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WATER RESOURCES MANAGEMENT: ECONOMIC VALUATION AND PARTICIPATORY MULTI-CRITERIA OPTIMIZATION

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ABSTRACT

OPTIMA (http://www.ess.co.at/OPTIMA) is a EU funded international RTD project on Integrated Water Resources Management (IWRM) on the river basin scale, based on the concepts of the EU Water Framework Directive (2000/60/EC). The project integrates a set of simulation models with data bases, GIS, and optimisation and DSS tools. The fully web-based management information system is being applied to several river basins ranging from 240 to 18,000 km2 in size around the Eastern and Southern Mediterranean. All these river systems are characterised by varying levels of water scarcity, allocation conflicts, and pollution problems. The system integrates a cascade of models, embedded in a framework for participatory multi-objective, multi-criteria optimization. Models include a dynamic water resources (network) model with a daily time step, coupled to one or more aquifers. The model performs economic evaluation of allocation scenarios including environmental water allocation and the reliability of supply/demand; a dynamic rainfall-runoff model with built-in automatic calibration that provides simulated flow from engaged sub catchments; an irrigation water demand model; a basin wide water quality model with economic evaluation including environmental and recreational benefits; and tools for multi-criteria techno-economic optimisation combining satisficing and reference point methods. Direct stakeholder involvement is supported with on-line questionnaires of issues and perceptions, interactive optimisation tools, but also more traditional workshops.

KEY WORDS

Water resources management, IWRM, multi-criteria optimization, participatory decision making, Mediterranean region, Internet, stakeholder involvement, economic valuation.

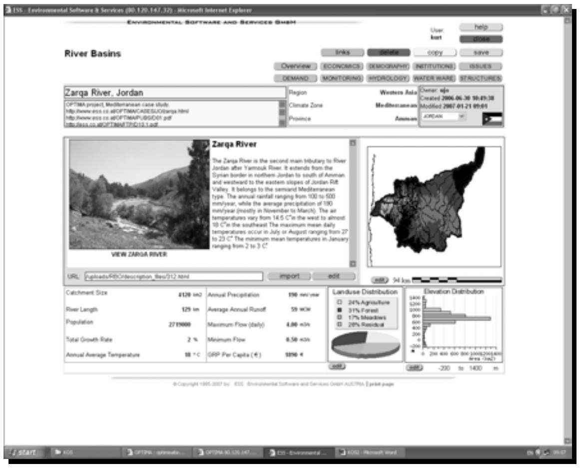
1. Introduction

Water is a key resource in the Mediterranean region, and efficient use and allocation are paramount to sustainable development, in particular in the coastal zone of the South and East, undergoing fast economic development, land use and demographic change [1,2]. Efficient and effective water resources management is as much a political as a scientific challenge, which not only requires a multi-disciplinary approach, but also the integration of key stakeholders into multi-objective, multi-criteria decision making processes. This in turn requires ease of use and direct access to a shared information basis and decision support tools that are intuitively understandable for a diverse user group, and that address not only hydrological and environmental engineering but also economic and social components directly. A participatory approach to decision making in a complex technical domain poses a few specific requirements that go beyond classical optimization paradigms [3]. These are addressed by:

- Preserving realism and detail of representation by using a set of cascading full-featured dynamic and distributed simulation models as the core to generate feasible and non-dominated alternatives in a two-step approach, combining satisficing and genetic programming with a discrete multi-criteria DSS [4]. Water technology alternatives including their cost structure, and economic valuation of water supply and use.
- Extending the set of objectives, criteria and constraints by economic evaluation estimating direct monetary and indirect costs derived with different valuation methods, including environmental and recreational benefits, penalties for shortfalls or flood damages, using expert systems technology to include difficult to quantify environmental and social dimensions.
- Putting specific emphasis on local acceptance and implementation through the active inclusion of stake-holders in an interactive, participatory decision making process carefully embedded in institutional structures, using a discrete multi-criteria reference point methodology, but also tools of structured stakeholder involvement such as dedicated web based tools and regular workshops.

