Risk-Dependent Integrated Water Resources Management: A conceptual model

Shaul Sorek, Wolf von Igel, Lea Kronaveter-Goldstein, Eugene Levner

Abstract: Decision making related to the interaction between water and environmental issues is associated with five inter-linked Principal Water Elements alternatives: Groundwater; Surface-water; Marginal-water; Anthropogenic impact on an aquifer; Optimal quantity/quality water management. The latter, in view of ongoing deterioration in water quality and quantity, should be the focal attention of a central water authority being the decision maker governing and implementing policy specifically when demand is growing at higher rates then availability. An integrated approach for management of water resources must account for often contradictory interests of various stakeholders (i.e. site criteria represented by its water related exploitations) while relying on a wide range of disciplines (physics of flow and solutes transport through aquifers; operations research; economics; politics etc.). We propose a conceptual Decisions Support System for establishing an Integrated Water Resources Management generic model. At its first phase this model, calibrated per a prescribed region, is aimed at providing optimum ranking scenarios between water related criteria (stakeholders such as urbanization, industry, agriculture, watersheds and economy) and action alternatives associated with the PWE (e.g. pumping/injection protocols and/or desalinization/purification degrees). The model following second DSS phase aims at judging its first phase resolution on the basis of simulations associated with the site criteria (e.g. predictions of its watershed subsurface flow and transport and/or water pricing associate with its economy). Iterations between these two phases will yield a balanced decision, bridging between policy and implementation.

Keywords: Decision Support Systems (DSS), Quantifiable Integrated Water Resources Management (IWRM), Generic Model, Stakeholders involvement

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Riassunto: *Le risoluzioni legate all'interazioni tra acque e le conseguenze ambientali è associata a 5 degli elementi principali relativi alle acque (*Principal Water Elements*) e legati tra di loro: le Acque sotterranee; le Acque di superficie; le Acque marginali; l'Impatto antropico sull'acquifero; la gestione ottimale del rapporto quantità qualità dell'acqua. Su quest'ultimo, in vista del deterioramento nella qualità e quantità delle acque, dovrebbe essere focalizzata l' attenzione di un'autorità centrale delle acque essendo un punto decisionale della politica di gestione e di attuazione, in particolare quando la domanda sta crescendo a tassi più elevati della disponibilità. Un approccio integrato per la gestione delle risorse delle acque deve rendere conto spesso di interessi contraddittori delle varie parti interessate (ad esempio i criteri locali messi in atto sull'uso delle acque ed i relativi sfruttamenti), mentre si basa su una vasta gamma di discipline (fisica dei fluidi e trasporto dei soluti attraverso gli acquiferi; operazioni di ricerca; economiche; politiche etc). Noi proponiamo un Sistema di Supporto Decisionale di tipo concettuale per stabilire un modello generico di Gestione delle Risorse Integrate delle Acque. In questa prima fase questo modello, calibrato per una determinata regione, si rivolge a fornire uno scenario ottimale di classificazione tra l'acqua correlata a certi criteri (fattori come l'urbanizzazione, l'industria, l'agricoltura, i bacini, e l'economia) ed i processi alternativi associati al PWE (ad esempio i metodi di pompaggio e iniezione e/o i gradi di desalinizzazione/purificazione). Il modello che segue, seconda fase del DDS, si rivolge ad analizzare la risoluzione della prima fase sulla base di simulazioni associate ai criteri locali (ad esempio predizione del flusso sotterraneo del bacino idrografico e trasporto e/o prezzo dell'acqua associato all'economia del bacino stesso). Le iterazioni tra queste due fasi produrranno una decisione equilibrata, di collegamento tra la politica delle acque e la loro gestione.*

Introduction

The alarming deterioration pace of water resources in recent years (in both quality and quantity) had led to the recognition of the urgent need in integrated approach for quantifiable water management model. Growing water demand and anthropogenic activity has increased the conflicts among competitive uses of water by different stakeholders, while also increasing the contamination of ecosystems and water sources. One of the eight principles and concepts concluded by the Agenda 21 and the Dublin Principles specifically referred to "integrated water resource management, implying an intersectorial approach, representation of all stakeholders, all physical aspects of water resources, and sustainability and environmental considerations" (UNCED, 1992). The imbalance in national/regional water system emanates from: (1) Lack of sustainable water quantity, and (2) Severe decline in water quality. The first is the result of overexploitation above natural renewable limits due to, e.g., increase of water demand (Municipal, Industry and Agriculture) associated with demographic and economic development, while delaying the introduction of alternative water sources (e.g. desalination plants).

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The second is the result of, e.g., neglect of pollution source impact on ground/surface water and lack of water quality monitoring systems.

Administrations of hydrological resources must reshape the water management practices and redesign its supporting tools. The guideline for an integrated water management approach is defined by the EC Water Framework Directive as “a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (GWP/TAC, 2000).

