WATER RESOURCES SIMULATION AND OPTIMIZATION: A WEB BASED APPROACH

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ABSTRACT

Water resources are one of the limiting factors of regional development around the Eastern and Southern Mediterranean. Scarcity and conflict, but also considerable uncertainty, inter-annual variability, and simple lack of reliable data characterize the problems of water resource management in many countries and river basins.

Within the EU sponsored international RTD project OPTIMA a water resources optimization system is being developed that addresses a broad range of objectives and criteria. A web based client-server implementation supports distributed use and easy access, providing considerable server side computing power for distributed web browser clients. This architecture supports a participatory approach involving local stake holders for multi-criteria optimisation and decision support.

The multi-criteria optimization approach covers global and sectoral demand and supply balances, reliability of supply, cost and benefits, as well as compliance with water quality standards. Arbitrary penalty functions can be used for the valuation of missing targets, both shortfalls of supply as well as excess (flooding or pollution), or exceeding water quality standards.

The approach and methodology are demonstrated using the case studies of the OPTIMA project that demonstrate the entire range of prototypical water management problems in the region, and their potential solutions.

KEY WORDS

Water resources, simulation optimization, multi-criteria, heuristics, Mediterranean.

1. Introduction

Water resources management lends itself to analysis by simulation and optimisation, as the basic principle of mass conservation provides a solid framework. Keeping track of the water in a river basin as a natural hydrographic unit in a dynamic water budget, and estimating the costs and benefits of supply and demands met should answer many questions.

Of course, 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 all contribute to make water resources management a challenging field.

While simulation modelling of WHAT IF scenarios can provide a high degree of detail and realism to problem representation, optimisation can answer the more interesting question of HOW TO. The challenge is in combining the best of both worlds, and at the same time integrate the tools into the real-world decision making processes, which requires a simple and intuitive representation and interface to end users for a participatory approach.

For the modelling approach, one possible solution is to build sets or cascades of 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 (e.g., [2], [3], [4]), i.e., finding one or more feasible solutions for a set of interactively defined constraints.

The latter requirement, the interactive involvement of stakeholders in a decision making process, requires easy access to tools that may require 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 [5].

2. The OPTIMA Project

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 (http://www.ess.co.at/OPTIMA)

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. Based on the European Water Framework Directive (2000/60/EC) the approach equally considers economic efficiency, environmental compatibility, and social equity as the pillars of sustainable development [6], [7].

The project also aims at building a wide dissemination network of expertise and knowledge exchange sharing its findings, generic data, and best practice examples.

For a broad geographical coverage and a good basis for comparative analysis, OPTIMA brings together partners from Austria, Italy, Greece, Cyprus, Malta, Turkey, Lebanon, Jordan, Palestine, Tunisia, and Morocco. OPTIMA is extending classical optimisation and mathematical programming methodology in several respects, by:

- Using a 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 up-to-date remote-sensing derived land use information 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;
- Comparative evaluation and benchmarking across the set of local and regional case studies in 7 countries, namely Cyprus, Turkey, Lebanon, Jordan, Palestine, Tunisia and Morocco around the Southern and Eastern Mediterranean.

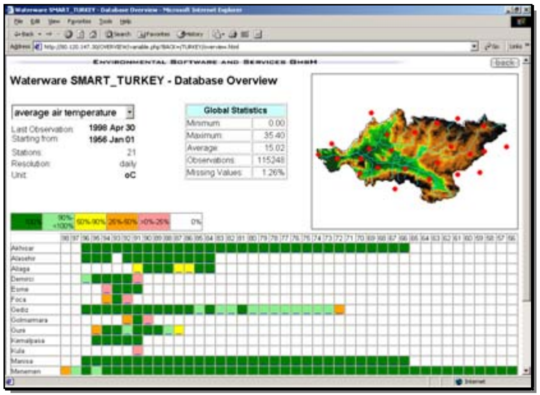
3. Models and Tools

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

- A dynamic land use change model (http://80.120.147.30/LUC/)
- A sub-basin scale dynamic rainfall-runoff that feeds the water resources model with flow inputs for ungaged basins;
- An irrigation water demand model estimating supplementary irrigation water demands as input for the water resources model;
- A river basin scale water resources modelling system operating on a topological network of nodes and reaches and linked to aquifers for conjunctive use scenarios: http://www.ess.co.at/WATERWARE [8], [9],[10].
- A dynamic basin-wide water quality model for DO/BOD and conservative or first-order decaying pollutants, linked to the water resources management information system.