2. The case studies

The approach, methods and tools are developed and tested in seven parallel case studies in Cyprus, Turkey, Lebanon, Jordan, Palestine and Israel, Tunisia, and Morocco, table 1. These case studies span a considerable range of basin size (from 240 to 18,000 km2), physiographical, hydrological, and socio-economic conditions. While they all share similar problems at a higher level of abstraction, the individual cases are sufficiently different to require a flexible set of fully data driven models and methods to be applicable in all cases.



Zarqa River, Jordan

OPTIMA project, Mediterranean case study

Region: Western Asia

Climate Zone: Mediterranean

Province: Amman

Owner: aje

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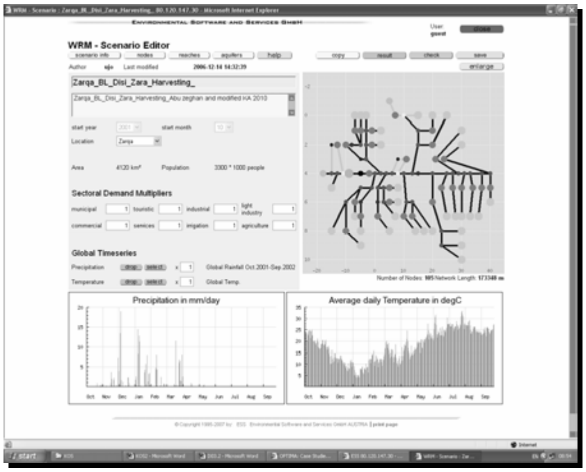
JORDAN

Zarqa River

The Zarqa River is the second main tributary to River Jordan after Yarmouk River. It extends from the Syrian border in northern Jordan to south of Amman and westward to the eastern slopes of Jordan Rift Valley. It belongs to the semiarid Mediterranean type. The annual rainfall ranging from 100 to 500 mm/year, while the average precipitation of 190 mm/year (mostly in November to March). The air temperatures vary from 14.5 C° in the west to almost 18 C° in the southeast The maximum mean daily temperatures occur in July or August ranging from 27 to 23 C° The minimum mean temperatures in January ranging from 2 to 3 C°

Catchment Size	4120 km2	Annual Precipitation	190 mm/year
River Length	129 km	Average Annual Runoff	59 MCM
Population	2719000	Maximum Flow (daily)	4.00 m3/s
Total Growth Rate	2 %	Minimum Flow	0.50 m3/s
Annual Average Temperature	18 °C	GRP Per Capita (€)	1890 €

Figure 1: River Basin Data Base



Author: aje   Last modified: 2006-12-14 14:32:39

Zarqa_BL_Disi_Zara_Harvesting_

Zarqa_BL_Disi_Zara_Harvesting_Abu zeghan and modified KA 2010

start year: 2001   start month: 10

Location: Zarqa

Area: 4120 km²   Population: 3000 * 1000 people

Sectoral Demand Multipliers

municipal: 1   touristic: 1   industrial: 1   light industry: 1

commercial: 1   services: 1   irrigation: 1   agriculture: 1

Global Timeseries

Precipitation   drop   select   x 1   Global Rainfall Oct 2001-Sep 2002

Temperature   drop   select   x 1   Global Temp.

Number of Nodes: 105 Network Length: 173348 m

Figure 2: Network representation of a river basin

At a high level of abstraction, in all cases water resources (in both quantitative and qualitative terms) are under stress, with the current demand (again both in terms of quantity and quality) barely met by the supply. The problems, whether current water scarcity, insufficient resources for further development, or primarily constraints imposed by low water quality, all seem to be amenable to better allocation strategies and the implementation of a range of policies, strategies or water technologies contributing to a reduction in demand, consumptive use, loss reductions, resulting in increased efficiency of use, reduced levels of pollution by emission reductions and better treatment.

