A WEB-BASED WATER RESOURCES SIMULATION AND OPTIMIZATION SYSTEM

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Abstract

Water is one of the controlling factors of regional development around the Eastern and Southern Mediterranean. Scarcity and conflict characterize water resource management in many countries and river basins. Rapid demographic and economic development especially of the coastal zone, urbanization, industrialization, tourism, and an often inefficient agricultural sector as the dominant water user contribute to the problem. Low availability of renewable water, overexploited groundwater, pollution, inefficient infrastructure, pronounced seasonality with unfavourable demand patterns very different from the seasonal supply aggravate the situation.

Within the Framework of a FW6 sponsored INCO-MPC project, OPTIMA, a simulation based water resources planning and optimization system is being developed and applied in case studies in Cyprus, Turkey, Lebanon, Jordan, Palestine and Israel, Tunisia and Morocco. The model system addresses 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 stake holders for multi-criteria optimisation and decision support.

The optimization uses heuristics and concepts of genetic programming, based on a realistic, detailed, dynamic and distributed representation of the individual river basins. The underlying dynamic (daily) simulation model describes the water resources systems at a 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).

The approach and methodology are demonstrated using the case study of the Gediz river basin, which covers about 18,000 km^2, approaches a total population of 2 million, and drains into the Aegean Sea. The case demonstrates the entire range of prototypical water management problems in the region, and their potential solutions. The case also demonstrates 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. A common shared and reliable information basis is a central element of the participatory approach.

Keywords
Water resources modelling, optimization, heuristics, discrete multi-criteria, decision support.

1. INTRODUCTION

The basic principle of mass conservation provides a solid framework for water resources management and thus lends itself to analysis by simulation and optimisation. This makes it possible to keep track of the water in a river basin as a natural hydrographic unit in a dynamic water budget, and to estimate the benefits and costs of demands met or shortfalls, with alternative structures, water technologies and efficiencies, allocation rules, and demand patterns. This in turn provides the basis for finding improved strategies and policies, given a large set of feasible alternatives to choose from. However, in any practical application there are uncertainties not only on the physical side, but even more so on the socio-economic and political front where criteria, objectives and constraints are being defined and evaluated. Multiple actors and their different views and preferences, conflicting objectives, hidden agenda, plural rationalities make a naïve concept of optimality impractical. Direct involvement of key actors in an interactive approach seems one possible solution.

Simulation modelling of dynamic and spatially "WHAT IF" scenarios can provide a high degree of detail and realism in problem representation. Optimisation can answer the more interesting question of "HOW TO", but often enough for the unacceptable price of considerable simplification of the problem. The challenge is to combine the best of both worlds, and integrate the tools into the real-world decision making processes, which requires easy access and a simple and intuitive representation and interface for end users in a participatory approach.

For the modelling approach, one possible solution to represent complexity at different scales is to build sets or cascades on linked models rather than one all encompassing representation [1] and switch from a classical optimisation paradigm that minimises or maximises an objective function to a concept of satisficing [2,3,4], 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 organised in a cluster to end users that only need a standard PC and web browser.

2. THE OPTIMA PROJECT

The overall aim of OPTIMA is to develop, implement, and critically evaluate, an innovative, scientifically rigorous yet practical approach to water resources management intended to increase efficiencies and to reconcile conflicting demands. Based on the European Water Framework Directive (2000/60/EC) as conceptual framework the approach equally considers economic efficiency, environmental compatibility, and social equity as three pillars of sustainable development [5].
OPTIMA is extending classical optimisation and mathematical programming methodology in several respects:

- Using full-featured dynamic and distributed simulation models and genetic programming as the core to generate feasible and non-dominated alternatives. Water technology alternatives including their cost structure, and long-term hydrometeorological data are 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 stake-holders in an interactive, participatory decision making process carefully embedded in institutional structures, using a discrete multi-criteria reference point methodology;
- Adding comparative evaluation and benchmarking across the set of local and regional case studies in seven countries, namely Cyprus, Turkey, Lebanon, Jordan, Palestine, Tunisia and Morocco around the Southern and Eastern Mediterranean as the final step of analysis to identify generic examples of best practice.

3.1 The Gediz River Basin Case Study

The Gediz Basin in Western Turkey has changed considerably in the past decade, moving from a comparatively water rich basin to one that is now under increasing water stress. This change has been in part a result of a severe drought that affected the Basin from 1989 to 1994, in part due to an above average increase in urban and industrial demand, and in part due to a rapidly growing concern for issues of water quality and environmental protection. Paralleling these hydrologic changes has been a much slower institutional response that has not kept up with the requirements for changes in the way water is allocated and managed [6].

