Discrete Multi-Criteria Optimization DSS for Water Scarce Basin: A case from Jordan

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Abstract: Discrete multi-criteria (DMC) optimization DSS tool was developed for water resources management of the Zarqa River Basin (ZRB) in Jordan. The basin is experiencing water management problems, undergoing fast economic expansion, land use and demographic change. Its water resources are under stress and the current demand barely met by the supply. This paper aims to present a DMC optimization decision support system (DSS) tool to evaluate the possible Pareto-optimal solutions within feasible set of 100 solutions. Various water technologies developed for the basin were be evaluated and compared (trade-offs) to arrive at a final preference ranking of the alternatives (Alt) and an eventual choice of a preferred alternative as the solution of the decision process. The study includes an interactive optimization and simulation models with related databases embedded into DMC optimization DSS tool. It also includes water technologies describing their affect on water supply, water demand, and efficiencies. In DMC optimization DSS, reference points (RP)-Pareto- approach was used to identifying an efficient "optimal" compromise solutions. The results obviously showed that the DMC optimization DSS tool can be utilized for selecting the efficient "optimal" water management solution. Reliable applications of well-integrated set of water technologies had generated feasible strategies to satisfy a set of constraints. Decision makers selected one efficient solution across 100 feasible alternatives. These tools are intended for a participatory decision making process in simulating scarce water basin system.

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1. Introduction

Sustainability has been a highly popular concept in environmental and water resources management. It is a philosophical concept, difficult to measure and it must be achieved in making decisions for overall development and resource management at regional and national scales. It also entails a long-term, instead of a short-term perspective in resource assessment and management, where the basic idea is that sustainable development "meets the needs of the present without compromising the ability of future generations to meet their own needs" (Harmancioglu et al., 2013; WCED, 1987).

Based on the above concept, an efficient use and management of water is paramount to sustainable development (Cetinkaya et al., 2008; Gasparino and Corpo, 2007; Bahrawi, 2014). Nevertheless, this is a scientific challenge, which not only requires a multidisciplinary approach, but also the integration of key stakeholders and decision makers to studying local water resources management into multi-objective, multi-criteria decision making processes (Global Water Partnership, 2000). This in turn requires direct access to decision support tools that address hydrological, environmental, economic and social components directly. Multi-criteria optimization decision support system (DSS) is a tool that can provide frameworks for stakeholder and decision makers' participation to lead decisions in a sustainable approach. Pardalos et al., (1995) showed that DSS enables the decision-maker to advance in solving a decision problem where several conflicting points of view (or criteria) must be taken into consideration. Typically, no unique optimal solution exists for such problems. However, DSS uses decision makers' preferences (DMP) to identify 'the most preferred solution'. It can be used for efficient "optimal" water management strategies and policies of use, designed for a participatory public decision making process in term of minimizing the losses and maximizing the gains and to economic, social and environmental systems (Kundzewicz, 1997). In sustainability issues in water management (Harmancioglu et al., 2013), DSS has allowed comparing various water management scenarios where the values of sustainability criteria are varied. This system is important to Jordan, a country of limited resources, where decision makers can select preferred applicable solution(s) of different water interventions and technology alternatives (Alt) to manage water resources.

Multi-criteria optimization decision support system (DSS) tool is needed in water scarce basins like the Mediterranean region to test the usefulness of selected criteria by using computer-based interactive optimization and simulation models with associated databases embedded into a decision support system (DSS). This approach has been developed and tested in seven parallel case studies in Cyprus, Turkey, Lebanon, Jordan, Palestine, Tunisia, and Morocco, where they all share similar problems (Fedra et al., 2007; Harmancioglu et al., 2008; Fedra and Harmancioglu, 2005; http://www.ess.co.at/OPTIMA). In particular, Zarqa River Basin (ZRB) is one case of these Mediterranean cases that has been selected because of its entire range of prototypical water management problems, undergoing fast economic expansion, land use (shammout, 2003), and demographic change. Furthermore, ZRB has a high level of abstraction, its water resources is under stress, with the current demand barely met by the supply (Shatanawi and Shammout, 2011). All these problems, whether current water scarcity, insufficient resources for further development, will raise the need to better allocation strategies, policies (Shatanawi et al., 2008; Jasem, 2011) as the implementation of a range of water technologies contributing to a reduction in demand, consumptive use, loss reductions, resulting in increased efficiency of use. ZRB also represents the significance of the institutional framework and the need for decision makers participatory in optimization processes to problem solving.