Perhaps the most complex existing water management system today is CALVIN (Lund and Howitt, 2001). The CALVIN system deals with operational options of water facilities for a variety of hydrologic conditions. It combines traditional storage, conveyance, and water conservation options with water exchanges, conjunctive use, water markets, recycling, and shared facilities. CALVIN operates essentially on one level of resolution, while not taking into account relative measures between all factors involved in the larger water management scheme. In particular, effects on (and by) upper-level decisions, such as purification, desalinization, public health considerations, regulations, water allocation, and feedback from stakeholders. However, unlike our proposed system, CALVIN is not autonomous. Another package, GoldSim (http://www.goldsim.com), claims to use a hierarchical approach to solve or integrate complex water management problems. However, despite their attempt to utilize the multi resolutional approach, their hierarchies are limited to the models themselves (from low-resolution simple models to high-resolution complex models) and to relatively limited problems, with a simplistic and limited treatment of optimization, and no automation.

Changes and disturbances in any unit or subunit (e.g., reduction of the water level in a major surface reservoir) may propagate and have major consequences on the entire water system. In the absence of a comprehensive model, one is forced to consider units and disciplines individually ignoring inter- and intra- dependencies. Consequently, the reactions to changes/failures and solutions to occurring problems may be far from optimal and may even have an overall destabilizing effect.

Hence, a generic DSS model for sustainable integrated water resources management will enable: 1) Quantifiably address complexities, uncertainties and temporal properties such as, conflicting stakeholders interests and agreements; technological developments; management of watersheds subject to ecological and health standards and 2) Dynamic and adaptive respond to changes in the complete water systems from draught to floods and from natural disasters to terrorist acts and wars.

Ranking of water related inter-linked alternatives and criteria

General

Figure 1 depicts the inter-linked PWE alternatives connected to a multi-criteria environment, accounted for when dealing with the complexity of a comprehensive regional/national water management system. In view of the ongoing process of depletion in fresh water resources, we maintain that the hydrology of the current millennium should rely on the central theme of optimal water management (see Figure 1) in terms of quantity and quality. This calls for decisions based on quantifiable measures regulating between competing criteria (stakeholders networks) and PWE alternatives. Criteria are inter-linked as, e.g., an aquifer affected by a variety of watershed physical factors (e.g. geological, chemical and hydrological), conditions associated with industry, agriculture and urbanization, all affecting the water economical aspects. Each of the PWE is associated with its own alternative branches that are not just affecting one another within their specific niche, but rather should be accounted by the decision maker as parts linked to a global map (Figure 1) of the studied site.

Hence, the map displayed in Figure 1 delivers the notion that different water related alternatives and criteria are all affecting the environment. The choices of selecting action scenarios are a decision task of different hierarchy levels.

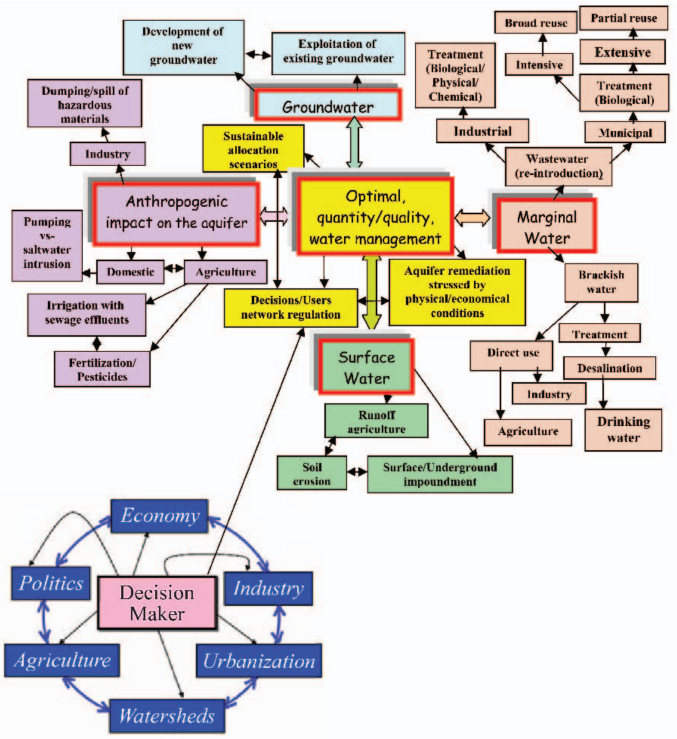

Fig. 1: *Inter-linked alternatives of Water, Environment and Stakeholders criteria.*

The complexity of the system is due to the requirements (i.e. state variables) characterizing each criterion (Figure 2), affecting other criteria. For example, industrial stakeholders with their water quantity (I_{WQ} in Fig. 2) and water quality (I_{Wq} in Fig. 2) requirements, will influence water economics stakeholder characterized by water pricing (E_{WP} in Fig. 2), linked to Urbanization stakeholders characterized by growth of inhabitance (U_I in Fig. 2) per area (U_A in Fig. 2), to Watersheds characterized by water level (W_{Wi} in Fig. 2) and the contaminants affecting water quality (W_{Wqi}) as well as Agriculture stakeholders with crop yield (A_{CYi}) requirements, and so on. The various criteria are in general time-varying. All that is known beforehand is that they are constrained by extreme values that cannot be exceeded for suitable functioning.