The models are linked to data bases that describe each of the cases in terms of georeferenced monitoring stations (Figure 1), and their time series of climatic and hydro-meteorological data (Figure 2), and the main components of the water resources system like major demand nodes. Linkage between the models is by means of indicators aggregated by rules that summarize the output from one model as boundary conditions for another, translating differences in dimensionality and resolution in time and space.

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.

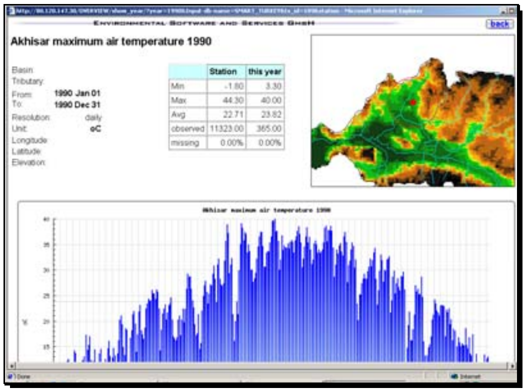


Waterware SMART_TURKEY - Database Overview

Last Observation 1998 Apr 30
Starting from 1956 Jan 01
Stations 21
Resolution daily
Unit oC

Global Statistics	
Minimum	0.00
Maximum	35.40
Average	15.02
Observations	115248
Missing Values	1.26%

Figure1: monitoring stations, location and temporal coverage



Akhisar maximum air temperature 1990

Basin:
Tributary:
From: 1990 Jan 01
To: 1990 Dec 31
Resolution: daily
Unit: oC
Longitude:
Latitude:
Elevation:

	Station	this year
Min	-1.80	3.30
Max	44.30	40.00
Avg	22.71	23.82
observed	11323.00	365.00
missing	0.00%	0.00%

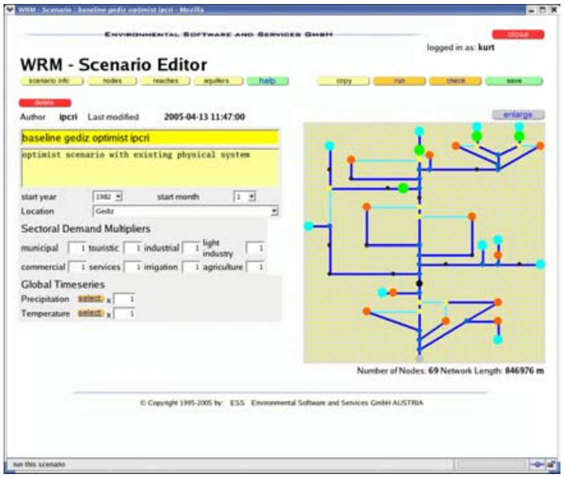
Figure2: Monitoring data display

4. Water Resources Modelling

The simulation system uses nested or cascading models that represent various parts of the water resources system with a high spatial and temporal resolution. Component models such as a daily rainfall-runoff model for sub-catchments use an automatic calibration methodology based on pattern matching and Gestalt rather than traditional statistical least square methods. This works very well in situations of limited data availability and high data uncertainty.

The central model is a dynamic, basin wide water resources model. It is using a topological network representation of a river basin, that consists of various node types and the river reaches and canals connecting them (Figure 3). 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 (Figure 4). 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 function.

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 (Figure 5). 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.