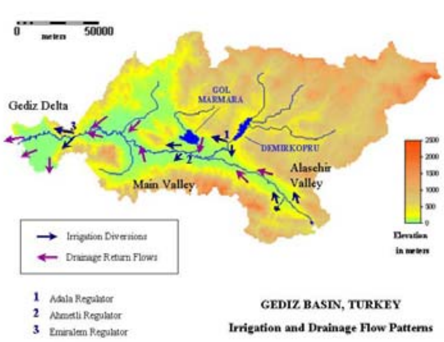
Before the drought, there was little competition for water, and the established mechanism for allocating water to different users through a set of bilateral agreements worked well. When the drought struck, irrigation issues in the peak summer season were reduced sharply, return flows diminished, and, as a consequence, water quality in the lower third of the Basin deteriorated. Rural residents began to complain that water was unsuitable for irrigation. At the same time, there was widespread desiccation of the important wetland areas in the Gediz Delta, leading to large reductions in bird populations and, possibly, loss of species diversity.

The Gediz River Basin borders the city of Izmir, which is the third largest city in the country and an important harbour along the Aegean. The Izmir metropolitan area, continuously growing, consumes a significant portion of the groundwater resources of the Gediz Basin. There is a good number of creeks that discharge directly into the inner Bay, causing significant pollution problems and flooding due to recent land use changes (primarily as a consequence of urbanization), which exert considerable pressure on the water resource system in general.
In essence, the Gediz River Basin is characterized by water shortage, environmental pollution and recurrent droughts. 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. Population growth in the basin is in the order of 2% per year for urban and 0.7 % per year for rural areas, marked by significant migration to big cities. Furthermore, there are serious institutional, legal, social and economic problems, which further complicate water allocation and environmental pollution problems. Current analyses on hydrologic budget of the basin indicate that the overall supply of water (~ 60 mm/year) for various uses is approximately equal to the overall demand (~ 50 mm/year). Practically, this means that there is hardly any 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.

In addition to water scarcity, the basin experiences further problems: the risk of floods is increasing due to misuse of land, urbanization, deforestation and soil erosion; low consumption and water conservation technologies and recycling are scarce, and irrigation technologies are obsolete and inefficient; water harvesting is scarce; there is significant water loss in domestic water supply systems (conveyance lines) which worsen the situation.

Apart from physical constraints, several problems emerge in connection with the institutional framework. First of all, the absence of a River Basin Management Plan and of regulation establishing a basin authority allow for a lack of cooperation among the different institutions and leaves the way to compartmentalized responsibilities for basin planning and monitoring. This causes an overlap of responsibilities among different institutions, and conflicts among longer-established institutions (charged with water resource development and water allocation) and emerging institutions (dealing primarily with water quality and environmental issues). The involvement of the private sector is minimal, especially for wastewater treatment, and covers basically operation. The regulatory framework (quotas and quality standards) is not adequate. There is a lack of regulation for surface water, groundwater, and waste disposal, and a slow institutional response in water allocation and management. Moreover, standards are poorly enforced and water quality monitoring is insufficient for the production of reliable information. Another problem is the proliferation of regulations on water quality: a separate Water Law by itself does not exist, so all regulations are dispersed among several different laws, from civil to criminal law.

In the institutional/regulatory framework, the basin experiences a proliferation of actors and regulations, which indicate too many objectives, too many constraints, and too many responsibilities and authorities. Thus, the management of the basin requires a large number of performance criteria to be evaluated. This characteristic of the basin defines the context for any optimization study, where the linkage between the physical constraints (water shortage, competing uses of natural resources and environmental pollution) and the institutional as well as policy shortcomings need to be addressed.



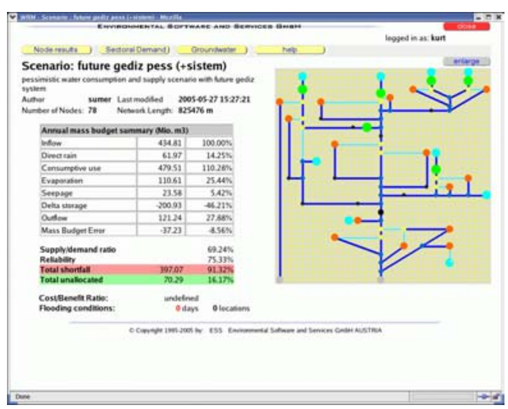


Figure1: The Gediz Basin.   Figure2: Network representation

4. MODELS AND TOOLS

A set of linked models is used for the simulation and optimisation of water resources management problems:

- A sub-basin scale dynamic rainfall-runoff 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 [7,8,9];
- 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 are linked to data bases that describe a river basin in terms of GIS layers, monitoring time series of climatic and hydro-meteorological data, and the main components of the water resources system like major demand nodes, configured in a topological network (Figure 2). 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. Empowerment through information as foreseen by Agenda 21's chapter 40 is the underlying concept.

