nodes and control nodes that compare the water available with user-defined needs/expectations as constraints.
- **Development potential**, which relates the unallocated water summed over all demand points to the total input: this, in principle, defines the amount of water that is available for further exploitation.
- **Costs and benefits**, derived from useful demand satisfied and the added value derived, versus the costs of shortfalls (again at any or all nodes), as well as the costs of supplying the water in terms of investment (annualized) and operating and maintenance costs of structures and institutions.
- **Groundwater sustainability**, which describes the ratio of content to the net withdrawal (balance of recharge, summed over natural and artificial) and evaporative and deep percolation losses, measured in years of reserves at current exploitation levels (ESS 2006a).

Structure of the water resources model

In order to simulate the behavior of a river basin over time, the river basin is described as a system of nodes and arcs. These nodes represent the different components of a river system (i.e. diversions, irrigation areas, reservoirs, etc.) and can indicate points of water inflow to the basin, storage facilities, control structures and demand for specific uses. The nodes are connected by arcs which represent natural or man-made channels which carry flow through the river system (http://www.ess.co.at/MANUALS/WATERWARE/wrmmodel.html). The WRM incorporates a number of river basin features (objects) which are represented by different node types explained as follows:

1. **Start** node provides the input flow at the beginning of a water course (main river or a tributary) considered explicitly in the model; this could represent a spring, an upstream catchment, a major input of groundwater to the surface water system, an inter-basin transfer, or a desalination plant.
2. **Confluence** nodes provide for the joining of several reaches that could represent natural tributaries or man-made conveyance channels.
3. **Diversion** nodes represent branching of flow to several channels; it is characterized by more than one outflow and rules to distribute the flow. Abstractions to demand nodes may be described by diversions.
4. **Demand** nodes describe the consumptive use of water. They include irrigation, municipal and industrial nodes to represent water demands for irrigation, domestic and industrial uses, respectively. Each of them can either be situated on the main water course, describing their net consumption, or at an abstraction from the main water course; the latter configuration allows for the explicit treatment of return flows or wastewater.
5. **Reservoir** nodes represent natural or controlled storage systems with a set of rules that prescribe outflow from the reservoir as a function of time, its inflow and storage.
6. **Control** nodes that do not change the flow but impose an in-stream flow demand (for allocation and performance accounting purposes), e.g. for environmental purposes.
7. **Auxiliary** or geometry nodes that again do not affect the flow directly, but are used to start a new reach or serve as a place holder to provide a network structure consistent with other models.
8. **Terminal** nodes represent outlets from the basin considered in the model, including outflow to the sea or inflow to lakes.

Nodes are connected by reaches. Water is routed along these reaches considering their length, slope and channel characteristics, including cross sections and roughness. Along a reach, lateral inflows or outflows (exfiltration) represent very small tributaries not treated explicitly and interactions with the groundwater. Each reach has its own local catchment area that provides the potential linkage to spatially distributed water budget models (http://www.ess.co.at/MANUALS/ WATERWARE/wrmmodel.html).

Water resources model dynamics

The model operates on a daily time step to represent the dynamics of water demand and supply, reservoir operations and the routing through the channel system. This daily time step can be aggregated, for output and reporting purposes, to a weekly, monthly and annual scale. Inputs at the individual nodes can again be specified at daily, weekly, or monthly resolution; different methods then construct a daily input data set from these more aggregate values.

Start node. This node provides the input flow to the simulation model, which represents the natural flows and the intervening flows (lateral inflow and subsurface base flow). The flow is represented in the following form:

$$Q_j = \beta I_j + QI_j \tag{1}$$

where

Q_j: outflow from start node in day j [m^3/d]

I_j: inflow at a start node in day j [m^3/d]

QI_j: input flow to a start node in day j [m^3/d]

β: is zero in the case where the start node represents a head water source.

Confluence node. This node provides for the joining of natural tributaries or man-made conveyance channels. The equation governing the flow at a confluence node is

$$Q_j = \sum_{i=1}^{n} I_j^i, \tag{2}$$

where

$Q\ _j$: outflow from a confluence node in day j [m^3/d]

I_j^i: ith channel inflow to a confluence node in day j [m^3/d].

Diversion node. This node represents diversions of flow to other nodes in the system or to other tributaries. The diversion rule is such that a minimum downstream release is given priority. The operation rule is described as follows:

$$\begin{array}{lll} Q_j{=}I_j, & AD_j{=}0 & \text{when} I_j{<}DWT_j, \\ Q_j{=}DWT_j, & AD_j{=}I_j{-}DWT_j & \text{when} DWT_j{\le}I_j{\le}DWT_j{+}TD_j, \\ Q_j{=}I_j{-}TD_j, & AD_j{=}TD_j & \text{when} I_j{>}DWT_j{+}TD_j, \end{array} \tag{3}$$

where

Q_j: actual downstream flow from a bifurcation node in day j [m^3/d]

I_j: inflow to a bifurcation node in day j [m^3/d]

AD_j: actual diversion flow in day j [m^3/d]

DWT: downstream target flow in day j [m^3/d]

TD_j: diversion target flow in day j [m^3/d].

Irrigation node. This node represents diversions of flow to the irrigation area:

$$\begin{array}{ll} AD_j = 0 & \text{when}\, I_j \le DWT_j, \\ AD_j = I_j - DWT_j & \text{when}\, DWT_j \le I_j \le TD_j + DWT_j, \\ AD_j = TD_j & \text{when}\, I_j > TD_j + DWT_j, \end{array} \tag{4}$$

where

I_j: inflow to an irrigation node in day j [m^3/d]

DWT_j: minimum downstream flow target in day j [m^3/d]

AD_j: actual diversion flow in day j [m^3/d]

TD_j: diversion target flow in day j [m^3/d].

The flow that actually reaches to the irrigation area is

$$IR_j = (1 - \varepsilon)AD_j. \tag{5}$$

where ϵ is the conveyance loss coefficient. On the other hand, the flow that is percolated to the groundwater is calculated as:

$$GW_j = (1 - k)R_j. \tag{6}$$

where k is the percolation loss coefficient. The outflow from the irrigation node is

$$\begin{array}{l} Q_j = [I_j - AD_j] + \varepsilon AD_j + \beta k R_j, \\ \quad R_j = (1 - c_u)[IR_j + P_j], \end{array} \tag{7}$$

where

R_j: amount of flow available after consumptive use by the crop

GW_j: flow percolated to groundwater

k: river return flow coefficient

β: flag for different cases of irrigation, $\beta = 1$ in implicit, $\beta = 0$ in explicit.

Municipal and industrial water supply node. The municipal and industrial water supply Nodes (MI) represent water demands for industry and other purposes. The allocation rule for diverting water to the MI node is described by the following equations:

$$\begin{aligned} AD_j &= 0 && \text{when } I_j \le DWT_j, \\ AD_j &= I_j - DWT && \text{when } DWT_j \le I_j \le TD_j + DWT_j, \\ AD_j &= TD_j && \text{when } I_j > TD_j + DWT_j, \end{aligned} \tag{8}$$

where

I_j: inflow to a MI node in day j [m^3/d]

AD_j: actual diversion flow in day j [m^3/d]

DWT_j: minimum downstream flow target in day j [m^3/d]

TD_j: diversion target flow in day j [m^3/d].

The downstream flow Q_j from the MI node is described by the equation:

$$\begin{aligned} Q_j &= [I_j - AD_j] + \varepsilon AD_j + R_j, \\ R_j &= (1 - c_u) AD_j, \end{aligned} \tag{9}$$

where

R_j: return flow to the river available

c_u: consumptive use coefficient.

Storage reservoir nodes. The operating policy of a reservoir used in WRM is the "Standard Operating Policy" (Fiering 1967). It is described by the following equations:

$$\begin{aligned} W_j &= S_j + I_j + P_j - EV_j, \\ P_j &= \alpha pr_j RA_j, \\ EV_j &= \alpha ev_j RA_j, \end{aligned} \tag{10}$$

The release policy is divided into three separate cases:

$$\begin{aligned} Q_j &= W_j && \text{when } W_j \le TR_j, \\ Q_j &= TR_j && \text{when } TR_j < W_j \le TR_j + V_j, \\ Q_j &= W_j - V_j && \text{when } W_j > TR_j + V_j, \end{aligned} \tag{11}$$

Similarly, the storage available in the reservoir at the beginning of day $(j+1)$ corresponds to the three cases as follows:

$$\begin{aligned} S_{j+1} &= 0 && \text{when } S_j + I_j \le TR_j, \\ S_{j+1} &= W_j - TR_j && \text{when } \mathrm{TR_j} < W_j \le TR_j + V_j, \\ S_{j+1} &= V_j && \text{when } W_j > TR_j + V_j, \end{aligned} \tag{12}$$

where

$$V_j = SMAX_j - SMIN_j.$$

The following notations are used:

I_j: inflow to reservoir in day j [m^3/d]

Q_j: reservoir reservoir in day j [m^3/d]

W_j: available water in day j [m^3]

S_j: reservoir storage at the beginning of day j [m^3]

$SMIN_j$: reservoir minimum storage [m^3]

$SMAX_j$: reservoir maximum storage [m^3]

V_j: reservoir storage capacity [m^3]

TR_j: target reservoir release in day j [m^3/d]

P_j: total reservoir area precipitation in day j [m^3/d]

EV_j: reservoir evaporation in day j [m^3/d]

pr_j: daily precipitation coefficient [mm/d]

ev_j: daily evaporation coefficient [mm/d]

RA_j: reservoir surface area at the beginning of day j [ha], is a function of the storage $RA_j = \xi\,[\mathrm{S_j}]$,

α: unit conversion coefficient.

Storage routing in tributaries. The Muskingum flood routing method is applied in WRM. In this method, the conditions relating inflows into, and outflows from, a river reach to the water stored within the reach are described by the continuity equation and an empirical linear storage equation:

$$\frac{\mathrm{d}s}{\mathrm{d}t} = I - Q, \tag{13}$$

where

I: rate of inflow [m^3/d]

Q: rate of outflow [m^3/d]

K: storage coefficient [d], approximates the time of travel of the wave through the reach, with

$$S = K[\sigma I + (1 - \sigma) Q], \quad Q_{j+1} = C_1 I_j + C_2 I_{j+1} + C_3 Q_j, \tag{14}$$

σ: weighting factor, in natural channels usually varies between 0.1–0.3, specifying the relative importance of the inflow and outflow in determining storage.

Scenario development

As noted above, the dynamic daily water budget is summarized in terms of supply/demand ratios, globally and by economic sector or administrative unit; reliability of supply; and the set of violations of any of the constraints defined for the control nodes. Economic valuation (expressed as net present values or annualized costs considering investments, operating costs, and project or technology lifetimes) includes estimates of the costs of various alternative water technologies (from non-conventional supply options like desalination, water harvesting, recycling and re-use to new or bigger reservoirs, lining irrigation canals and more efficient irrigation technologies to water saving showers) versus the benefits generated by supplying water for useful demands (Fedra & Harmancioglu 2005).