WRM - Scenario Editor

Author ipcri Last modified 2005-04-13 11:47:00

baseline gediz optimist ipcri

optimist scenario with existing physical system

start year 1982 start month 1

Location Gediz

Sectoral Demand Multipliers

municipal 1 touristic 1 industrial 1 light industry 1

commercial 1 services 1 irrigation 1 agriculture 1

Global Timeseries

Precipitation select x 1

Temperature select x 1

Number of Nodes: 69 Network Length: 846976 m

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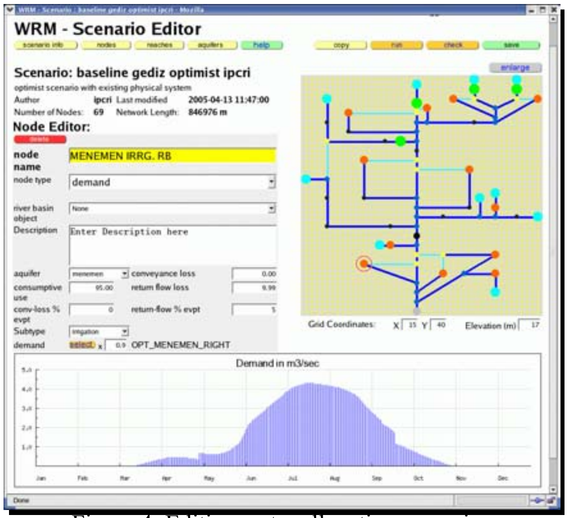
Figure3: water resources model network

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 specific 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 of domestic water supply less than 50% of the specified demand. A maximum number of such events – which could be as low as 0 – defines one possible constraint.



WRM - Scenario Editor

Scenario: baseline gediz optimist ipcri

optimist scenario with existing physical system

Author ipcri Last modified 2005-04-13 11:47:00

Number of Nodes: 69 Network Length: 846976 m

Node Editor:

node name MENEMEN IRRG. RB

node type demand

river basin object None

Description Enter Description here

aquifer menemen conveyance loss 0.00

consumptive use 95.00 return flow loss 9.99

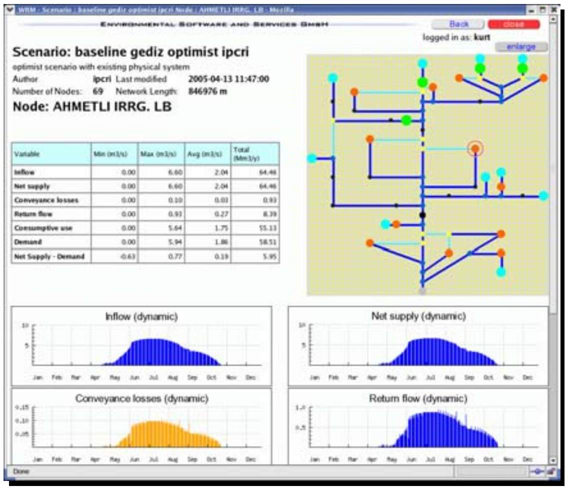
conv-loss % evpt 0 return-flow % evpt 5

Subtype irrigation

demand select x 0.9 OPT_MENEMEN_RIGHT

Grid Coordinates: X 15 Y 40 Elevation (m) 17

Figure 4: Editing water allocation scenarios



Scenario: baseline gediz optimist ipcri

optimist scenario with existing physical system

Author ipcri Last modified 2005-04-13 11:47:00

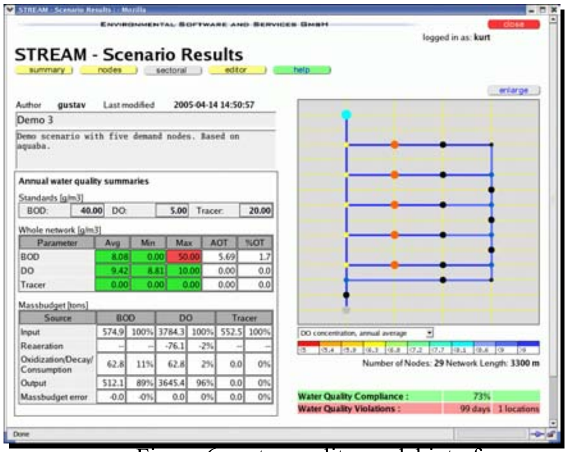
Number of Nodes: 69 Network Length: 846976 m

Node: AHMETLI IRRG. LB

Variable	Min (m3/s)	Max (m3/s)	Avg (m3/s)	Total (Mm3/y)
Inflow	0.00	6.60	2.04	64.46
Net supply	0.00	6.60	2.04	64.46
Conveyance losses	0.00	0.10	0.03	0.93
Return flow	0.00	0.93	0.27	8.39
Consumptive use	0.00	5.64	1.75	55.13
Demand	0.00	5.94	1.86	58.51
Net Supply - Demand	-0.63	0.77	0.19	5.95

Figure 5 : Node specific model results

The water quality model that post-processes the daily flow regimes from the water resources scenarios adds additional criteria for describing and evaluating a given scenario in terms of meeting or violating water quality standards in space and time. The dynamic (daily) model shares the network and uses the flow scenarios generated by the water resources model, and adds pollutant load data to the return flow from demand nodes (domestic, industrial, agricultural) as well as from lateral inflow to the individual reaches (Figure 6).