Methodology

The approach of our proposed DSS for an integrated water management generic model is composed of two stages that can be iterated to yield a sustainable optimum solution. The objective of the first stage is to determine an allocation of resources (r_k) to different types of alternative actions (A_k) to improve a set of criteria state variables (v_i) that characterizes a water related system, at the prescribed site. The

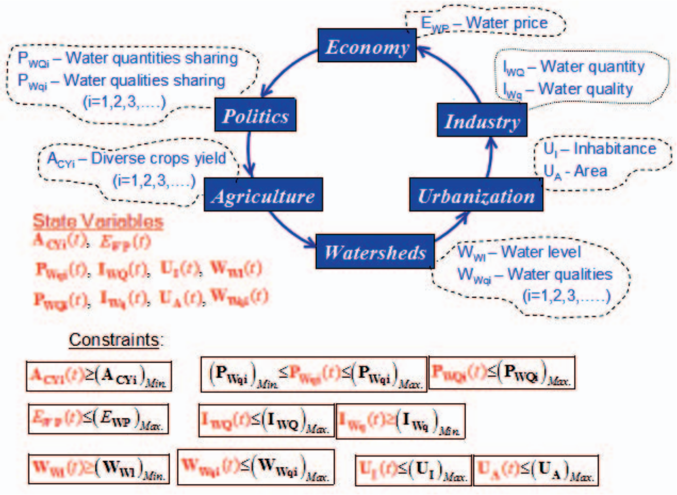

Fig. 2: *Stakeholders criteria their temporal state variables and constraints.*

objective of the second stage is to analyze how the budget for each action-type (A_k) is optimally distributed in time and space through the application of simulation models associated with criteria relevant to the water system of the investigated site. If no distribution satisfies the criteria (i.e. stakeholders demand) and the environmental ecological constraints simultaneously, a new allocation of resources (stage I) can be chosen and again be evaluated for its impact on stage II.

State variables characterizing the water system

With no loss of generality let the temporal state variables (v_i) represent the water system criteria at a prescribed site. Ideally, these variables, their desired state and the constraints on their maximum/minimum accepted levels are defined by a consensus reached in the site stakeholders' participation process. Following Figure 2, Figure 3 delineates a synthetic example of a site with its possible criteria state variables grouped into a typical water system tree.

In view of the example displayed in Figure 3, we suppose that the following time-dependent state variables (part of those described in Figure 2) define the cardinal aspects facing a decision maker and the stakeholders' desire:

a. Economy:
  i. Water cost, $v_1(\equiv E_{WP})$ [\$/m^3]: mean amount of money spent to obtain one cubic meter of an appropriate quality.
b. Industry
  i. Water quantity, $v_2(\equiv I_{WQ})$ [m^3/kg]: volume of water per unit mass of various produce.
  ii. Water quality, $v_3(\equiv I_{Wq})$ [mg/l]: concentration of different solute effluents.

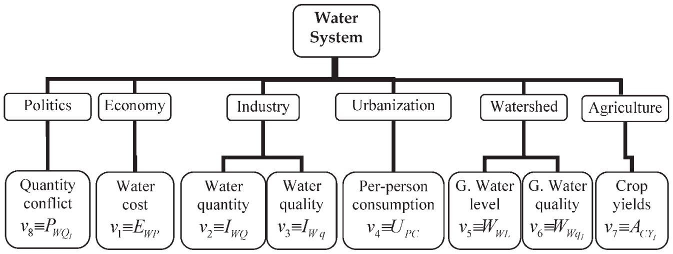

Fig. 3: *Tree of possible criteria state variables (v_i), representing a water system.*

c. Urbanization
  i. Per-person-consumption, $v_4(\equiv U_{PC})$ [l/day/person]
d. Watershed
  i. Groundwater-level, $v_5(\equiv W_{WL})$ [m]: mean groundwater level in the aquifer.
  ii. Water quality, $v_6(\equiv W_{Wq_i})$ [mg/l]: concentration of different contaminants in groundwater.
e. Agriculture
  i. Crop yield, $v_7(\equiv A_{CY_i})$ [m^3/kg]: volume of water per unit mass of various produce.
f. Politics
  i. Water quantity sharing, $v_8(\equiv P_{WQ_i})$ [m^3/kg/\$]: volume of water per unit mass of various stakeholders' produce, per mean amount of money spent.