Different allocation scenarios and also the use of different water technologies lead to different cost–benefit ratios for the system. From the set of results generated, any number of constraints can be derived for the optimization, both global criteria aggregated over all nodes and a yearly simulation run such as overall reliability of water supply, as well as node- and location-specific constraints defined as minimum or maximal flow (or supply) expectations, again with different temporal resolution and aggregation.

The optimization approach of OPTIMA

Basic features

The optimization approach is conceptually simple, and the full complexity of the simulation models is used to retain the distributed, non-linear and dynamic features of the problem. The optimization is split into two steps: in the first step, a set of feasible, non-dominated solutions are applied, using a large, inclusive set of criteria and options expressed as combinations of decision variables. The decision variables can represent structural changes, alternative allocation rules, different efficiencies through alternative technologies and changes in demand patterns. Alternatives are generated by a Monte Carlo approach embedded in a heurist driving framework that uses concepts of genetic algorithm, including the "re-combination" of parameter sets of successful trial runs (Fedra & Harmancioglu 2005). The set of alternatives is tagged with their expected effects in terms of selected performance criteria, so that after a failure, violating one or more constraints, one can select alternative values for the decision variables using these heuristics. Once a solution that meets the constraints is found, its local neighborhood in parameter or decision space is explored, using a stochastic hill climbing method. Populations of feasible solutions are developed around major structural alternatives, which are then used as the starting points for the next round of generating alternatives with modified constraints.

Next, a discrete multi-criteria methodology is used to identify the optimal solution, given a reference point in performance space (Fedra & Harmancioglu 2005). The default reference point is utopia, and the performance space for all criteria is normalized as a degree of achievement in the interval between nadir and utopia. The last step of defining reference points is done interactively with the actors and stakeholders or their proxies involved: criteria can be excluded or included (which leads to different sets of non-dominated alternatives), constraints moved and different reference points defined to immediately see the consequences of each preference structure, expressed in natural units for all constraints, and learn about trade-offs and possible solutions.

Objectives, criteria and constraints

The optimization problem is formulated, in general, for meeting as many targets as possible, and minimizing costs or maximizing a benefit/cost ratio. Targets can be defined for each diversion node, each demand node, reservoirs and an arbitrary set of control nodes along the reaches. The system records any deviations from these targets, i.e. flows above or below the pre-specified value. From that, a given scenario run can be characterized in terms of its overall supply/demand ratio, the sectoral values for agriculture, industry and domestic demand; reliability of supply, which describes the percentage of all shortfalls, and overall efficiency, which measures the demands satisfied versus all losses. Other criteria used are flooding conditions when prescribed maximal flows are exceeded at given control nodes. In addition, users can define arbitrary non-linear penalty functions for deviations from a target, non-linear both in parameter space and time: consecutive shortfalls of supply may be more serious than the same mass budget deficit distributed over time.

Estimates of costs are based on the investment and operating costs of alternative structural measures and water technologies. For each type of node, a set of alternatives can be defined which affect the water flow, production, storage characteristics, losses or efficiency of use, and water quality, respectively. Basic elements are new or larger reservoirs, water saving technologies, alternative irrigation technology or wastewater treatment plants. Basic results revolve around the re-allocation of water for irrigation to other uses, made possible through the implementation of alternative water saving irrigation technology, as well as reduction of losses, e.g. by lining of canals. Combined with more efficient use of water throughout the system, including re-use and recycling, the potential for water savings is considerable. The effectiveness of such solutions, however, depends on the existence of an appropriate regulatory framework and exchange mechanisms, i.e. a water market, and the appropriate economic incentives. Since this implies institutional and behavioral changes, the direct involvement of major actors and stakeholders in the water sector to arrive at what must ultimately be a political solution and consensus is essential (Fedra & Harmancioglu 2005).

Discrete multi-criteria optimization

The basic logic of a discrete (multi-criteria) decision support approach is simple: a set of possible alternatives for the systems behavior is generated (by various modeling techniques), each representing an alternative control or management strategy leading to a corresponding performance of the system. This performance is described in terms of criteria that can be evaluated and compared (explicit or implicit trade-offs) to arrive at a final preference ranking of the alternatives and an eventual choice of a preferred alternative as the solution of the decision process. This set of alternatives to choose from can be generated within a single, or several alternative sets of scenarios of assumptions on uncontrollable external variables. However, it is important to remember that these assumptions on uncontrollable external factors are not subject to choice and thus the decision-making process (ESS 2006*b*).

The first phase of the optimization process is based on a complex water resources simulation model, WRM, which can generate one or more feasible solutions. If there is more than one feasible solution, a second selection process has to be used to identify a preferred solution from the set of feasible alternatives with multiple criteria. This is a classical discrete multi-criteria decision problem (Bell *et al.* 1977).

A decision involves the choice between alternatives $A_{1,}$ …, A_n. These are described by a set of attributes $X_1, \dots,$ $X_j, \dots, X_n$ and each alternative A_i can be described in terms of these attributes or criteria. Thus, the choice or alternative A_i can be described with the attribute vector $X_i = (x_{i1}, \dots,$ $x_{ij}, \dots, x_{in})$. The attribute set X is not given *a priori*. Its selection and definition is one of the most critical steps in the decision-making process. It can easily be demonstrated that adding or deleting criteria from consideration is a very powerful way to influence decisions. Once the vector is defined, the task is to measure the distance, in some sense, of each alternative (a point in this criteria hyperspace) to the decision-maker's expectations or aspirations – this involves the problem of scaling incommensurate dimensions (Bell *et al.* 1977; ESS 2006*b*).

Since each scenario is described by more than one performance variable or criterion, the direct comparison does not necessarily result in a clear ranking structure: improvements in some criteria may be offset by deterioration in others (ESS 2006b). This can only be resolved through the introduction of a preference structure that defines the trade-offs between objectives.

The basic optimization problem can be formulated as

$$\min F(x), \quad x \in X_0 \tag{15}$$

where

$$x = (x_1, x_2, \dots, x_n); \quad x \in R^n$$

is the vector of decision variables (the scenario parameters) and

$$f(x) = (f_1(x), f_2(x), \dots, f_p(x)) \in R^p$$

defines the objective function. X_0 defines the set of feasible alternatives that satisfy the constraints

$$X_0 = x \in R^n \in \|h_1(x) \in 0, \dots, h_k(x) \in 0.$$

In the case of numerous scenarios with multiple criteria, one can define the partial ordering

$$f(x_1) \leq f(x_2) : \leftrightarrow f_i(x_1) \leq fi(x_2)$$

$$\forall_i = 1, 2, \dots, pf(x_1), f(x_2) \in R^p$$

where at least one of the inequalities is strict. A solution for the overall problem is a Pareto-optimal solution:

$$f(\hat{x})\epsilon R_p \leftrightarrow \exists f(\hat{x}) \neq f(\hat{x}) \leq f(\text{and}\, x \in X_0)$$

As a generic decision support tool, a discrete multi-criteria approach is to be implemented to find an efficient strategy (scenario) that satisfies all the actors and stakeholders involved in the water resources management decision processes. The preferences of decision-makers can conveniently be defined in terms of a reference point that indicates one (arbitrary but preferred) location in the solution space. Normalizing the solution space in terms of achievement or degree of satisfying each of the criteria between nadir and utopia allows one to find the nearest available Pareto solution efficiently by a simple distance calculation (ESS 2006*b*).

In the optimization case, there are implicit trade-offs between the objectives, expressed in terms of the criteria implied. In the case of expressing aspiration as a set of constraints, the procedure is simple, intuitively understandable and lends itself well to a participatory approach: (a) an initial set of reasonable constraint values are defined in the natural units of the criteria which makes the procedure easy to understand; (b) a solution or a set of solutions that meets the criteria is “found” in the set of available alternatives or generated, for example, by simulation modeling. If the set is empty, the constraints are relaxed – the sequence and degree of relaxation are a reflection of the decision-maker’s preferences, but at the same time, a negotiation process between several decision-makers with conflicting objectives is needed. If the set includes more than one solution, the constraints can be tightened in the same interactive and iterative procedure as above, but in the opposite direction. Finally the procedure ends whenever the decision-makers are satisfied (ESS 2006*b*).

CASE STUDY

Gediz River Basin in Turkey

The Turkish case study of both SMART and OPTIMA focuses on the Gediz River Basin along the Aegean coast (Figure 1), where water scarcity is a significant problem. Water shortage is due basically to competition for water among various uses (water allocation problems), mainly irrigation with a total command area of 110 000 ha versus the domestic and fast growing industrial demand in the coastal zone, and environmental pollution although the basin experiences droughts from time to time. The basin encompasses an extensive irrigation system, as shown in Figure 2, which is the major consumer of surface waters.

Current analyses on the hydrologic budget of the basin indicate that the overall supply of water for various uses is approximately equal to the overall demand. In practice, this means that there is no reserve for further water allocation in Gediz. Thus, water allocation is a major problem, which has to be optimized among various competing water uses under environmental as well as institutional, legal, social and economic constraints (Svendsen *et al.* 2005).

The basin experienced periods of significant droughts in the past, the most severe one to occur being between the

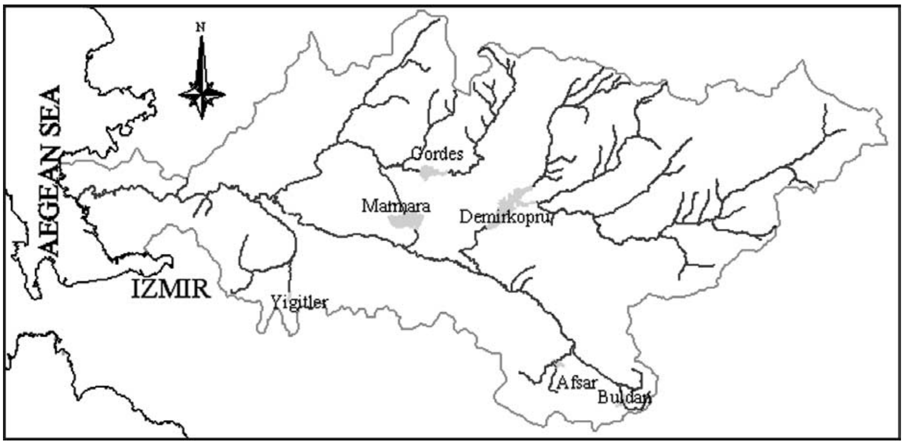
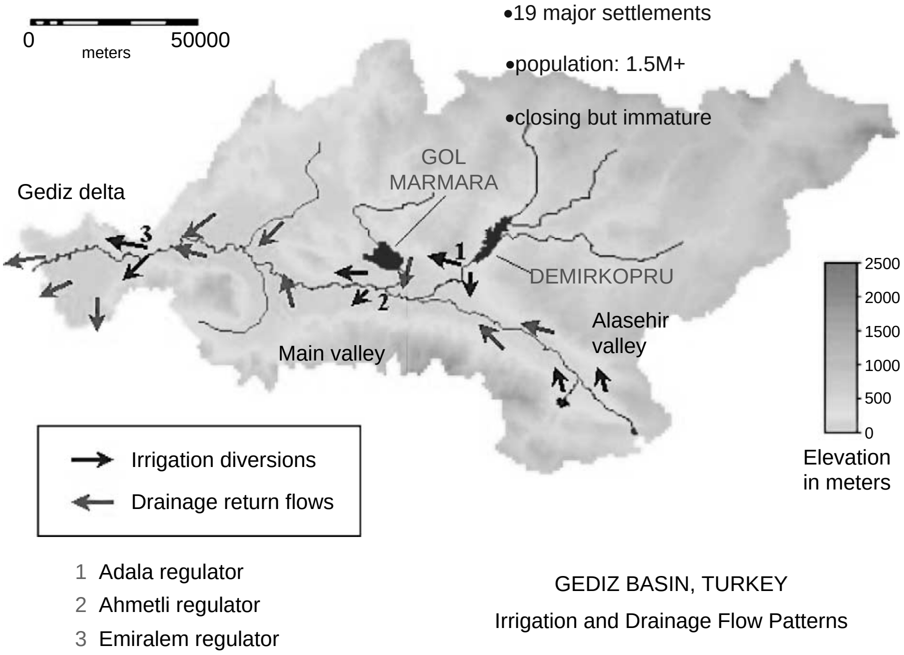


Figure 1 | The location of the Gediz River Basin in Turkey.