The relative importance of different issues is subject to individual or group perceptions, a socially constructed reality, as it includes the valuation of very different aspects of the system performance. To analyse the range of issues the different stakeholders in each case deemed important, a set of (on-line) questionnaires and interviews was used on over 300 institutions and individuals.

Table 1: The case studies

Basin	Size (km2)	Population	Precipitation (mm)	Country
Dhiarizos River	260	3,550	680	Cyprus
Gediz River	18,000	1,700,000	700	Turkey
Lower Litani River	600	390,000	700	Lebanon
Zarqa River	4,120	2,720,000	190	Jordan
Wadi Zeimar, Alexander River	500	600,000	640	Palestine, Israel
Melian River	553	390,500	490	Tunisia
Martil River	1,129	445,000	650	Morocco

In all case studies, we can identify a set of expectations on the performance of the water resources system in terms of multiple criteria and multiple, conflicting objectives and constraints. At the same time, one can identify a set of measures, that are thought to potentially contribute to an improvement of the perceived current and expected future problems and issues.

To evaluate the expected effects, and the efficiency of any and all such measures in terms of the criteria, objectives and constraints formulated, a number of elements in the decision making process are required:

- A set of (shared, common) models that can evaluate the impacts of any such measure by simulating their effects in WHAT-IF scenarios with a high degree of detail and reliability as the basis for any further design;
- A clear understanding of the decision making processes at work and the major stakeholders that need to be involved to identify the issues, criteria, objectives, constraints and measure contemplated in each case;
- An agreed upon "preference structure" that defines the goals of the exercise, defined together with the stakeholders;
- Tools to generate and evaluate feasible alternatives within this stakeholder defined preference structure using the model tools.

3. The model representation

The optimization uses a web-based water resources management information and simulation system, that implements basic concepts of the EU Water Framework Directive 2000/60/EC [5,6,7]. The primary objective of the model system is a realistic and detailed dynamic water budget for each case that is the basis for

annualized investment and operating costs, and the (production) benefits of water demand met [9,10].

- Indirect economic criteria. These describe non-monetary costs and benefits or those that are very difficult to estimate and contain a considerable amount of subjective elements, such as the cost of shortfall (not meeting specified flow or supply targets at any given location, expressed by a non-linear threshold function, for example, penalties for violations of (quality) standards, flood damages, etc, but also benefits like in-stream recreational benefits, environmental water supply (minimum flow or supply to wetlands, etc.), environmental water supply (maintaining in-stream minimum flow or supply to wetlands, etc); Estimates for the costs and benefits for the non-market values are derived from contingent valuation methods that again involve the stakeholders as the primary "economic agents" in each basin [11]. The repertoire of cost functions associated with all nodes types provides a rich set of instruments to reflect stakeholder expectations on systems performance.