Stage I

The optimal quality and quantity management of a water system is generally characterized by complex interactions between the action-type (A_k) alternatives associated with the PWE (Figure 1). The historic analysis (e.g. a learning process based on the ANN – Artificial Neural Network and/or the facilitation by FL – Fuzzy Logic) of the system's water management is used (Table 1, for the case of future evaluation) to elicit the consequences of diverse A_k alternatives on the criteria state variables (v_i). Using, e.g., the ANN method it is possible to assess how each of the v_i state variables has been influenced by the A_k alternatives and how these are interlinked between them. The water management problem at stage I is thus addressed by a multi-criteria impact matrix exemplified in Table 1 for four PWE [$(\text{PWE})_1\equiv$Groundwater (GW); $(\text{PWE})_2\equiv$Surface Water (SW); $(\text{PWE})_3\equiv$Marginal Water (MW); $(\text{PWE})_4\equiv$Anthropogenic Impact (AI)] and water system characterized by six stakeholders (Economy; Industry; Urban; Watershed; Agriculture; Politics).

The impact or influence of A_k on a given v_i is a measure of the degree of efficiency to which the latter changes per unit of resources invested in A_k. These efficiency scores (e_{ki}) that are elements of an impact matrix (**E**), may therefore be compared to analyze which A_k has been more cost-efficient on a given v_i, per unit of r_k. Thus in view of the example displayed in Table 1 we note that investing in artificial recharge is more efficient to improve the state of groundwater levels than investing in desalination. We can also infer (Table 1) that each unit of resources invested in augmenting the extraction rates of existing well-fields had a higher (negative) impact on the rate of groundwater levels than exploring new groundwater resources. The analysis of the evolution of these state variables along time is vital to learn about the system behavior and possible future trends.

An example of synthetic v_i criteria state variables displayed in Figure 3 and referred in Table 1, is depicted in Figure 4 concerning their historic evolution. Time extrapolation of the v_i temporal variation for the future evolution of the efficiency scores can be assumed. Under this assumption, what has been learned from the water system response to diverse A_k alternative actions in the past can be utilized to study the consequences of diverse r_k resource allocations on the system.

Concluding the procedure involved with ranking the criteria and thereby the optimal resources apportion to the preferred alternatives reads:

1. Define the set of criteria state variables (v_i) that characterizes the site water system.

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2. Construct the historic evolution data base for each of the state variables.

3. Investigate (ANN and/or FL) the relationships among the various state variables to establish the w_i weights ranking between these variables (i.e. $v_i = f(v_j); \forall i \neq j$).

4. Analyze the historic water activities applied in the study area to define the set of A_k alternative actions.

5. Determine the ranking (i.e. relative preference) of the various A_k alternative actions and assign the historic r_k resource allocation invested to each.

6. Investigate (ANN and/or FL) the historical data to elicit how each A_k alternative has influenced the site water system $v_i(t)$ state variables per unit of r_k resource invested, to obtain (following the idea of cost-efficiency analysis) the influence or efficiency scores e_{ki} representing the score obtained when associating (or interacting) A_k with v_i.

7. Elicit the degree of satisfaction obtained by the decision maker with each e_{ki} to obtain the 'satisfaction scores' $s_{ki}|_{v_i} = w_i e_{ki}$ per v_i, or $s_{ki}|_{A_k} = r_k e_{ki}$ per A_k. The weighted sum $HIA_k (= r_k \sum_i s_{ki}|_{v_i})$ of historic satisfaction scores per A_k alternative action suggests a measure of the relative impact this alternative has had on the (overall) water system (i.e. via its representing criteria) per unit of invested resources. The weighted sum $HIV_i (= w_i \sum_k s_{ki}|_{A_k})$ of historic satisfaction scores per v_i criteria state variable weighted by the resources invested for each A_k alternative, suggests a measure of the relative importance associated with the state variable (assuming that the water system response to implementation of diverse alternatives is time invariant). We note that $\sum_i HIV_i = \sum_k HIA_k$ and that higher scores represent imply better performance.

8. For the analysis of future policies (Table 1), the decision maker can appoint his preferred weight choice p_k for each A_k alternative action and consequently change the future impact per v_i criteria state variable ($FIV_i = w_i \sum_k p_k s_{ki}|_{A_k}$) and the expected future impact of the water system ($FIA_k = p_k r_k \sum_i s_{ki}|_{v_i}$) per A_k alternative action. Similar to the historic evaluations we note that $\sum_i FIV_i = \sum_k FIA_k$ and that a better water management performance will thus seek at higher values of these total scores. Moreover, a future water policy for efficient management should seek for a higher FIV_i score per any v_i criteria state variable while lowering the FIV score associated with the water cost state variable (FIV_1 in Table 1), even to the extent of obtaining $FIV \leq 0$.

9. By changing his preferences for the A_k alternative actions, the decision maker can learn how the $p_k r_k$ resources allocation would impact the water system and stakeholders represented via the v_i criteria state variables. The process of resources allocation can be performed in a group setting incorporating the relevant stakeholders in a learning- and negotiation process.