STREAM - Scenario Results

logged in as: **kurt**

Author **gustav** Last modified **2005-04-14 14:50:57**

Demo 3

Demo scenario with five demand nodes. Based on aquaba.

Annual water quality summaries

Standards [g/m3]

BOD:	**40.00**	DO:	**5.00**	Tracer:	**20.00**

Whole network [g/m3]

Parameter	Avg	Min	Max	AOT	%OT
BOD	8.08	0.00	50.00	5.69	1.7
DO	9.42	8.81	10.00	0.00	0.0
Tracer	0.00	0.00	0.00	0.00	0.0

Massbudget [tons]

Source	BOD		DO		Tracer	
Input	574.9	100%	3784.3	100%	552.5	100%
Reaeration	--	--	-76.1	-2%	--	--
Oxidization/Decay/ Consumption	62.8	11%	62.8	2%	0.0	0%
Output	512.1	89%	3645.4	96%	0.0	0%
Massbudget error	-0.0	-0%	0.0	0%	0.0	0%

Number of Nodes: **29** Network Length: **3300 m**

Water Quality Compliance :	73%	
Water Quality Violations :	99 days	1 locations

Figure 6: water quality model interface

The models, their display, analysis, and summary pages and the interactive scenario editors are implemented as web-accessible applications: dynamic pages generated server side with cgis and PHP can be viewed and edited from any web browser by a user with the required access privileges and authentication.

5. Calibration and Optimization

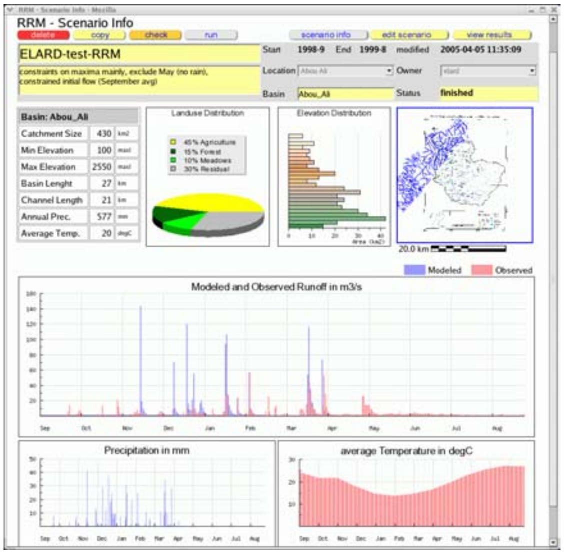
The optimisation approach is conceptually simple. We use the full complexity of the simulation models to retain their distributed, non-linear and dynamic features deemed essential for the problem. We then split the optimisation into two steps: in a first step, we identify a set of feasible, non-dominated 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 [11], [14]. 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 [12]. 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.

The optimization of the overall water resources system uses similar heuristics and concepts of genetic programming, based on a realistic, detailed, dynamic and distributed representation of the individual river basins. The underlying dynamic (daily) water resources simulation model describes the water resources systems at a basin scale including the groundwater system for conjunctive use. A coupled dynamic, daily water quality model simulates DO/BOD as well as conservative and first-order decaying pollutants and sediments with the full resolution of the basin wide river network topology. This provides additional criteria for the optimization. The primary unsupervised optimization identifies sets of feasible and non-dominated pareto-optimal solutions in heavily constrained scenarios; these are the basis for an interactive discrete multi-criteria selection using a reference point approach with the participation of end users.

Calibration and optimisation are conceptually similar: we consider the set of models as a transfer function that translates a point in the parameter space (including decision variables) into a point in a behaviour space of high dimensionality. The acceptable sub-region in the behaviour space that defines a feasible scenario can represent both observations as well as expectations of the systems performance [11].

A simple example is the calibration of the rainfall-runoff model (Figure 7,8): rather than using a least-square approach, we define a set of constraints in terms of inequalities or ranges around a given concept that the model has to meet. The constraints can be derived from the observation data, but also represent expert knowledge. They can represent ranges or boxes around observed flow, but also the relationships between various observation data or derived metrics, e.g., to describe hydrograph recession, ratios between minimum maximum flows, averages or totals over selected periods, and in general, any or all patterns that can define plausible expected behaviour or Gestalt of the system modelled rather than some statistical properties of highly uncertain observation data.