Q1



Q1

Figure 2 | The layout of the Gediz River Basin in Turkey.

years 1989 and 1995. Before the drought, there was little competition for water, and the established mechanism for allocating water to different users through a set of bilateral agreements worked well. When the drought struck, irrigation issues in the peak summer season were reduced sharply, return flows diminished and, as a consequence, water quality in the lower third of the basin deteriorated.

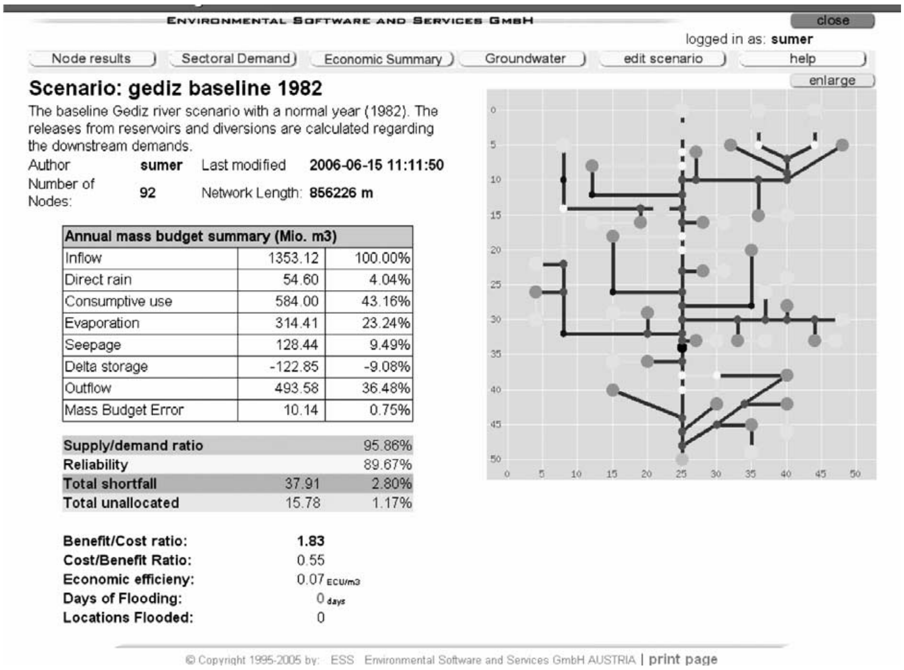
There is a close interaction between these issues as the inland practices of water and land management led to coastal problems in the Bay of the city of Izmir, which neighbors and consumes a significant portion of the Gediz Basin water resources. Thus, the region as a whole requires analysis into sustainable management of natural resources from various perspectives. The case study involves the problems of water shortage, competing uses and high levels of pollution that are typical for the coastal zone and its rapid economic development. An optimization approach is required to solve problems of water shortage and competing uses of natural resources under physical, institutional, legal, social and economic constraints.

Modeling studies

WaterWare (WRM) of both SMART and OPTIMA is used to identify the basin as a system operating on a topological network of nodes and reaches. Figure 3 shows the network representation within WRM for the Gediz Basin. WRM simulates the river system on a daily basis; hence, daily hydrometeorological data within a certain year are compiled for the Gediz River Basin on the basis of its topological features. Data on inflows, precipitation, temperature and dynamic demand series are compiled to satisfy the data needs of WaterWare. In addition, some physical features and characteristics of reservoirs, reaches and aquifers are considered in the data compilation process.

In the current topology of the basin, the main upstream subcatchments shown in Figure 2, like Gordes, Medar, upstream Demirkopru and Nif, are identified as "start nodes". The three main reservoirs; Demirkopru, Afsar and Buldan, which feed the downstream irrigation districts, are defined as supply nodes. Although there are many irrigation schemes of varying sizes in the basin, only the largest and the most important ones, which consume almost 96% of available irrigation water, are taken into account, together with their conveyance and drainage systems, canals and weirs. At the downstream part of the system, the wetland called "Bird Paradise" is also identified as a demand node.

In Figure 4, the two ongoing reservoir projects (Gordes and Yigitler dams), which will be operational by 2025, are added to



Scenario: gediz baseline 1982

The baseline Gediz river scenario with a normal year (1982). The releases from reservoirs and diversions are calculated regarding the downstream demands.

Author	**sumer**	Last modified	**2006-06-15 11:11:50**
Number of Nodes:	**92**	Network Length:	**856226 m**

Annual mass budget summary (Mio. m3)		
Inflow	1353.12	100.00%
Direct rain	54.60	4.04%
Consumptive use	584.00	43.16%
Evaporation	314.41	23.24%
Seepage	128.44	9.49%
Delta storage	-122.85	-9.08%
Outflow	493.58	36.48%
Mass Budget Error	10.14	0.75%

Supply/demand ratio		95.86%
Reliability		89.67%
Total shortfall	37.91	2.80%
Total unallocated	15.78	1.17%

Benefit/Cost ratio:	**1.83**
Cost/Benefit Ratio:	0.55
Economic efficieny:	0.07 ECU/m3
Days of Flooding:	0 days
Locations Flooded:	0

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Figure 3 | Gediz River network representation in WaterWare.

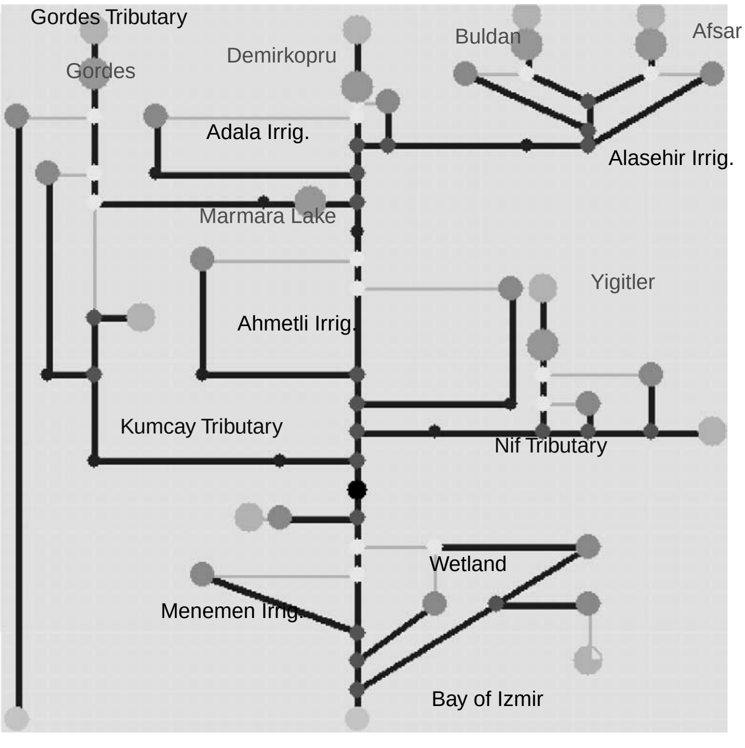


Figure 4 | Representation of the future topology of Gediz River system in the WaterWare model.

the topology. The Gordes Dam transfers domestic water to Izmir, which is represented by a demand node; and its return flow is diverted to an "end node". The Yigitler Dam on the Nif tributary is connected to the Kemalpasa industrial zone. In the current studies presented in this paper, these two projects are not taken into account in WRM for development of future scenarios.

The above model is linked to the Gediz database that describes the river basin in terms of GIS layers, monitoring time series of climatic and hydrometeorological data, and the main components of the water resources system like major demand nodes (e.g. settlements) which are configured in the topological network of Figure 3. The WRM model is run for two typical years: 1982, which is a wet year with above-average flow conditions, and 1991, which represents a typical dry year. These two specific years are selected as various types of basin data are complete only for these periods.

In the SMART project, the above topology of the Gediz Basin is introduced into the WRM, all required data compiled and model runs are performed. The study was then limited only to the analysis of the irrigation system, with scenarios based on changes in crop pattern and irrigation technologies. Regarding the basic management problems in the basin, Gediz was again used as the case study area in OPTIMA to elaborate on the work initiated in SMART and, in particular, to arrive at optimal solutions for water resources management.

As noted previously, the dynamic daily water budget is summarized in terms of supply/demand ratios, globally and by economic sector or administrative unit; reliability of supply; and the set of violations of any of the constraints defined for the control nodes. Accordingly, the initial step of the optimization procedure is to identify the criteria, objectives and constraints for management of the case basin. These factors essentially relate to the preferences and priorities of basin stakeholders; thus, a stakeholder workshop was held to specify the inputs to the optimization process. The workshop has identified two major problems within the basin: water pollution and over-exploitation of water resources. As the water quality component of the OPTIMA modeling system is still being developed and revised, the current studies presented in this paper relate mainly to water scarcity problems.

Gediz Basin stakeholders have identified, in global terms, the expected supply/demand ratio as 1.13, reliability of supply as 86% and the benefit/cost ratio as 1.25. Similar figures have also been specified by each economic sector, such as agriculture, industry, tourism, commerce, households and services. Furthermore, the stakeholders have specified constraints and instruments for remediation of the major problem of water scarcity. The majority agreed on rehabilitation of the existing irrigation system and the use of more efficient irrigation technologies as the initial activities to be undertaken towards optimization of basin management.

In respect of the basin management objectives, criteria, constraints and instruments specified by the stakeholders, an economic assessment of two baseline scenarios, i.e. those for the years 1982 and 1991, is realized. Here, economic valuation is expressed as annualized costs, considering investments, maintenance and operational costs, and project or technology lifetimes. It includes estimates of the cost of various alternative water technologies versus the benefits generated by supplying water for useful demands. Different allocation scenarios, and also the use of different water technologies, lead to different cost–benefit ratios for the system.