GEDIZ BASELINE 1982

Created 2006-11-13 20:44
Modified 2006-12-15 07:43

gediz baseline 1982: the constraints from the end user DSI

Feasible set

Results for node type: demand

NAME	%app	%min	%max	INV	OP	Min%	Max%	Node name
Education and training of farmers (irrigational)	78	58	89	795	644	50	90	ADALA IR RB
Education and training of farmers (irrigational)	76	53	90	911	738	50	90	ADALA IR LB
Education and training of farmers (irrigational)	76	51	90	1966	1594	50	90	AHMETLI IRRG. LB
Education and training of farmers (irrigational)	84	55	90	2236	1812	50	90	MENEMEN IRRG. LB
Education and training of farmers (irrigational)	76	51	90	723	586	50	90	MENEMEN IRRG. RB
Education and training of farmers (irrigational)	78	51	90	1904	1543	50	90	AHMETLI IRRG. RB
Education and training of farmers (irrigational)	82	51	90	153	124	50	90	SARIGOL IR
Education and training of farmers (irrigational)	82	0	90	1122	910	50	90	ALASEHIR IR
Education and training of urban water users	82	25	75	1340	1110	25	75	Manisa Municipality
Education and training of urban water users	74	25	78	65	54	25	75	Ahmetli Municipality
Education and training of urban water users	80	25	72	520	431	25	75	Akhisar Municipality
Education and training of urban water users	78	0	74	257	213	25	75	Alasehir Municipality
Education and training of urban water users	82	0	73	79	66	25	75	Golmarmara Municipality
Education and training of urban water users	82	25	75	171	141	25	75	Kemalpasa Municipality
Education and training of urban water users	66	27	74	257	213	25	75	Menemen Municipality
Education and training of urban water users	66	0	69	445	369	25	75	Salihli Municipality
Education and training of urban water users	82	27	78	94	77	25	75	Saruhanli Municipality
Education and training of urban water users	74	0	74	614	509	25	75	Turgutlu Municipality
URBAN WATER SAVING (RESIDENTIAL PLUMBING FIXTURE)	38	0	50	89659	0	25	50	Akhisar Municipality
URBAN WATER SAVING (RESIDENTIAL PLUMBING FIXTURE)	32	0	50	86211	0	25	50	Salihli Municipality
URBAN WATER SAVING (RESIDENTIAL PLUMBING FIXTURE)	38	0	50	80583	0	25	50	Turgutlu Municipality
URBAN WATER SAVING (RESIDENTIAL PLUMBING FIXTURE)	38	0	49	178396	0	25	50	Manisa Municipality
URBAN WATER SAVING (RESIDENTIAL PLUMBING FIXTURE)	42	0	49	30407	0	25	50	Kemalpasa Municipality
URBAN WATER SAVING (RESIDENTIAL PLUMBING FIXTURE)	32	0	50	44308	0	25	50	Menemen Municipality

Figure 4: node-specific instruments, cost functions

From this set of criteria (a total of 25 were formulated at the basin level that can be applied to individual nodes or sectors as well), any number of derived criteria or indices can be generated, examples would include various measure of (economic and water) efficiency, different estimates for the cost of water (services), or measure of equity by comparing sectoral or node specific criteria.

These criteria provide the language with which the stakeholders can express their preferences or expectations. In the first round of a two stage optimization approach this is based on a satisficing paradigm [14], i.e., exclusively in terms of constraints expressed in natural units for the criteria. This is an intuitive and easy to understand expression of preferences that doe not require any more abstract concepts like weights or comparative ranking, pair-wise comparisons, etc.

6. The optimization approach

The dynamic simulation system and the stakeholders' preferences form the basis for the optimization and decision support approach developed in OPTIMA. This simulation based DSS approach [12] is implementing concepts of satisficing with a modified reference point paradigm for multi-criteria, multi-objective problems [13,14] using an inverse problem solving approach in a simulation based Monte Carlo framework [15], extended by concepts of evolutionary programming and domain specific heuristics [16].

The basic approach of OPTIMA is one of participatory decision making within this multi-criteria framework. The basic DSS approach is based on a satisficing paradigm [14], chosen and further developed specifically for the participatory approach. The basic model paradigm is dynamic mass budget simulation as a straight forward implementation of the conservation laws of classical physics, even though the system representation for the optimization can be understood as a simplified Hamiltonian set of state space "fiber bundles", and in it possible probabilistic extension as a Riemannian manifold representation of the state space. 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.

The multi-criteria optimization is based on a two stage approach. In the first step, and given the models structure and stakeholder preferences identified, we generate sets of feasible solutions that meet all the criteria.

The procedure is as follows: The starting point is a baseline scenario that includes the basic economic (e)valuation so that all the criteria accepted by the stakeholders are generated as part of the models results.

On this basis, optimization scenaria are formulated. These consists of

- The set of CONSTRAINTS described above
- The set of INSTRUMENTS that can be applied to the baseline system.