Multi-criteria optimization DSS tool requires two approaches: The first approach is "Participatory Optimization Scenario" using Water Resources Model (WRM) as the core to generate feasible alternatives (Alt). This approach which was presented in details in a previous paper (Shammout et al., 2013), showed that optimization scenario via stakeholders participatory can generated 100 feasible solutions. Choosing any of the solutions depends on its applicability by the decision makers. The Second approach is a higher participatory level to decision making using a discrete multi-criteria reference point (RP) methodology and combining water technology alternatives including their cost structure, applicability rate and economic valuation of water supply and demand. This tool also requires structured decision maker's involvement such as dedicated web based tools, regular workshops and interviews. The study herein intends to present the second approach.

Therefore, this paper aims are presenting a discrete multi-criteria optimization DSS for Zarqa River Basin to evaluate possible Pareto-optimal solutions within feasible set of 100 solutions. Various water technology alternatives developed for the basin can be evaluated and compared (trade-offs) to arrive at a final preference ranking of the alternatives and an eventual choice of a preferred alternative as the solution of the decision process. The case study is a result of the analyses carried out in OPTIMA (Optimization for Sustainable Water Resources Management) project, funded by the 6th Framework Programmes of the European Union with contract No. INCO-CT-2004-509091.

2. Analytical Tool: Multi-Criteria Optimization

The basic analytical tool in water modelling system (Water-Ware); a river basin scale water resources management information and decision support system (Shatanawi and Shammout, 2011). The system describes a dynamic water budget for a given catchment in terms of water demand and supply, efficiency of use, and the economics of demand and supply (Fedra and Harmancioglu, 2005). Water Resources Model (WRM) is the main element of Water-Ware system, which is operational in a web environment accessible with a standard web browser, and the associated manual pages (http://www.ess.co.at/MANUALS/WATERWARE/). WRM consists of integrated cascade of modules, embedded in a framework of a participatory approach in water resources optimization. The system includes baseline scenario, identification of constrains and water technology (instruments), participatory optimization scenario, and a discrete multi-criteria optimization DSS. This is addressed by:

1- The starting point is a baseline scenario that includes the basic economic evaluation so that all the criteria accepted by the stakeholders are generated as part of the models results. On this basis, optimization scenario is formulated. According to model configuration Zarqa River Basin case study under analysis was represented by means of a network of nodes and arcs (Strzepek, 1981; Fiering, 1967). A node represents a structural or non structural component of the river basin system at which water, enters the river system, leaves the system by consumption or diversion, has its temporal distribution altered, or is to be observed for some special purpose. The WRM calculates demand and supply over time on a daily basis with annual summaries at the nodes. Costs are accounted for all elements of water supply and water demand. The detailed methodology and results of application of WRM to ZRB were presented in previous papers (Shammout et al., 2013; Shatanawi and Shammout, 2011) for the baseline scenario and a participatory optimization scenario with complete description of its components including nodes and reaches.

The results of the WRM baseline scenario of the year 2001/ 2002 highlighted several parameters, from which, the supply to demand ratio was 90%, the system reliability was 58%, the water shortfall was 4.35%, and the total unallocated water within the basin was 17%. The benefit/ cost ratio was 0.91 while the economic efficiency reached -0.03 EURO/m^3. These results show that Zarqa system cannot add any profits. In addition, the baseline results from WRM model runs were entered in WRM optimization model to analyze the sets of alternatives. Instruments and constraints were defined for the model and entered in WRM optimization model. Figure 1 shows the application of WRM to ZRB.

2- In the participatory optimization scenario for Zarqa River Basin, stakeholders identified the optimization criteria (constraints) and the management interventions (instruments). Constraints were set to securing high supply/demand ratio of 0.98 and improving reliability of supply to 75%, where the specific eight instruments were suggested and manipulated by the model to achieve the optimization criteria. These instruments include different water technologies (Tech) as; artificial groundwater recharge (GWR), inter basin transfer (IBT), irrigation water management (IWM), public awareness program (PAW), rehabilitation of pipe networks (RPN), runoff harvesting (RH), wastewater reuse (WWR), and water desalination (WD). The instruments were suggested by stakeholders and managed at the supply- demand nodes including their cost and an application range.