Tables 1 and 2 summarize the general economic assessment of 1982 and 1991 baseline scenarios. The top portions of the tables reflect the results of the WRM model runs which provide a general summary of the annual mass budget for the years selected. The second half of each table summarizes the global criteria, where "total shortfall" describes restrictions on supply and "total unallocated" refers to the amount of water that is not allocated to any use. The optimization procedure uses two indicators for economic efficiency: (a) direct economic efficiency, which is defined, in Euros/cubic meters of water, as the net direct benefit divided by total supply to demand nodes; (b) combined economic efficiency, which is defined, in Euros/cubic meters of water, as the net benefit divided by total water input (inflow plus effective rain). Reliability refers to the total number of days within a year where the difference between supply and demand is equal to or greater than demand, divided by the total number of days within a year where demand exists (i.e. 365 days).

In terms of water scarcity, it is apparent from the tables that, for a dry year, when restrictions on water supplied amount to over 50%, the benefit/cost ratio falls below 1. Yet, the global reliability levels for the two years are approximately the same, as municipal and industrial water demands are satisfied with 100% reliability, using groundwater. However, reliability is decreased for irrigation water supply in 1991 since this sectoral water demand is met by

Table 1 | General results of the 1982 baseline management scenario for the Gediz Basin

Annual mass budget summary	(Mio. m^3)	Percentage (%)
Inflow	1,353.12	100.00
Direct rain	54.60	4.04
Consumptive use	584.00	43.16
Evaporation	314.41	23.24
Seepage	128.44	9.49
Delta storage	− 122.85	− 9.08
Outflow	493.58	36.48
Mass budget error	10.14	0.75
Global criteria		
Supply/demand ratio		95.86
Reliability		89.67
Total shortfall	37.91	2.80
Total unallocated	15.78	1.17
Benefit/cost ratio	1.83	
Cost/benefit ratio	0.05	
Economic efficiency	0.07	€/m^3

Table 2 | General results of the 1991 baseline management scenario for the Gediz Basin

Annual mass budget summary	(Mio. m^3)	Percentage (%)
Inflow	563.10	100.00
Direct rain	54.55	9.69
Consumptive use	332.99	59.13
Evaporation	144.84	25.72
Seepage	63.67	11.31
Delta storage	− 82.71	− 14.69
Outflow	157.09	27.90
Mass budget error	1.77	0.31
Global criteria		
Supply/demand ratio		49.52
Reliability		80.53
Total shortfall	290.04	51.51
Total unallocated	9.72	1.73
Benefit/cost ratio	0.97	
Cost/benefit ratio	1.03	
Economic efficiency	− 0.01	€/m^3

surface waters. The problem to be stressed here is that, in a dry year like 1991, groundwater reserves are significantly depleted when municipal and industrial demands are totally met. In such a case, the water table is lowered so that, eventually, pumping and conveyance costs increase.

Tables 3 and 4 summarize water budget criteria similar to those in Tables 1 and 2 but this time separately for each water use sector. The amounts of net water supplied for municipal and industrial uses are the same for both years since, as described previously, these water demands are met by groundwater. The main consumer of surface waters is irrigation, for which the demand is met by approximately 95% in 1982 and by only 48% in 1991.

The WRM model also simulates the annual groundwater budget. For the 1982 baseline scenario, the budget shows a surplus of 20% groundwater reserves, which are then transferred to the following year's budget. In contrast, 1991 ends with a negative budget of 7% deficit so that, in the following year, the groundwater reserves are totally depleted.

Tables 5 and 6 summarize the general results of the economic assessment for the two baseline scenarios, respectively. It may be observed from these tables that the benefit/cost ratio of the year 1991 is approximately half of that for the year 1982. In addition, the combined economic efficiency of 1991 is reduced to below 0 and the price of water supplied increases to two times that of the year 1982. The latter is due to the fact that penalties (i.e. the price of water that cannot be supplied) that occur as a result of restrictions on supply are inversely related to the amounts of water supplied.

Table 3 | Sectoral water budget for the 1982 scenario

Sector	Demand (Mm^3)	Net supply (Mm^3)	Cons.use (Mm^3)	Losses (Mm^3)	Shortfall (Mm^3)	Unallocated (Mm^3)	Supp./Dem. (%)	Reliability (%)
Municipal	38.73	39.60	23.31	17.12	0.00	0.88	100.00	100.00
Irrigation	559.21	547.84	515.97	73.36	26.27	14.90	95.30	65.79
Industrial	63.07	63.07	28.38	1.58	0.00	0.00	100.00	100.00
Light ind.	31.54	31.54	15.77	0.79	0.00	0.00	100.00	100.00
Total	692.54	682.05	583.44	92.85	26.27	15.78	96.21	86.79

The model runs for the Gediz River Basin, first implemented in the SMART project and further elaborated in OPTIMA to include techno-economic parameters, basically relate to the baseline scenarios, which refer to the business-as-usual state of basin management practice. This is the initial step to be performed before developing future scenarios based on "instruments" specified by Gediz stakeholders. Once these scenarios are set up and assessed for their economic parameters, one can select the "optimum" management plan from among a number of alternatives.

Optimization studies

Basic optimization scenarios

Optimization studies for Gediz Basin management are based on WRM scenarios of the previous sections, where the years 1982 and 1991 are selected to investigate the differences between dry and wet climatic conditions in the basin. As noted earlier, basin stakeholders have identified water scarcity as one of the priority problems so that the reduction of sectoral water demands is essentially the objective to be optimized. To this end, stakeholders have also proposed the use of new instruments, i.e. water technologies that serve to reduce the demands and conveyance losses at irrigation and municipal demand nodes identified in WRM. For purposes of comparison, the implementation rates of new technologies, priorities in their application and relevant costs are selected the same for 1982 and 1991 scenarios.

Water technologies used for optimization

Gediz stakeholders have identified two basic instruments which can reduce sectoral water demands in the basin: education and training of water users and rehabilitation of the existing irrigation system. Domestic water saving measures at residential scale have also been proposed. These instruments, described further in the following sections, are defined in specific terms and uploaded to the online water technologies database maintained by ESS at the OPTIMA website.

Education and training of irrigation water users. This instrument foresees the design of an Education and Training Program to support the implementation of Water Saving

Table 4 | Sectoral water budget for the 1991 scenario

Sector	Demand (Mm^3)	Net supply (Mm^3)	Cons.use (Mm^3)	Losses (Mm^3)	Shortfall (Mm^3)	Unallocated (Mm^3)	Supp./ Dem. (%)	Reliability (%)
Municipal	38.51	39.67	23.10	17.17	0.00	1.16	100.00	100.00
Irrigation	559.21	277.73	265.17	37.02	290.04	8.55	48.13	54.52
Industrial	63.07	63.07	28.38	1.58	0.00	0.00	100.00	100.00
Light ind.	31.54	31.54	15.77	0.79	0.00	0.00	100.00	100.00
Total	692.32	412.00	332.42	56.55	290.04	9.72	58.15	82.69

Table 5 | General results of the economic assessment for the 1982 baseline scenario

Economic Summary:	**Economic Summary:**
direct monetary benefits and costs	direct monetary benefits and costs
including indirect benefits and costs	including indirect benefits and costs
Benefit/cost ratio:	**Total cost:**
1.94	113,779 k€
1.83	121,154 k€
Cost/benefit ratio:	**Total benefit:**
0.51	221,201 k€
0.55	221,201 k€
	Net benefits:
	107,422 k€
	100,047 k€
	Economic efficiency:
	0.16 €/m^3
	0.07 €/m^3
	Water costs:
	0.17 €/m^3
	0.09 €/m^3

Table 6 | General results of the economic assessment for the 1991 baseline scenario

Economic Summary:	**Economic Summary:**
direct monetary benefits and costs	direct monetary benefits and costs
including indirect benefits and costs	including indirect benefits and costs
Benefit/cost ratio:	**Total cost:**
2.30	54,532 k€
0.97	129,054 k€
Cost/benefit ratio:	**Total benefit:**
0.44	125,356 k€
1.03	125,356 k€
	Net benefits:
	70,824 k€
	−3,698 k€
	Economic efficiency:
	0.17 €/m^3
	−0.01 €/m^3
	Water costs:
	0.13 €/m^3
	0.21 €/m^3

Policies by ensuring that the farming community accepts responsibility in reducing the demand for water and securing a sustainable long term water supply.

For the Menemen Left Bank irrigation district, this instrument is expected to have an annual investment cost of 3715 € and an annual operation cost of 3012 €. These figures are defined for every other irrigation district on the basis of its areal extent in proportion to that of the Menemen Left Bank district. The demand nodes where the instrument is applied and the relevant costs at each node are summarized in Table 7.

The minimum implementation rate of the above technology is set as 50%, and the expected reduction in water demand/consumptive use is 10%. The reduction in return flow losses is expected to be 50% and the lifetime of the technology is foreseen as 10 years.

Education and training of urban water users. The application domain of this technology comprises municipal demand nodes. The annual investment cost for application of the instrument at Manisa Municipality, which is the largest municipality in the basin, is estimated to be of the order of 3500 € and the annual operational cost of the order of 2900 €. These costs are then downscaled to other municipalities, regarding their population in proportion to that of Manisa. The distribution of costs for the technology at each municipal

Table 7 | Cost distribution for the instrument of "Education and Training of Irrigation Water Users" (100% implementation; LB: left bank; RB: right bank)

Irrigation district	Area (ha)	Investment (€/yr)	Operational costs (€/yr)
Adala LB	6,150	1,609	1,304
Adala RB	6,300	1,648	1,336
Sarıgöl	1,000	262	2,12
Alaşehir	7,500	1,962	1,591
Ahmetli RB	14,750	3,859	3,129
Ahmetli LB	14,550	3,807	3,086
Menemen RB	5,250	1,374	1,114
Menemen LB	14,200	3,715	3,012

demand node is presented in Table 8. Here, the lifetime of the technology is set to 10 years with a minimum implementation rate of 25% and the expected reduction in urban demand/consumptive use is 10%.

Urban water savings: the use of residential plumbing fixtures. Low-flow plumbing fixtures are one-time conservation measures that can be implemented with little or no additional cost over the lifetime of the fixtures. Residential water demands account for about three-fourths of the total urban water demand. Indoor use roughly makes up 60% of the total residential water use, and, of this, toilets use nearly 40%. Restroom reservoir fixing, maintenance and use of more efficient taps are the main steps to be taken towards residential water savings.

Table 8 | Cost distribution for the instrument of "Education and Training of Urban Water Users" (100% implementation)

Settlement	Population	Investment (€/yr)	Operational costs (€/yr)
Akhisar	81,510	1331	1,103
Salihli	83,137	1358	1,125
Turgutlu	93,727	1530	1,268
Manisa, Center	214,345	3500	2,900
Kemalpasa	25,448	416	344
Menemen	46,079	752	623
Saruhanli	13,025	213	176
Golmarmara	11,205	183	152
Alasehir	39,590	646	536
Ahmetli	11,011	180	149

The economic lifetime of the technology is restricted to that of the installed apparatus, and it is set to 10 years. The residential plumbing fixtures can be applied at household scale for 30 € each, and there are no operational costs involved. The minimum implementation rate of the technology is 25%, and 25% reduction in urban water consumption is expected. Table 9 summarizes the application costs for this technology at each municipal demand node.