The instruments or measures will affect the behaviour of the individual nodes or classes or nodes. Typical example will be alternative irrigation technologies, canal lining, upgrade of pipe networks, water saving appliances, recycling and re-use of water, awareness raising campaigns, improved enforcement of regulations, etc. Structural measures include alternative reservoirs, modified allocation/diversion rules and strategies, increased inputs (e.g., bigger pumps, inter-basin transfers, desalination, water harvesting) and alternative production technologies and waste water treatment on the quality side. The instruments are loaded from a data base of generic water technologies.

Each of these instruments or strategies is defined by a cost function (investment and operating costs) and effects. These may relate to different aspects of a node's behaviour and include water demands, consumptive use, or losses, or alternative physical properties of structural system components.

The optimization model then uses a heuristic method to generate and evaluate alternatives. Scenarios are generated by applying the alternative instruments (for a given node, they may either be combined or mutually exclusive) to a (initially) randomly selected degree with a user defined interval of a minimum and a maximum application rate or percentage. The initial *a priori* probability of selecting a specific instrument can be affected by a weight defined in the optimization scenario. With an increasing number of scenarios generated, simulated, and evaluated, a co-variance (cross-correlation) matrix of decision variables versus performance criteria can be built.

Water Technologies

CHANNEL PIPING (PVC)

Owner: intergeo

Created 2005-12-08 11:48:00

Modified 2006-12-11 14:41

newly created Water Technologies Object

Application Domain: demand

Technology Type: distribution

Cost estimates:

Unit investment cost: 0 EUR

Investment reference unit: m

Unit operating cost: 2.00 EUR

Operating cost reference unit: m3

Technology Life Time: 50 year

Minimum implementation: 50 %

Water Demand and Losses:

Demand reduction: 0.00 %

Consumptive use reduction: 0.00 %

Conveyance loss reduction: 95.00 %

Return flow loss reduction: 95.00 %

Water Quality:

BOD reduction: 0.00 %

Tracer reduction: 0.00 %

Water Supply:

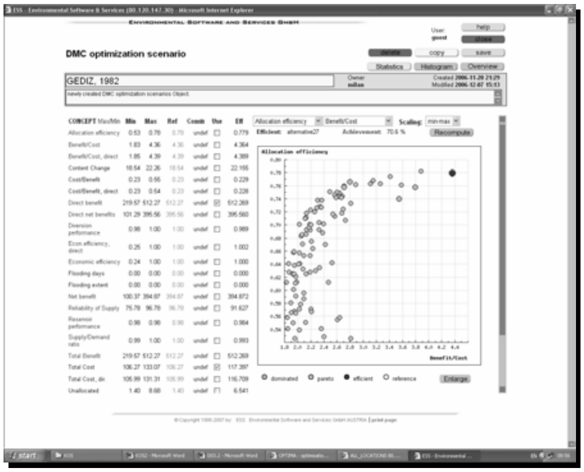
Supply Multiplier: undefined

Incremental water supply: undefined m3/s

Scaling: (in investment reference units)