Tab. 1: *Example of multi-criteria (9∗8) impact matrix associated with stage I.*

		Criteria (stakeholders)	**Economy**	**Industry**		**Urban**	**Watershed**		**Agriculture**	**Politics**	
Evaluation of FUTURE policies			W. cost	W. quantity	W. quality	Per-person consumption	Ground W. level	Ground W. quality	Crop yield	Quantity conflict	
			v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	**FIA**$_k$
			[-10,10]	[-10,10]	[-10,10]	[-10,10]	[-10,10]	[-10,10]	[-10,10]	[-10,10]	
Weights (w_i)			10	7	10	7	5	7	5	6	
Preferred weight(p_k) Resource (r_k) allocation ($p_k r_k$)											
Groundwater (PWE)$_1$											
Augment extraction rates of existing well-fields	A_1	0	5	-1	0	-2	-10	-8	-2	-4	0
Explore new groundwater resources	A_2	8	4	-2	0	-2	-5	-7	-1	3	-392
Artificial recharge	A_3	12	-4	-1	1	-1	5	4	1	5	780
Surface water (PWE)$_2$											
Construct a new dam	A_4	6	5	-3	1	-3	0	-3	-3	-5	-288
Marginal water (PWE)$_3$											
Desalination	A_5	0	-7	5	2	2	3	2	2	1	0
Reuse of treated wastewater	A_6	14	2	6	4	0	2	1	0	2	1834
Anthropogenic impact (PWE)$_4$											
Reduce leakage from pipelines	A_7	30	1	1	1	5	5	4	0	2	3810
Seal abandoned wells	A_8	10	0	0	5	0	0	8	0	2	1180
Increase sewage coverage	A_9	10	-10	8	3	7	2	1	4	3	900
$\sum_k p_k r_k$		90									
FIV$_i$			-280	1288	1840	1218	1090	1386	130	1152	7824

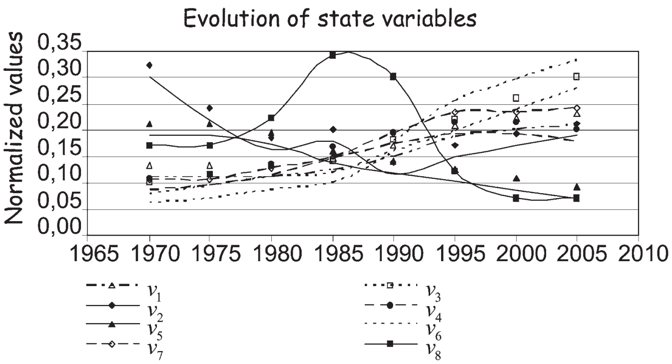

Fig. 4: *Possible historic evolution of data associated with Table 1.*

Stage II

In this stage the objectives are to verify in space and time the consequences of allocations decided in stage I, through the impact of simultaneous distribution of all these allocations over the criteria domain without violating some of the criteria constraints (Figure 2). To address these, the essence of stage II is to analyze via the criteria simulation models how the resource allocation appointed for each alternative action A_k can optimally be distributed at the studied site. In doing so the decision maker can "on-line" assess the stresses due to changes induced by resources allocations over sub-domains (geographical and/or such that address prescribed functions) of the criteria. The satisfactory of resources allocations (stage I) and the judgment on their impact at the studied site (stage II), are implemented via an iterative process. As a valid quantitative example we consider hypothetically in Figure 5 a section of Israel's coastal aquifer underlying the Tel-Aviv municipality, as a site at which an optimal water management is to be achieved. We note (Fig. 5) that the watershed is subdivided into three domains at which different $p_k r_k$ resources allocations are implemented in reference to A_k alternative actions associated with (PWE)$_1$ (≡GW), (PWE)$_2$ (≡SW), (PWE)$_3$ (≡ MW) and (PWE)$_4$ (≡AI). The stakeholders (criteria) considered are the Tel-Aviv urban area, the surrounding industry and agricultural fields.

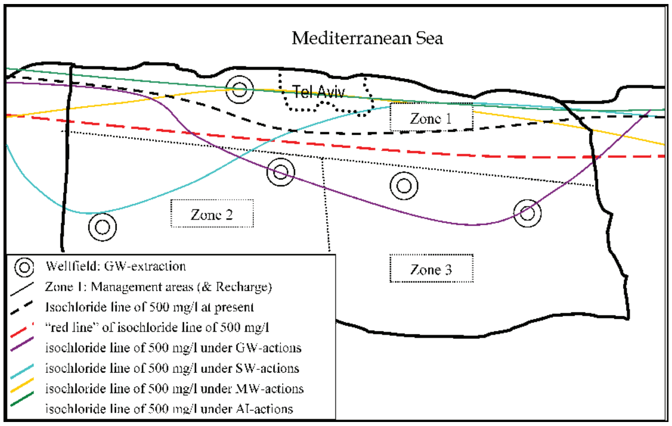

Fig. 5: *Qualitative example demonstrating hypothetical isochloride contours predicted by a watershed flow and transport model, resulting from different alternative actions.*

Possible hypothetical predictions of different 500 mg/L isochloride contours simulated by a flow and transport model are depicted in Figure 5, expressing outcome of stressing (e.g. where, when and at what cost change intensity of pumping/recharge) the watershed per alternative action. These results enable the decision maker the comparison with the prescribed constraint isochloride "red-line" and the current line, before implementing any water management protocol.