Channel lining and irrigation technologies. Gediz stakeholders stress that the water conveyance systems of the existing large-scale irrigation schemes should be replaced by pressured pipeline systems to reduce water losses due to high evaporation and seepage along the canals. Furthermore, the current classical flooding-based field irrigation practices should be changed in favor of water saving technologies, such as drip, subsurface or sprinkling irrigation techniques. Thus, channel lining and change of irrigation technology are identified in the instruments database as irrigation water saving measures. It is estimated by officials of the State Hydraulic Works (DSI) that the annualized capital cost of

Table 9 | Costs for the "Urban Water Savings" technology at each demand node (100% implementation)

Settlement	Household	Investment (€/yr)
Akhisar	21,507	645,198
Salihli	22,903	687,083
Turgutlu	24,094	722,830
Manisa, Center	57,159	1714,760
Kemalpasa	6,362	190,860
Menemen	12,288	368,632
Saruhanli	3,240	97,201
Golmarmara	2,541	76,224
Alasehir	10,936	328,094

such changes in the irrigation system may be as high as 6970 € / ha per year for an economic operation period of 75 years. The unit operating cost is foreseen as 700 € / ha per year, and the minimum implementation rate of the technology is 50%. It is expected that this implementation will reduce the water conveyance losses by 100% and return flow losses by 50%. Furthermore, the change in field irrigation techniques is considered to reduce irrigation water demand and consumptive use by 35%. Table 10 summarizes the investment and operational costs for the above instruments at each irrigation district.

Optimization scenarios and results

The basic (rigid) constraints used in optimization are prescribed on the basis of stakeholder questionnaires where the stakeholders were first asked to define the significance levels of indicators on basin physical conditions, water management, demand and supply. Next, stakeholders identified specific indicators to describe the overall performance of the basin. Table 11 summarizes these indicators and their ranges as dictated by the stakeholders. The last column indicates, in particular, the preferences of DSI, as it is the sole governmental planning agency that is responsible for water allocation in the basin.

The economic indicators as defined in Table 11 are highly varied, and the expected net benefit and economic efficiency values do not appear to be realistic. This is due to stakeholders' lack of information on basin economics; in fact, basin stakeholders do not consider the economic dimension of basin management as one of their top priorities. In the optimization procedure, the target constraints set by stakeholders are far from representing the performance of the basin system for the dry year (1991) baseline scenario where the drought is highly effective. Accordingly, the rigid constraints used for this scenario are relaxed to arrive at some set of feasible results. In contrast, the 1982 scenario seems to easily meet the rigid constraints, except for the economic ones, so that these values are tightened to identify the best system performance.

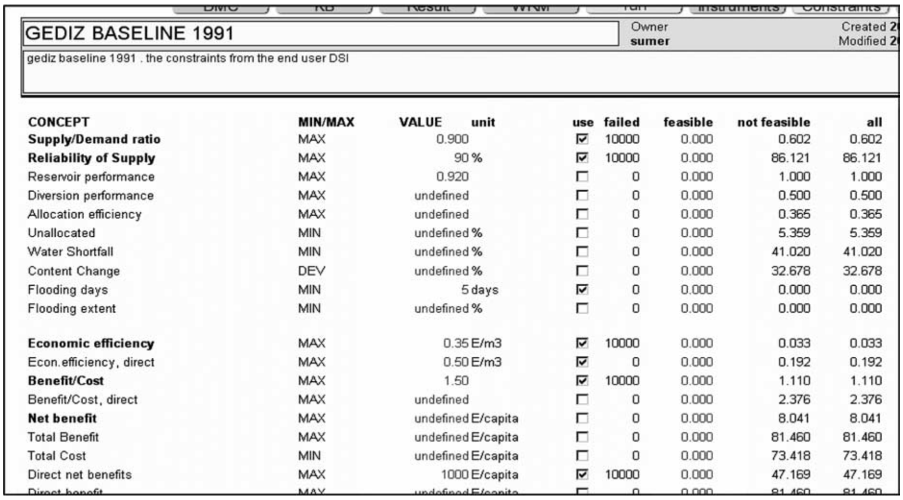
Table 10 | Cost distribution for the "Channel Lining and Irrigation Technologies" instrument (100% implementation)

Irrigation district	Area (ha)	Annual investment (€/yr)	Operational (€/yr)
Adala LB	6,150	1,810,167	181,796
Adala RB	6,300	1,854,318	186,230
Sarıgöl	1,000	294,336	29,560
Alaşehir	7,500	2,207,521	221,702
Ahmetli RB	14,750	4,341,458	436,014
Ahmetli LB	14,550	4,282,591	430,102
Menemen RB	5,250	1,545,265	155,192
Menemen LB	14,200	4,179,573	419,756

Table 11 | The range of "rigid constraints" for optimization, identified by basin stakeholders

Indicator	Min & max value	DSI
Overall supply/demand ratio	$>$ 70–95%	$>$ 90%
Reliability of supply	$>$ 70–95%	$>$ 90%
Benefit/cost ratio	$>$ 0.8–2.0	$>$ 1.5
Economic efficiency (direct)	0.10–0.70 €/m^3	0.5 €/m^3
Economic efficiency (indirect)	0.08–0.9 €/m^3	0.35 €/m^3
Net benefit (direct or indirect)	960–1200 €/ca	1000 €/ca
Cost of water (direct)	0.10–0.7 €/m^3	0.4 €/m^3
Cost of water (indirect)	0.08–0.7 €/m^3	0.25 €/m^3

The optimization procedure is run first for the year 1991, as the WRM simulations for this period indicated that system performance is negatively affected by drought conditions. In this case, the rigid constraints specified by basin stakeholders are used; that is, the supply/demand ratio and reliability of supply are set to 90%, and the benefit/cost ratio is taken as 1.5 while the direct net benefits is prescribed as 1000 €/ca (Figure 5). After the first run of the optimization procedure, it was observed that the above constraints were far from describing the baseline system performance so that the result was a "failure", i.e. none of the 10,000 runs were able to meet the specified rigid constraints (Figure 6). For example, the expected net benefit was set as 1000 €/ca, whereas the optimizations runs showed that the maximum net benefit should be less than 50 €/ca when the water technologies are implemented. Even the selected



GEDIZ BASELINE 1991

Owner
sumer

Created
Modified

gediz baseline 1991 . the constraints from the end user DSI

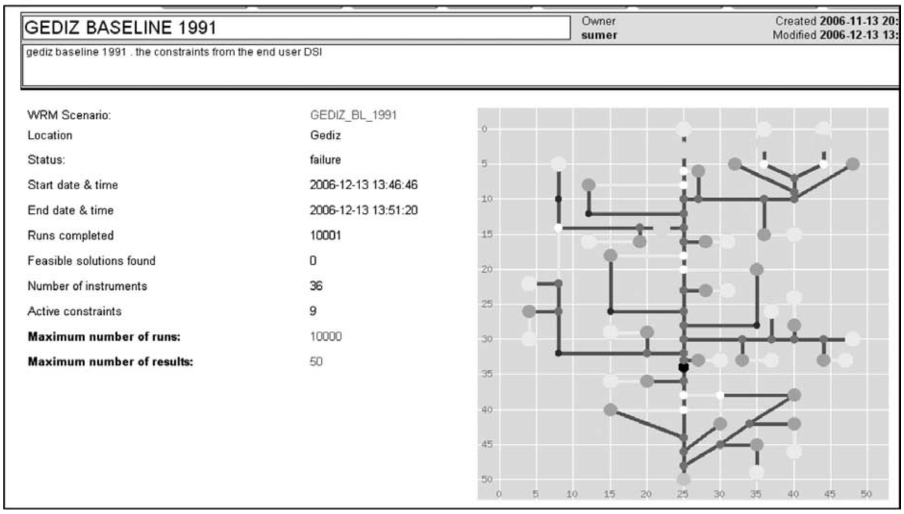
CONCEPT	MIN/MAX	VALUE	unit	use	failed	feasible	not feasible	all
Supply/Demand ratio	MAX	0.900		☑	10000	0.000	0.602	0.602
Reliability of Supply	MAX	90	%	☑	10000	0.000	86.121	86.121
Reservoir performance	MAX	0.920		☐	0	0.000	1.000	1.000
Diversion performance	MAX	undefined		☐	0	0.000	0.500	0.500
Allocation efficiency	MAX	undefined		☐	0	0.000	0.365	0.365
Unallocated	MIN	undefined	%	☐	0	0.000	5.359	5.359
Water Shortfall	MIN	undefined	%	☐	0	0.000	41.020	41.020
Content Change	DEV	undefined	%	☐	0	0.000	32.678	32.678
Flooding days	MIN	5	days	☑	0	0.000	0.000	0.000
Flooding extent	MIN	undefined	%	☐	0	0.000	0.000	0.000
Economic efficiency	MAX	0.35	E/m3	☑	10000	0.000	0.033	0.033
Econ.efficiency, direct	MAX	0.50	E/m3	☑	0	0.000	0.192	0.192
Benefit/Cost	MAX	1.50		☑	10000	0.000	1.110	1.110
Benefit/Cost, direct	MAX	undefined		☐	0	0.000	2.376	2.376
Net benefit	MAX	undefined	E/capita	☐	0	0.000	8.041	8.041
Total Benefit	MAX	undefined	E/capita	☐	0	0.000	81.460	81.460
Total Cost	MIN	undefined	E/capita	☐	0	0.000	73.418	73.418
Direct net benefits	MAX	1000	E/capita	☑	10000	0.000	47.169	47.169

Figure 5 | An overview of the "failed" GEDIZ BASELINE optimization scenarios for 1991.

supply/demand ratio of 90% was not realistic as it barely reached 60%. The same is true for the benefit/cost ratio of 1.5 as the optimization runs produced a value just above 1. Despite these discrepancies, the optimization procedure clearly showed that the implementation of water technologies improves the overall performance of the system.

In view of the above results of the first optimization runs for 1991, rigid constraints were relaxed to arrive at a feasible solution set. The supply/demand ratio, reliability of supply and benefit/-cost ratio were then set to 61%, 86% and 1.15, respectively, while the economic efficiency was defined as 0 €/m^3. These changes in rigid constraints produced 50 feasible solutions for the baseline 1991 scenario, which were then used for post-optimization analysis with the Discrete Multi-Criteria optimization (DMC) tool provided by ESS-Austria. Figure 7 shows an overview of the GEDIZ BASELINE 1991 optimization scenario, where 50 feasible solutions were reached after 2176 runs.