ELARD-test-RRM

constraints on maxima mainly, exclude May (no rain), constrained initial flow (September avg)

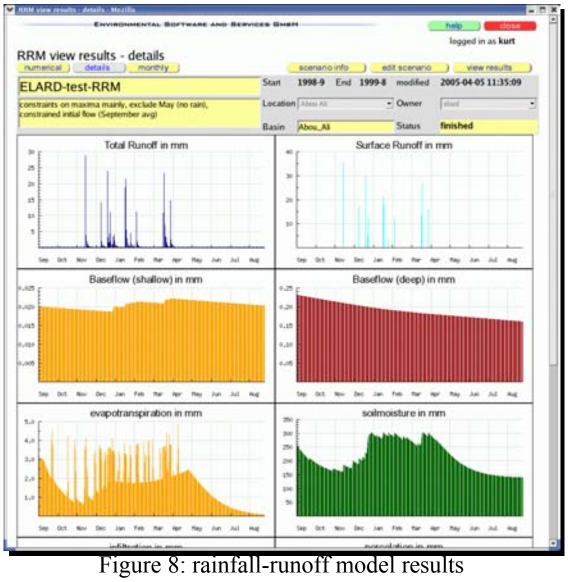
Start 1998-9 End 1999-8 modified 2005-04-05 11:35:09

Location Abou Ali Owner elard

Basin Abou_Ali Status finished

Basin: Abou_Ali		
Catchment Size	430	km2
Min Elevation	100	masl
Max Elevation	2550	masl
Basin Lenght	27	km
Channel Length	21	km
Annual Prec.	577	mm
Average Temp.	20	degC

Figure 7: rainfall-runoff model scenario



logged in as **kurt**

ELARD-test-RRM

constraints on maxima mainly, exclude May (no rain), constrained initial flow (September avg)

Start 1998-9 End 1999-8 modified 2005-04-05 11:35:09

Location Abou Ali Owner elard

Basin Abou_Ali Status finished

Figure 8: rainfall-runoff model results

The same concept is used for the optimization of the water resources model. Using a combination of brute forward Monte Carlo and local stochastic hill climbing, we can identify sets or populations of scenarios (parameter sets) to meet a given set of constraints. These sets are used as the basis of several cycles of evolutionary programming, using a standard set of operators on the respective parameter vectors. These operators affect both structural binary changes (choice of structures, allocation rules and water technologies) as well as continuous modification (the scaling of technology parameters). Parameters that affect the same object in the system are grouped together, and are more likely to be exchanged as a group rather than individually, thus preserving cross-correlation patterns within the set or population of feasible solutions. Progress is being made by iteratively tightening the constraints, both by making acceptable ranges smaller, and by adding new concepts or dimensions. Since several population can be explored independently, an efficient task parallel implementation on several multi-processor machines is possible to speed up the optimisation process.

Rather than using a completely random search approach, we formulate a set of rules or heuristics that exploit knowledge about the effects of parameter changes: depending on the constraints violated, we can identify sub-sets of the parameter vector and preferred directions for modification that are more likely to succeed: rather than blind mutations and selection, we generate feasible solutions more efficiently.

The results of the optimisation process are several possible or feasible solutions that meet all constraints specified – this of course can be interpreted as meeting a minimal value of an objective function, is considerably more flexible and can represent several concepts in their natural units and an easy to understand multi-criteria and multi-objective model. These solutions are now available for a final, interactive step with the direct involvement of end users and stakeholders to define their preference structures in terms of implicit trade-offs, using a reference point approach [12]. An important advantage of the methodology is in its intuitive and simple interface, and the minimisation of assumptions that must be made.

6. Conclusion

The primary objective of the OPTIMA project is to contribute to better policy and decision making for resource management in the coastal zone [7]. 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 [13]. 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 thuds 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 [14]. 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. Using a reference point approach to simplify the expression of preferences and trade-offs, this combined method supports interactive, exploratory use and aims at easy integration in the planning and policy making process, facilitating the participation of all major institutions, actors and stakeholders in water resources, which is more or less everybody, i.e., the public.

7. Acknowledgements

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