Hence, the decision making per criterion can be summarized by the following steps:

1. Aggregate the individual satisfaction scores $s_{ki}\big|_{A_k}$ to calculate the mean or equivalent satisfaction scores $m_{ki}\big|_{A_k}$ for each group of A_k alternative actions (i.e. the PWE) to analyze future investments. Similarly, aggregating $s_{ki}\big|_{v_i}$ per v_i will enable the calculation of the $m_{ki}\big|_{v_i}$ mean when seeking for the inputs of the corresponding criterion (stakeholder).
2. Subdivide the study site geographical domain into stress-zones J_k addressing management requirements for each PWE, along a determined time period. Distribute in space the resources allocated to the analyzed alternative action d_J^k and change accordingly the stresses associated with the relevant criterion model. Per the satisfaction scores $s_{ki}\big|_{A_k}$ and the resources distribution d_J^k for each PWE, define a Stress Factor SF_J^k indicating the relative change in stresses in the different management zones for all PWEs.
3. Run simulations with diverse spatial distributions to find the best set of consequences on the water system, respecting predefined restrictions on state variables.
4. Verify the resultant outcome due to super imposing the results of similar simulations of preferred (or all) criteria involved with the management of the study site. A systematic search for the most satisfying management scheme is obtained via the sensitivity to the various SF_J^k Stress Factors.

Ranking criteria and alternatives, inter-related parameters

Decision making processes relies in certain cases on non-unique definition of the subject to be evaluated. Such a situation is termed "fuzzy" (Saaty, 1978), i.e., a non-specific question may generate a fuzzy set of data that can mislead the decision-maker. A possible approach to minimize the fuzziness in the system, when evaluating alternatives, Saaty (1981) determines the system by constructing hierarchical branching criteria common to all tested options. Other approaches for ranking alternatives in multi-criteria environment rely e.g. on summing grades using relative weights associated with hierarchical structure of the criteria (Hwang and Yoon, 1981) or adopting of criteria ranking without using quantitative values (Hwang and Yoon, 1981; Crama and Hansen, 1982). Determination of the importance and grades of the criteria can be achieved by: 1) Using the minimum and maximum values as the basis of selecting a grading scale; 2) Fixing an alternative as the one with the optimal criterion and comparing the others in relation to it; 3) Comparing alternatives and criteria pairs involving graded scales and eigen vectors (Saaty, 1974; Hwang and Yoon, 1981) and 4) Adopting a grading approach to each given criterion which will lead to a normalized scheme composed of several ranking methods.

Saaty's analytical hierarchy approach has been a milestone and a guide for decision–making. However, his use of optimization is limited to linear programming and comparisons between a few alternatives, while leaving, much work to the decision maker. In particular, the assignment of Value Judgment implies no actual modeling or automated control. Nevertheless, his approach can be adopted in assigning ranks for the various resources r_k invested for each of the A_k alternative actions and for the criteria state variables v_i (e.g. Table 1).

The underlying dynamics describing various units of the water system can be highly complex and uncertain. This is due to the complex interactions between numerous factors, the stochastic processes involved, and the inherent difficulty in measuring the relevant criteria state variables v_i, as described in Figure 2, and determining their dependency to the various A_k alternative actions, referred to as the efficiency scores e_{ki} that are elements of an impact matrix **E** (e.g. Table 1). The various e_{ki} values can be established via the Artificial Neural Networks (ANNs) that are a data-driven modeling tool inspired by mimicking the brain's ability to learn from examples. It can be used locally (as learning modules) or globally (as clustering tools in an auto-associative mode Boger 2003). In real-world applications with many variables, the Guterman-Boger (Boger and Guterman, 1997) algorithm set enables efficient modeling of high dimensional datasets, and identifies the most relevant variables that influence the output, as applied to water and wastewater modeling (Boger, 1992; Boger and Hao, 2006).

Another efficient approach to learning is based on using the knowledge of an expert, who is familiar with the behavior of the relevant unit. Such an expert may be able to provide a clear explanation of the important variables and their relations (e.g., as can be inferred from information available in some UNESCO reports related to water systems or similar reports, McKinney, 2004). Such an explanation will be stated using natural language and fuzzy modeling may be used to transform it into a well-defined mathematical model. Indeed, the real power of FL lies in its ability to link verbally-stated information with well-defined mathematical formulas (Dubois et al., 1998).