The optimization runs for the year of 1982 basically represent a "water-rich" period, as the WRM simulations for this year indicated that the system performance was much better than that in dry years. For the 1982 baseline and future optimization scenarios, the rigid constraints specified by basin stakeholders are used again so that the supply/demand ratio and the reliability of supply are both set to 90%, the benefit/cost ratio is taken as 1.5 and the direct net benefits are set to 1,000 €/ca. With these inputs, the hydrologic performance constraints were



GEDIZ BASELINE 1991

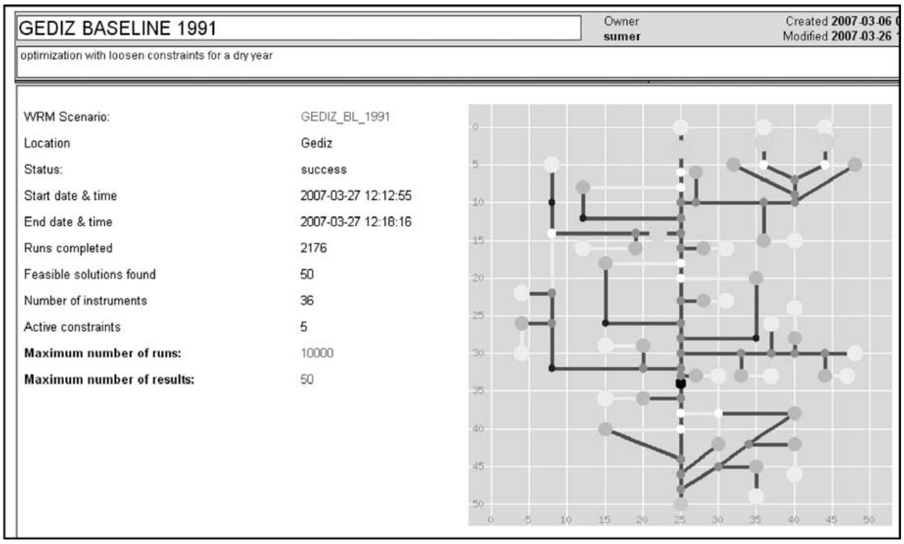
Owner
sumer

Created **2006-11-13 20:**
Modified **2006-12-13 13:**

gediz baseline 1991 . the constraints from the end user DSI

WRM Scenario:	GEDIZ_BL_1991
Location	Gediz
Status:	failure
Start date & time	2006-12-13 13:46:46
End date & time	2006-12-13 13:51:20
Runs completed	10001
Feasible solutions found	0
Number of instruments	36
Active constraints	9
Maximum number of runs:	10000
Maximum number of results:	50

Figure 6 | The failed optimization result for the GEDIZ BASELINE 1991 scenario.



GEDIZ BASELINE 1991 Owner **sumer** Created **2007-03-06** Modified **2007-03-26**

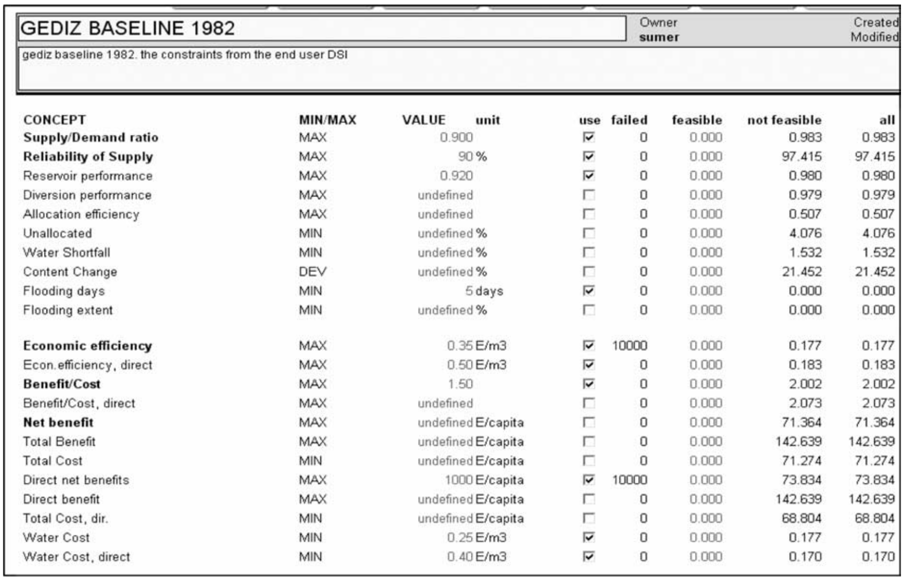
optimization with loosen constraints for a dry year

WRM Scenario:	GEDIZ_BL_1991
Location	Gediz
Status:	success
Start date & time	2007-03-27 12:12:55
End date & time	2007-03-27 12:18:16
Runs completed	2176
Feasible solutions found	50
Number of instruments	36
Active constraints	5
Maximum number of runs:	10000
Maximum number of results:	50

Figure 7 | The "successful" optimization attempt of GEDIZ BASELINE 1991 scenario with loosened constraints.

successfully met but optimization failed after 10,000 runs due to high direct net benefit value selected, which, in reality, has to be around 70 €/ca (Figure 8). On the other hand, the optimization runs easily met the supply/demand ratio and the reliability of supply constraints so that none of the attempted solutions failed. Even the benefit/cost ratio set initially to 1.5 was found to be around 2, which means that the system itself performs better in a wet year than expected by the stakeholders. Another criterion, i.e. "water cost", was derived to be below 0.20 €/m^3, which again is better than the stakeholders' desirable value of 0.25 €/m^3.

Following from the above results, the hydrologic constraints were then tightened and economic constraints relaxed to arrive at a feasible solution set. The supply/-demand ratio, reliability of supply and the benefit/cost ratio were tightened to 0.985, 0.98 and 2, respectively; the economic constraints were set as 73 €/ca for direct benefit and 0.18 €/m^3 for economic efficiency. Other constraints such as water cost, net benefit, total benefit, etc., were used as rigid constraints to find a better set of feasible solutions. Eventually, a feasible set of 50 solutions were obtained for

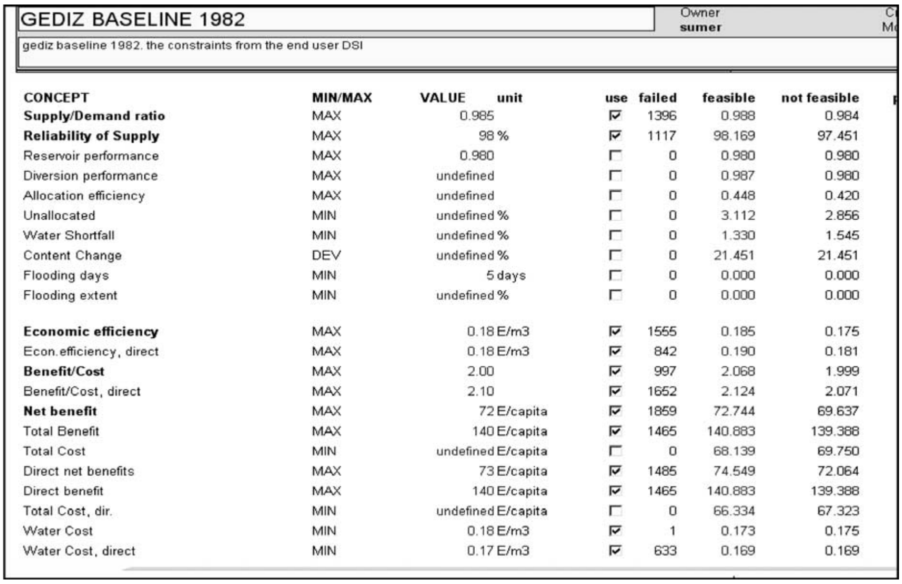


GEDIZ BASELINE 1982 Owner **sumer** Created Modified

gediz baseline 1982. the constraints from the end user DSI

CONCEPT	MIN/MAX	VALUE	unit	use	failed	feasible	not feasible	all
Supply/Demand ratio	MAX	0.900		☑	0	0.000	0.983	0.983
Reliability of Supply	MAX	90	%	☑	0	0.000	97.415	97.415
Reservoir performance	MAX	0.920		☑	0	0.000	0.980	0.980
Diversion performance	MAX	undefined		☐	0	0.000	0.979	0.979
Allocation efficiency	MAX	undefined		☐	0	0.000	0.507	0.507
Unallocated	MIN	undefined	%	☐	0	0.000	4.076	4.076
Water Shortfall	MIN	undefined	%	☐	0	0.000	1.532	1.532
Content Change	DEV	undefined	%	☐	0	0.000	21.452	21.452
Flooding days	MIN	5	days	☑	0	0.000	0.000	0.000
Flooding extent	MIN	undefined	%	☐	0	0.000	0.000	0.000
Economic efficiency	MAX	0.35	E/m3	☑	10000	0.000	0.177	0.177
Econ.efficiency, direct	MAX	0.50	E/m3	☑	0	0.000	0.183	0.183
Benefit/Cost	MAX	1.50		☑	0	0.000	2.002	2.002
Benefit/Cost, direct	MAX	undefined		☐	0	0.000	2.073	2.073
Net benefit	MAX	undefined	E/capita	☐	0	0.000	71.364	71.364
Total Benefit	MAX	undefined	E/capita	☐	0	0.000	142.639	142.639
Total Cost	MIN	undefined	E/capita	☐	0	0.000	71.274	71.274
Direct net benefits	MAX	1000	E/capita	☑	10000	0.000	73.834	73.834
Direct benefit	MAX	undefined	E/capita	☐	0	0.000	142.639	142.639
Total Cost, dir.	MIN	undefined	E/capita	☐	0	0.000	68.804	68.804
Water Cost	MIN	0.25	E/m3	☑	0	0.000	0.177	0.177
Water Cost, direct	MIN	0.40	E/m3	☑	0	0.000	0.170	0.170

Figure 8 | The "failed" optimization run of the GEDIZ BASELINE 1982 scenario based on stakeholders' constraints.