3.1 Water Resources Modelling

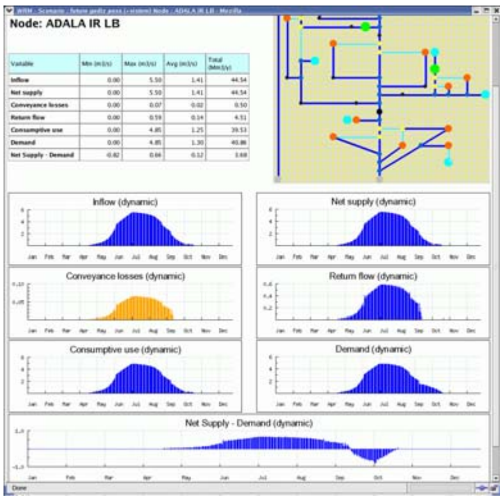
The central model is a dynamic, basin wide water resources model. It is using a topological network representation of a river basin, which consists of various node types and the river reaches and canals connecting them. Nodes represent objects such as sub-catchments, reservoirs, wells, diversions and 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, environmental water demands such as for the nourishment of wetlands, as well as flooding conditions with arbitrary penalty functions.

The dynamic, daily water budget is summarised 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 annualised costs considering investments, operating costs, and project or technology life times) includes estimates of the cost 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. Different allocation scenarios but 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. An example would be the number of all periods days when domestic water supply is less than 50% of the specified water demand for any or all of the domestic demand nodes representing cities. A maximum number of such events – which could be as low as 0 – defines one possible constraint.

3.2 The Optimisation Approach

The optimisation approach is conceptually simple. We use the full complexity of the simulation models to retain their distributed, non-linear and dynamic features deemed essential for the problem. We then split the optimisation into two steps: in a first step, we identify a set of feasible, non-dominated solutions 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 programming including the "re-combination" of parameter sets of successful trial runs [9, 10]. The set of alternatives are tagged with their expected effects in terms of selected performance criteria, so that after a failure, violating one or more constraints, we can select alternative values for the decision variables using these heuristics. Once a solution that meets the constraints is found, we explore its local neighbourhood in parameter or decision space 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.

We then use a discrete multi-criteria methodology to identify the optimal solution given a reference point in performance space [11]. The default reference point is utopia, and we normalise the performance space for all criteria as a degree of achievement in the interval between nadir and utopia. The last step of defining reference points step 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 such preference structure, expressed in natural units for all constraints, and learn about trade offs and possible solutions.



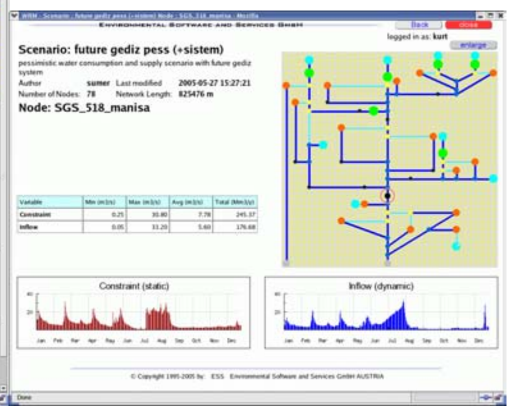


Figure 3: Node specific results. *Figure 4: Control node results: constraint versus simulated inflow.*

3.3 Criteria, Objectives and Constraints

The optimisation problem is formulated, in general as meeting as many targets as possible, and minimizing costs or maximising 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 characterised 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. Another of the 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 measure 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 behavioural changes, the direct involvement of major actors and stakeholders in the water sector to arrive at what must an ultimately be a political solution and consensus is essential.

4. FROM OPTIMISATION TO DECISION SUPPORT

The primary objective of the methodology is to contribute to better policy and decision making for resource management at the basin scale. The basic elements are reliable data and information, exploiting modern information technology, an integration of qualitative and quantitative tools for rational and scientifically based design and analysis of options and alternatives, and the support for wide participation in the decision making process. DSS based on optimisation technologies are a central element of operations research, and an established technology in water resources research [12]. Their practical applicability for complex problems, however, is limited by the fact that efficient optimisation requires a sometimes gross simplification (usually based on linearization) of the problem to arrive at an optimal solution with guaranteed convergence. A secondary problem is that the formalisation and related abstraction and simplifications make assumptions and results difficult to understand and communicate, which hinders broad participation in the decision making process and thus often generates barriers to the actual implementation of technically optimal solutions. Brute forward numerical optimisation, based on simulation modelling can retain a sufficiently detailed, realistic description. However, the combinatorial explosion of alternatives makes an exhaustive search of the decision space impossible for even moderately complex problems.

An alternative is the introduction of domain specific heuristics in a multi-tiered approach, using rule-based expert systems, and genetic algorithms, which can make the search much more efficient than traditional methods. Iterating between different levels of aggregation and representation, evolutionary strategies and local stochastic gradient search, a screening level approach and the use of evolutionary concepts of good enough rather than optimal can lead to efficient solutions even for very complex and large-scale problems.

This innovative approach to the optimisation of complex, non-linear, distributed and dynamic systems is embedded in a framework of interactive, participatory decision support based on a secondary layer of discrete multi-criteria optimisation. The reference point approach simplifies the expression of preferences and trade-offs, which can be expressed directly in natural terms and units. The method supports interactive, exploratory use and aims at easy integration in the planning and policy making process. The tools primarily provide a framework for structured, rational discourse facilitating the participation of all major institutions, actors and stakeholders in water resources management with a common, shared and sound information basis.

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