Ranking of the environmental risks: A multi-portfolio approach

Environmental risk related to the IWRM is a complex function of the probability of failure and its consequences. The integrated approach to water resources planning and operation aims to reduce not only technical and economic but also environmental and social risks in order to achieve sustainable development from the following different (and possibly contradictory) points of view:

1. Technical reliability.
2. Economic effectiveness.
3. Environmental safety.
4. Social equity.

Each of the above points of view and of the corresponding interests can be represented by its own set of risk-mitigating policies, which we will call a *portfolio of strategies*. In this context the ranking of risks in the IWRM problem can be set up as a *multi-portfolio choice problem* which allows a scientifically motivated compromise between the individual utilities (interests) of all stakeholders (i.e. alternatives), where technological, economic, and social conditions are taken into account in form of constraints in problem formulation.

In this approach we follow and extend Markowitz's portfolio choice model (1952, 1999). We develop and simplify an approach suggested in Levner et al., 2008. The compromise between the stakeholders is achieved by using the multicriteria mathematical programming (in fact, the quadratic programming) approach. The multi-portfolio choice problem could be formulated as follows.

Given an *n*-dimensional vector budget (amount of money available to invest, along with other tools, such as human and information resources) and a list of management strategies requiring investment in the main inter-linked alternatives in the IWRM system presented in Fig. 1 how can the vector budget be optimally divided among the various water resources management strategies? If there is a chance of doing wrong, the risk is understood as a probability of this undesirable situation or, alternatively, the impact of the undesirable consequences, or a two dimensional factor containing both components. An important feature is that the expected "return" on investment; i.e., the resultant economic and social welfare benefits of environmental protection, is a composite return "paid out" over the life of the considered management strategy. Moreover, it is not necessarily a scalar defining economic welfare in monetary form, but rather a vector characterizing technical, economic, environmental, social, and other dimensions of the expected return from the integrated water resources management strategy in question.

Denote by x_{ij} the amount of the *j*th ($j = 1, \dots, n$) component of the *n*-dimensional vector budget allocated to management strategy i ($= 1, \dots, m$). Then the $m \times n$ matrix x, that we call a *multi-portfolio*, is a multidimensional decision variable set for the problem. The goal of the optimization process is to characterize and find the optimum portfolio of water resources management strategies.

Let the total return from portfolio x be the random (scalar) variable $v(x)$ and $\mu(x)$ denotes the expected value of $v(x)$ in a specified period which is a measure of the long-term average return per period from the portfolio. Note that the return $v(x)$ is a scalar which is a weighted combination of its component returns reflecting separate economic, technical, environmental, and social returns (benefits, welfare) that are quantitatively estimated by using the right alternative for each stakeholder.

Another very important parameter for characterizing an optimum portfolio is the *measure of risk* associated with portfolio x addressing the water resources management. The challenge for environmental management is to select a suitable unit of measurement for *environmental risk*. Following a financial risk management approach proposed by Markowitz in 1952, we may recall that the environmental risk of a portfolio can be quantitatively characterized by (is a single function of) the *variance of returns* from portfolio x. We follow two basic risk concepts, the first one being the Markowitzean measure of risk; namely, variance of returns. The second one is a two-dimensional array R_{ij} = (Probability_of_Damage p_{ij}, Amount_of_Damage d_{ij}). The first concept basically defines the risk of ineffective (failed) investments in environmental protection projects, associated with water resources management, whereas the second type of environmental risks are defined as threats to human health, to the natural environment-air, water, and land-upon which life depends, and to health of flora and fauna. In the model presented, we take into account both risk types.

Table 2 below depicts a template showing the relations between strategies and budget components. The cell at the intersection of each row (strategy) and column (budget component) contains three entries: decision variable x_{ij} = *portfolio component*, the expected value of return μ_{ij} = *returns*, and the environmental risk R_{ij}, which, in turn, is either the variance of returns or the two-dimensional array defined just above.

Tab. 2: *The portfolio matrix.*

Budget component *Strategies*	*1*	*2*	...	*j*	...	*n*
1						
2						
...						
i				(x_{ij}, μ_{ij}, R_{ij})		
...						
m						

The basic Markowitz portfolio selection model (for the case of a single portfolio) in the vector form is the following quadratic programming problem:

Let $\mu = (\mu_i)^T$ be a vector of expected values of returns (yields), where μ_i is the expected return for the environmental protection strategy i, and let $\Sigma = (\sigma_{ij})$ be the variance-covariance $m \times m$ matrix. Then the expected return from portfolio x in a period is $(\mu_i)^T x$, and the variance of this return is $x^T \Sigma x$. The basic problem is:

Minimize the variance of returns

$$R = x^T \Sigma x$$

Maximize the expected return

$$D = (\mu_i)^T x$$

[or restrict the latter to be in the given bounds $(\mu_i)^T x \geq \delta L$]
(where L is given), subject to the feasibility and resource conditions

$$x \in S$$

where S is the set of feasible solutions, which will also be considered later.