GEDIZ BASELINE 1982

Owner sumer

gediz baseline 1982. the constraints from the end user DSI

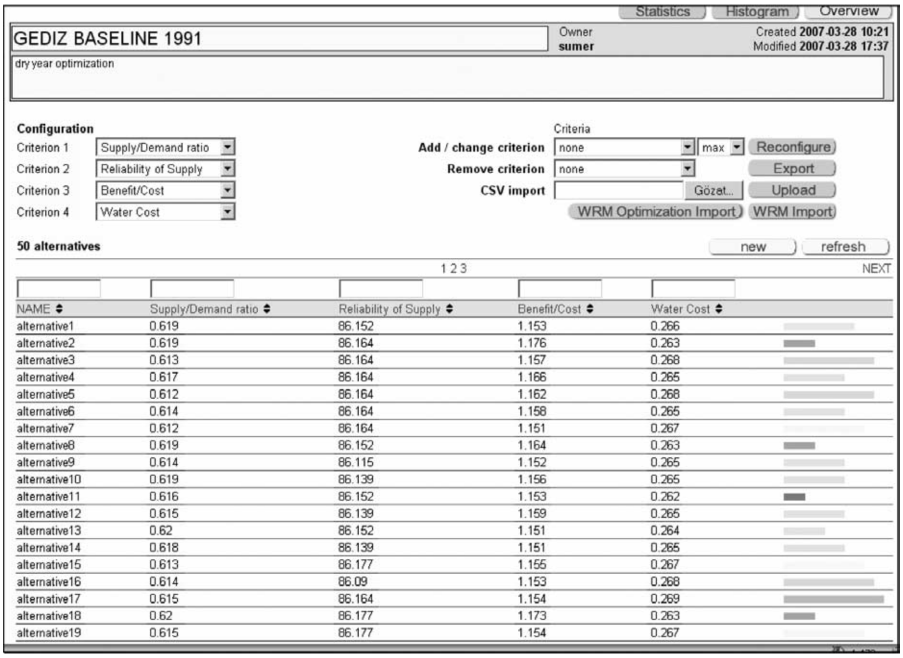
CONCEPT	MIN/MAX	VALUE	unit	use	failed	feasible	not feasible
Supply/Demand ratio	MAX	0.985		☑	1396	0.988	0.984
Reliability of Supply	MAX	98	%	☑	1117	98.169	97.451
Reservoir performance	MAX	0.980		☐	0	0.980	0.980
Diversion performance	MAX	undefined		☐	0	0.987	0.980
Allocation efficiency	MAX	undefined		☐	0	0.448	0.420
Unallocated	MIN	undefined	%	☐	0	3.112	2.856
Water Shortfall	MIN	undefined	%	☐	0	1.330	1.545
Content Change	DEV	undefined	%	☐	0	21.451	21.451
Flooding days	MIN	5	days	☐	0	0.000	0.000
Flooding extent	MIN	undefined	%	☐	0	0.000	0.000
Economic efficiency	MAX	0.18	E/m3	☑	1555	0.185	0.175
Econ.efficiency, direct	MAX	0.18	E/m3	☑	842	0.190	0.181
Benefit/Cost	MAX	2.00		☑	997	2.068	1.999
Benefit/Cost, direct	MAX	2.10		☑	1652	2.124	2.071
Net benefit	MAX	72	E/capita	☑	1859	72.744	69.637
Total Benefit	MAX	140	E/capita	☑	1465	140.883	139.388
Total Cost	MIN	undefined	E/capita	☐	0	68.139	69.750
Direct net benefits	MAX	73	E/capita	☑	1485	74.549	72.064
Direct benefit	MAX	140	E/capita	☑	1465	140.883	139.388
Total Cost, dir.	MIN	undefined	E/capita	☐	0	66.334	67.323
Water Cost	MIN	0.18	E/m3	☑	1	0.173	0.175
Water Cost, direct	MIN	0.17	E/m3	☑	633	0.169	0.169

Figure 9 | The "successful" optimization of GEDIZ BASELINE 1982 scenario with new constraints.

GEDIZ BASELINE 1982 scenario after 2028 runs, for which the rigid constraints selected are shown in Figure 9.

Post-optimal analysis

OPTIMA uses a two-stage optimization approach specifically designed to facilitate a participatory approach and continuing stakeholder involvement. The first phase presented above is based on evolutionary algorithms for complex optimization that identifies feasible solutions meeting all or as many as possible of the user expectations expressed in terms of constraints on performance criteria. The second phase is a subsequent discrete multi-criteria decision-making that is oriented towards conflict resol-



GEDIZ BASELINE 1991

Owner sumer

Created 2007-03-28 10:21
Modified 2007-03-28 17:37

dry year optimization

Configuration

Criterion 1 Supply/Demand ratio
Criterion 2 Reliability of Supply
Criterion 3 Benefit/Cost
Criterion 4 Water Cost

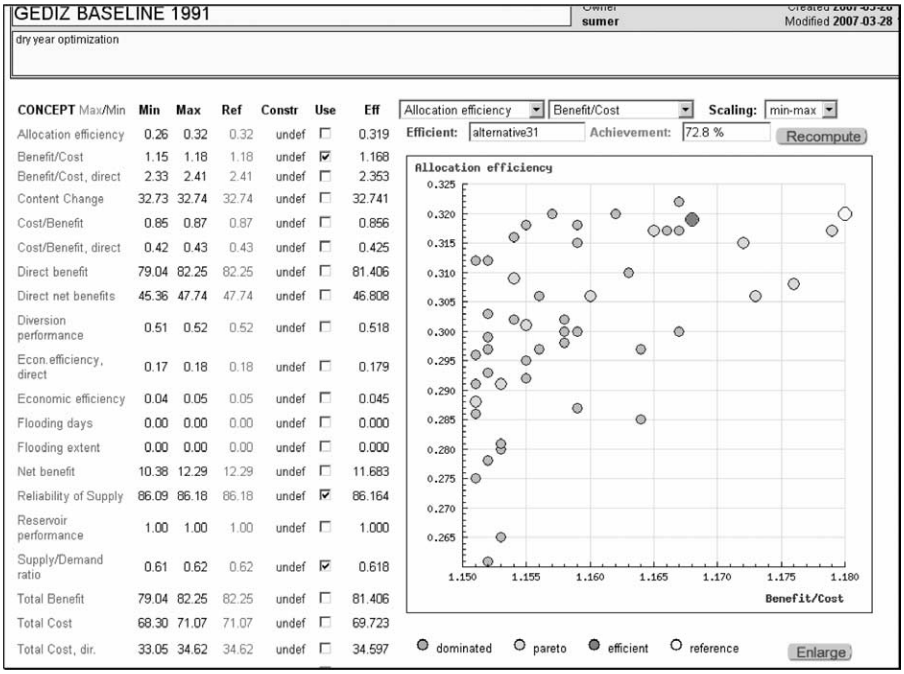
Criteria

Add / change criterion none max
Remove criterion none
CSV import

50 alternatives

NAME	Supply/Demand ratio	Reliability of Supply	Benefit/Cost	Water Cost
alternative1	0.619	86.152	1.153	0.266
alternative2	0.619	86.164	1.176	0.263
alternative3	0.613	86.164	1.157	0.268
alternative4	0.617	86.164	1.166	0.265
alternative5	0.612	86.164	1.162	0.268
alternative6	0.614	86.164	1.158	0.265
alternative7	0.612	86.164	1.151	0.267
alternative8	0.619	86.152	1.164	0.263
alternative9	0.614	86.115	1.152	0.265
alternative10	0.619	86.139	1.156	0.265
alternative11	0.616	86.152	1.153	0.262
alternative12	0.615	86.139	1.159	0.265
alternative13	0.62	86.152	1.151	0.264
alternative14	0.618	86.139	1.151	0.265
alternative15	0.613	86.177	1.155	0.267
alternative16	0.614	86.09	1.153	0.268
alternative17	0.615	86.164	1.154	0.269
alternative18	0.62	86.177	1.173	0.263
alternative19	0.615	86.177	1.154	0.267

Figure 10 | The set of feasible alternatives derived through the optimization of GEDIZ BASELINE 1991 scenarios.



GEDIZ BASELINE 1991

sumer

Modified 2007-03-28

dry year optimization

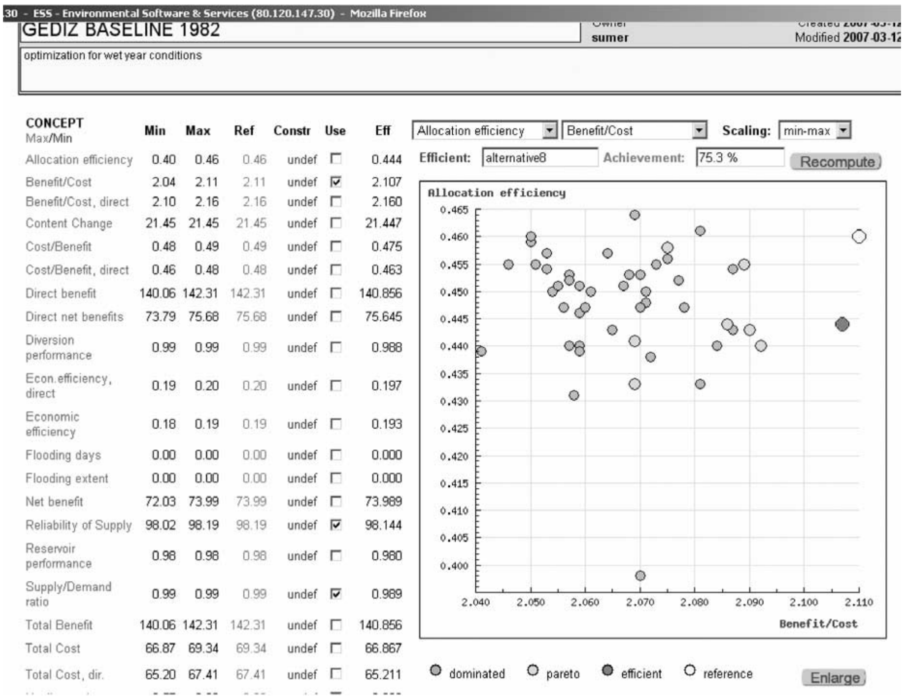
CONCEPT Max/Min	Min	Max	Ref	Constr	Use	Eff
Allocation efficiency	0.26	0.32	0.32	undef	☐	0.319
Benefit/Cost	1.15	1.18	1.18	undef	☑	1.168
Benefit/Cost, direct	2.33	2.41	2.41	undef	☐	2.353
Content Change	32.73	32.74	32.74	undef	☐	32.741
Cost/Benefit	0.85	0.87	0.87	undef	☐	0.856
Cost/Benefit, direct	0.42	0.43	0.43	undef	☐	0.425
Direct benefit	79.04	82.25	82.25	undef	☐	81.406
Direct net benefits	45.36	47.74	47.74	undef	☐	46.808
Diversion performance	0.51	0.52	0.52	undef	☐	0.518
Econ.efficiency, direct	0.17	0.18	0.18	undef	☐	0.179
Economic efficiency	0.04	0.05	0.05	undef	☐	0.045
Flooding days	0.00	0.00	0.00	undef	☐	0.000
Flooding extent	0.00	0.00	0.00	undef	☐	0.000
Net benefit	10.38	12.29	12.29	undef	☐	11.683
Reliability of Supply	86.09	86.18	86.18	undef	☑	86.164
Reservoir performance	1.00	1.00	1.00	undef	☐	1.000
Supply/Demand ratio	0.61	0.62	0.62	undef	☑	0.618
Total Benefit	79.04	82.25	82.25	undef	☐	81.406
Total Cost	68.30	71.07	71.07	undef	☐	69.723
Total Cost, dir.	33.05	34.62	34.62	undef	☐	34.597

Allocation efficiency | Benefit/Cost | Scaling: min-max

Efficient: alternative31

Achievement: 72.8 %

Figure 11 | Alternative solutions for the GEDIZ BASELINE 1991 scenario under selected criteria.