small	medium	large

Figure 5: Water technologies data base



DMC optimization scenario

GEDIZ, 1982

Owner: millan

Created 2006-11-29 21:29

Modified 2006-12-07 15:13

newly created DMC optimization scenarios Object

Efficient: alternative27 Achievement: 70.6 %

CONCEPT Max/Min	Min	Max	Ref	Comb	Use	Eff
Allocation efficiency	0.53	0.78	0.78	undef	☐	0.779
Benefit/Cost	1.83	4.36	4.36	undef	☐	4.364
Benefit/Cost, direct	1.85	4.39	4.39	undef	☐	4.389
Content Change	18.54	22.26	18.54	undef	☐	22.156
Cost/Benefit	0.23	0.55	0.23	undef	☐	0.229
Cost/Benefit, direct	0.23	0.54	0.23	undef	☐	0.228
Direct benefit	219.57	512.27	512.27	undef	☑	512.269
Direct net benefits	101.29	395.56	395.56	undef	☐	395.560
Diversion performance	0.98	1.00	1.00	undef	☐	0.989
Econ efficiency, direct	0.25	1.00	1.00	undef	☐	1.002
Economic efficiency	0.24	1.00	1.00	undef	☐	1.000
Flooding days	0.00	0.00	0.00	undef	☐	0.000
Flooding extent	0.00	0.00	0.00	undef	☐	0.000
Net benefit	100.37	394.87	394.87	undef	☐	394.872
Reliability of Supply	75.78	96.78	96.78	undef	☐	91.627
Reservoir performance	0.98	0.98	0.98	undef	☐	0.984
Supply/Demand ratio	0.99	1.00	1.00	undef	☐	0.993
Total Benefit	219.57	512.27	512.27	undef	☐	512.269
Total Cost	106.27	133.07	106.27	undef	☑	117.397
Total Cost, dir.	105.99	131.31	105.99	undef	☐	116.709
Unallocated	1.40	8.68	1.40	undef	☐	6.541

Figure 6: plotting alternatives

With that, and using concepts of genetic algorithms and machine learning [17] to speed up the search in a discontinuous decision space, the *a priori* probabilities for selecting and configuring instruments can slowly be adjusted for a more efficient search in decision space, increasing the efficiency with which feasible alternatives can be generated. The optimization continues until a user defined counter for the maximum number of trial runs or a minimum number of feasible solutions has been reached.

If no feasible solutions can be found, the scenario must be modified to

- Add more and more effective instruments
- Relax the set of constraints.

The second step of the optimization is then a discrete multi-criteria assessment of the set of feasible solutions generated in the first phase using a reference point methodology [18]. This can be done automatically, using UTOPIA as the default reference point, and all initially generated criteria simultaneously or interactively with a final round of stakeholder participation.

7. Discrete multi-criteria: stakeholder participation

In the final round of optimization with stakeholder involvement an efficient or compromise solution from the set of feasible solutions can be found. The first step is performed automatically: we can separate dominated from pareto optimal solutions and eliminate the dominated subset. Dominated and non-dominated subsets however, depend on the choice of the (sub)set of criteria the stakeholders can agree to consider. Another form of interactive control is the introduction of secondary or a posteriori constraints on the feasible set. And finally, the users can move the reference point away from UTOPIA which basically implies a weighting of criteria for the trade offs [18]. In all cases, the software can show the consequences of any such change in the preference structure immediately and graphically. The main power and function of the methodology however, is not so much the efficient manipulation of large and complex data sets, but to stimulate and facilitate the discussions between the stakeholders that have to explain and defend their choices and preferences made explicit now.

8. Discussion and concluding remarks

A river basin a or water resources system is complex, dynamic, non-linear, distributed, and subject to numerous views, perceptions and expectations which leads to a multi-criteria representations and a multi-objective expectation on its performance. The behaviour of such a system given the numerous and often highly correlated and antagonistic decision variables is (very) non differentiable.

At the same time, this representation is needed to provide a sufficiently detailed and realistic representation in terms of natural concepts that are directly relevant to the stakeholders who will usually preclude any aggregate and simplified, linearized representation.

It is critical to strike a balance between necessary detail and ease of use or at least understanding, which is essential for the involvement of stakeholders that typically have a broad range of non-technical backgrounds. Another important closely related aspect is the explicit treatment of economics. While all the physical and hydrological details is necessary for a reliable and detailed representation of the systems functions, the ultimate criteria relevant to the decision making process are monetary. Costs and benefits are easy enough to interpret and understand, and are directly relevant to all stakeholders.

In summary however, the utility and power of quantitative analysis i.e., modelling and optimization notwithstanding, their primary role is not so much to provide ready made "optimal" answers, but to facilitate more open, informed, and participatory decision making processes.

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