As mentioned above, in the IWRM approach four basic risk dimensions-technical, economic, environmental, and social-are considered. In this perspective, an optimum portfolio of water resources management strategies should maximize the expected return and minimize the environmental risk; these objectives should be achieved simultaneously. Finding an optimum portfolio of IWRM strategies is therefore a multicriteria optimization problem. Our Markowitzean approach is applicable to water resources management and extends the basic Markowitz model in that (A) the variable portfolio x is the $m \times n$ matrix rather than an n-dimensional vector of variable assets, and (B) each objective function (i.e., the return and risk) is in fact a vector of several functions.

We suggest the following iterative procedure for finding the best compromise solution for minimizing and ranking environmental risks.

Step 1. *Data collecting.* All problem constraints (hydrological, economic, and technological data) and different objectives of the stakeholders are also obtained in this step.

Step 2. *Finding weights for all objective functions.* Using the fuzzy Saaty's ranking method, the compromised integrated weights w_{ij} for all objectives of the stakeholders are found.

Step 3. *Finding a compromise solution minimizing the total risk for all stakeholders.*
Minimize the impact (total damage)

$$\mathrm{D(x)} = \sum_{i=1}^{m} \sum_{j=1}^{n} d_{ij} x_{ij} \qquad (1)$$

where there are n risk classes, for each of m different alternatives; d_{ij} denotes an individual damage (risk) of class j with respect to strategy i;

$$\sum_{i=1}^{m} \sum_{j=1}^{n} p_{ij} x_{ij} \le p_0 \,, \qquad (2)$$

$$\mathrm{x} \in \mathrm{S} \qquad (3)$$

where p_0 *is a given value of parameter p.*

Step 4. *Ranking the risks in K prescribed levels.* Fix K different values of p_0 in increasing order: $p_0^{(1)} < p_0^{(2)} < \ldots < p_0^{(K)}$. Rank the risks in the following manner: If x_{ij} is a strictly positive solution of parametric problem (1)-(3) in which $p_0 = p_0^{(k)}$, then assign rank k (=1,…,K) to risk of class j attributed to strategy j.

Constraint (2) requires that the total probability of damage does not exceed the acceptable risk level p_0, whereas constraint (3) defines that the matrix solution x satisfies all the given technological, logical and resource conditions. It is assumed here that elementary probabilities p_{ij} independent and sufficiently small.

The feasible solution, which satisfies (1)–(3), is found using one of the standard methods of multicriteria mathematical programming. Then go to Step 2 and, if necessary, change the weights provided by the stakeholders. Iteratively repeat Steps 2 and 3 until a compromise portfolio of management alternatives satisfying all stakeholders is found.

Many standard methods are known for solving the obtained multicriteria programming problem: surrogate relaxation (integration of two constraints into one), continuous relaxation, Lagrange relaxation, reduction of variables, approximation schemes, and various heuristics. Despite the fact that the latter definition is computationally simple and widely accepted, it does not offer the same opportunities as the multidimensional approach to risk evaluation. The present multi-portfolio methodology is more complicated and computationally less tractable than the classical Markowitz model. However, it allows powerful mathematical methods of financial risk analysis and multicriteria mathematical programming (see e.g. Rockafellar and Uryasev 2000) to be exploited for measuring and ranking the environmental risks.

Summary

We introduced the theoretical background for building a quantitative generic model as a working DSS tool to support decisions for the integrated regional/national management of water resources. At the first stage this DSS tool is aimed at providing the ranking of alternative actions emerging from PWE across criteria associated with the water system at the studied site. At the second stage, and through an iterative process, the achieved resolution of the first stage introduces stresses distributed over the criteria domains that are judged for their impact by the criteria simulating models enabling the response assessments of different demand scenarios and management decisions. Hence, the proposed water management model quantifiably addresses complexities, uncertainties and temporal properties such as:

- International and regional economic and political implications.
- Conflicting stakeholders interests (e.g. urbanization, agriculture and industrial sectors).
- Stakeholders' agreements (e.g. prices, allocations).
- Technological developments (e.g. desalination and purification processes).
- Ecological and health standards related to sustainable management of aquifers.
- Facilitate policy-making alternatives concerning management of allocations associated with water quantity/quality distributions.
- Facilitate structured and rational negation by enabling each stakeholder to choose his subjective view for the considered scenario and policy alternative. Furthermore, the individually customized views will help clarifying the interests of other parties and converge to a viable and agreeable policy, closer to optimality.

Hence, through such ordered processes, obtaining fashionable ("forget about hydrological investigation as desalinization is the sole cure to growing demands") and/or haste decisions will become of a low likelihood.

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