30 - ESS - Environmental Software & Services (80.120.147.30) - Mozilla Firefox

GEDIZ BASELINE 1982

sumer

Modified 2007-03-12

optimization for wet year conditions

CONCEPT Max/Min	Min	Max	Ref	Constr	Use	Eff
Allocation efficiency	0.40	0.46	0.46	undef	☐	0.444
Benefit/Cost	2.04	2.11	2.11	undef	☑	2.107
Benefit/Cost, direct	2.10	2.16	2.16	undef	☐	2.160
Content Change	21.45	21.45	21.45	undef	☐	21.447
Cost/Benefit	0.48	0.49	0.49	undef	☐	0.475
Cost/Benefit, direct	0.46	0.48	0.48	undef	☐	0.463
Direct benefit	140.06	142.31	142.31	undef	☐	140.856
Direct net benefits	73.79	75.68	75.68	undef	☐	75.645
Diversion performance	0.99	0.99	0.99	undef	☐	0.988
Econ.efficiency, direct	0.19	0.20	0.20	undef	☐	0.197
Economic efficiency	0.18	0.19	0.19	undef	☐	0.193
Flooding days	0.00	0.00	0.00	undef	☐	0.000
Flooding extent	0.00	0.00	0.00	undef	☐	0.000
Net benefit	72.03	73.99	73.99	undef	☐	73.989
Reliability of Supply	98.02	98.19	98.19	undef	☑	98.144
Reservoir performance	0.98	0.98	0.98	undef	☐	0.980
Supply/Demand ratio	0.99	0.99	0.99	undef	☑	0.989
Total Benefit	140.06	142.31	142.31	undef	☐	140.856
Total Cost	66.87	69.34	69.34	undef	☐	66.867
Total Cost, dir.	65.20	67.41	67.41	undef	☐	65.211

Allocation efficiency | Benefit/Cost | Scaling: min-max

Efficient: alternative8

Achievement: 75.3 %

Figure 12 | Alternative solutions for the GEDIZ BASELINE 1982 scenario under selected criteria.

Table 12(a) | Application rates and projected costs of water technologies at municipal demand nodes in the 1982 BASELINE scenario

Node name	Water technology	Application rate (%)	Investment cost (€/yr)	Operational cost (€/yr)
Ahmetli	Urban water savings	0	0	0
	Education & training-urban users	59	107	88
Akhisar	Urban water savings	0	0	0
	Education & training-urban users	35	462	383
Alasehir	Urban water savings	26	86,137	0
	Education & training-urban users	54	346	287
Golmarmara	Urban water savings	0	0	0
	Education & training-urban users	48	87	72
Kemalpasa	Urban water savings	38	71,931	0
	Education & training-urban users	50	209	173
Manisa	Urban water savings	27	466,497	0
	Education & training-urban users	36	1 271	1,053
Menemen	Urban water savings	47	174 824	0
	Education & training-urban users	75	563	466
Salihli	Urban water savings	0	0	0
	Education & training-urban users	61	827	685
Saruhanli	Urban water savings	50	48,316	0
	Education & training-urban users	33	69	57
Turgutlu	Urban water savings	0	0	0
	Education & training-urban users	43	651	540

Table 12(b) | Application rates and projected costs of water technologies at irrigation demand nodes in the 1982 BASELINE scenario

Node name	Water technology	Application rate (%)	Investment cost (€/yr)	Operational cost (€/yr)
Adala Left	Channel lining and irrigation water savings	68	1,238,920	124,426
	Education & training of farmers	89	1,425	1,154
Adala Right	Channel lining and irrigation water savings	0	0	0
	Education & training of farmers	53	876	710
Ahmetli Left	Channel lining and irrigation water savings	0	0	0
	Education & training of farmers	77	2,932	2,377
Ahmetli Right	Channel lining and irrigation water savings	0	0	0
	Education & training of farmers	77	2,954	2,396
Alasehir	Channel lining and irrigation water savings	78	1,728,080	173,552
	Education & training of farmers	77	1,512	1,226
Menemen Left	Channel lining and irrigation water savings	0	0	0
	Education & training of farmers	86	3,196	2,591
Menemen Right	Channel lining and irrigation water savings	0	0	0
	Education & training of farmers	0	0	0
Sarigol	Channel lining and irrigation water savings	0	0	0
	Education & training of farmers	85	224	181

Table 13(a) | Application rates and projected costs of water technologies at municipal demand nodes in the 1991 BASELINE scenario

Node name	Water technology	Application rate (%)	Investment cost (€/yr)	Operational cost (€/yr)
Ahmetli	Urban water saving	0	0	0
	Education&training-urban users	52	94	78
Akhisar	Urban water saving	43	274,841	0
	Education&training-urban users	48	642	532
Alasehir	Urban water saving	0	0	0
	Education&training-urban users	47	306	254
Golmarmara	Urban water saving	0	0	0
	Education&training-urban users	52	95	79
Kemalpasa	Urban water saving	0	0	0
	Education&training-urban users	64	268	222
Manisa	Urban water saving	41	700,544	0
Education&training-urban users	64	2,257	1,870	
Menemen	Urban water saving	0	0	0
	Education&training-urban users	29	215	178
Salihli	Urban water saving	40	276 708	0
	Education&training-urban users	0	0	0
Saruhanli	Urban water saving	44	42,748	0
	Education&training-urban users	49	104	86
Turgutlu	Urban water saving	0	0	0
	Education&training-urban users	31	471	390

ution. The latter defines the trade-offs between the conflicting objectives using a reference point methodology and the concept of Pareto-efficiency to arrive at a generally acceptable solution as a global optimum (ESS 2006*b*).

ESS-Austria has provided a decision support system tool called Discrete Multi-Criteria (DMC), which is utilized for post-optimal analysis to satisfy the second phase of the optimization procedure. DMC implements the reference point methodology of multi-attribute theory. Its basic advantage is simplicity, i.e. the use of a minimum set of assumptions, so that it lends itself to interactive use. The method first partitions the search space into dominated and non-dominated alternatives (i.e. generating a Pareto-optimal subset), always depending on the user's choice of the criteria to be considered and any constraints specified (ESS 2006*b*).

Evaluation of Gediz baseline optimization scenario results with DMC

The sets of feasible solutions for the baseline scenarios of 1991 and 1982 are imported into the DMC tool to obtain possible Pareto-optimal and non-dominated alternative solutions within the feasible sets. Although the primary concern of this step of the optimization procedure is conflict resolution and trade-offs among different stakeholder preferences, it also enables us to assess the implementation rates of the planned water technology investments and system performance through this investment.

Assessment of feasible solution sets with the DMC tool requires again a consideration of stakeholder priorities. Gediz stakeholders have agreed on maximizing criteria such as the overall supply/demand and benefit/cost ratios. The reliability of supply criterion is also important for the

Table 13(b) | Application rates and projected costs of water technologies at irrigation demand nodes in the 1991 BASELINE scenario

Node name	Water technology	Application rate (%)	Investment cost (€/yr)	Operational cost (€/yr)
Adala Left	Channel lining and irrigation water savings	55	996,346	100,064
	Education & training of farmers	62	994	805
Adala Right	Channel lining and irrigation water savings	0	0	0
	Education & training of farmers	63	1,039	842
Ahmetli Left	Channel lining and irrigation water savings	0	0	0
	Education & training of farmers	82	3,139	2,545
Ahmetli Right	Channel lining and irrigation water savings	0	0	0
	Education & training of farmers	68	2,617	2,122
Alasehir	Channel lining and irrigation water savings	84	1,861,230	186,924
	Education & training of farmers	73	1,433	1,162
Menemen Left	Channel lining and irrigation water savings	0	0	0
	Education & training of farmers	81	2,995	2,429
Menemen Right	Channel lining and irrigation water savings	0	0	0
	Education & training of farmers	83	1,147	930
Sarigol	Channel lining and irrigation water savings	0	0	0
	Education & training of farmers	63	166	134

stakeholders as the agricultural sector in particular is sensitive to supply reliability, and farmers do not favor restricted irrigation under drought conditions. Accordingly, all optimization scenarios were re-evaluated through maximizing supply/demand ratio, reliability of supply and benefit/cost ratio criteria while keeping the direct and indirect water costs to a minimum.

As an example, the list of feasible alternatives imported to the DMC tool is given in Figure 10 for the GEDIZ BASELINE 1991 scenario. The results of post-optimal analysis of the GEDIZ BASELINE 1991 and 1982 optimization scenarios are shown in Figures 11 and 12, respectively. The reference point used in comparison with alternative solutions in the feasible set is the maximum or the minimum value for each criterion. The alternatives selected for both the 1991 and 1982 scenarios represent one derived solution out of the feasible set of 50 solutions. These alternatives foresee the steps to be taken in the basin in terms of planned investments for improvement

Table 14 | Some key indicators for baseline scenarios and their improved values after optimization

Indicator	1991 baseline	Optimized 1991	1982 baseline	Optimized 1982
Supply/demand (%)	49.52	61.80	95.86	98.90
Reliability of supply (%)	80.53	86.16	89.67	98.14
Benefit/cost	0.97	1.17	1.83	2.107
Econ. Efficiency (€/m^3, indirect)	−0.01	0.045	0.07	0.193
Cost of water (€/m^3, direct)	0.13	0.133	0.17	0.170
Cost of water (€/m^3, indirect)	0.21	0.267	0.09	0.174

of system performance. Tables 12(a, b) and 13(a, b) show the rates and the magnitudes of the investments required for meeting municipal and irrigational demands. These investments relate to the water technologies prescribed for 1991 and 1982 scenarios.

Discussion of results

The results of optimization runs and post-optimal analysis have shown for 1991 scenarios that education and training of users are more effective in meeting stakeholders' constraints. This measure is followed by the rehabilitation of irrigation systems and urban water savings in the priority list of technologies to be applied. The result is basically the same for 1982 scenarios where education and training of users again appears as the priority technology to be selected. Rehabilitation of the existing irrigation systems requires significant investment so that basin stakeholders have not favored this technology to have top priority. On the other hand, application of all selected technologies under the given constraints improves general system performance as shown by various indicators in Table 14.

CONCLUSION

Simulation studies within OPTIMA have shown that the Gediz Basin is highly sensitive to drought conditions, and irrigation is the sector that is affected the most by water scarcity. Basin stakeholders consider rehabilitation of the existing irrigation systems and improvement of in-field irrigation practices as possible measures to cope with droughts or water-scarce years.

In the optimization studies, the hydrologic constraints specified by basin stakeholders could not be met for dry year simulations. On the other hand, economic constraints cannot be met even during wet years. The basic reason for this situation is the stakeholders' lack of information on the economic performance of the Gediz Basin. Another deficiency in terms of basin management is that, except for domestic water use, prices per m^3 of water consumed have not yet been specified so that a significant factor in terms of water economics cannot be assessed.

The post-optimal analysis of feasible scenarios allows determining the best solution in terms of investments to be realized under the specified constraints. For the Gediz case, investments for education and training of water users appear to have the priority among other instruments considered. Channel lining and irrigation water saving technologies are the most effective in particular irrigation districts, i.e. Adala Left and Right, Alasehir and Sarigol. Thus, if a decision is to be made on investment for rehabilitation of the existing irrigation system, it would be reasonable to initiate such improvement in the above-mentioned districts.

As a general concluding remark for the presented study, it can be stated that the results obtained so far clearly illustrate how a consistent and well-integrated set of advanced but practical Decision Support System (DSS) tools can be used for efficient "optimal" water management strategies and policies of use, designed for a participatory public decision-making process.

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