The results of the WRM optimization scenario (Shammout et al., 2013) showed that the specified constraints were met when the supply/ demand ratio increased from 0.90 to 0.996 and the reliability of supply improved from 58% to 84%. The benefit/cost ratio, water shortfall, and the economic efficiency had responded effectively. A feasible set of 100 solutions out of 50,000 runs were obtained for Zarqa Basin as shown in Figure 2.

At this stage, the model proved its efficiency in using the full featured basin characteristics towards baseline and optimization scenarios with the support of stakeholder's solutions (instruments) in simulating the basin behavior using the model parameters.

3- The final step of the optimization is a discrete multi-criteria (DMC) optimization DSS and assessment of the set of feasible solutions generated in a participatory optimization scenario using a reference point methodology (Fedra et al., 2007). This can be done automatically, using UTOPIA, and generated criteria simultaneously or interactively with a final round of stakeholder participation.

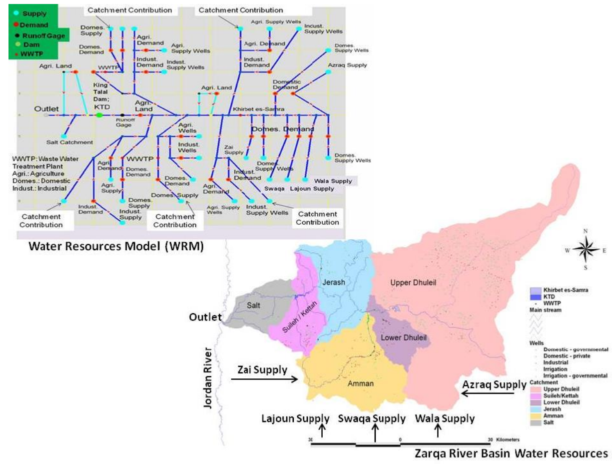

Figure 1. Application of WRM to Zarqa River Basin

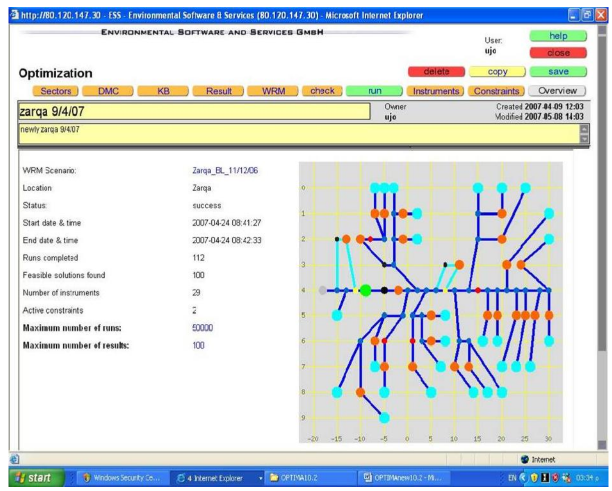

Figure 2. The Summary of WRM Optimization Scenario for Zarqa Basin

3. Management Tool: DMC Optimization DSS

Discrete multi-criteria (DMC) optimization DSS stage is an analytical tool for decision making. It is used to identify the optimal (efficient) compromise solution from the non-dominated subset, given a reference point (RP) in performance space (Fedra and Harmancioglu, 2005). The default reference point is utopia, and the performance space for all criteria is normalized as a degree of achievement in the interval between NADIR and UTOPIA; where:

a. UTOPIA: the "best" value for each criterion in the set.

b. NADIR: the "worst" value for each of the criteria in the set.

The Efficient Point is the feasible and non-dominated alternative "nearest" to the Reference Point (RP). The distance is described as a level of achievement; 100% would be UTOPIA itself, and 0% would represent the position of NADIR.

Defining reference points is done interactively with the stakeholders and decision makers or their proxies involved: criteria can be excluded or included. This leads to different sets of non-dominated alternatives, constraints moved and different reference points defined to immediately see the consequences of each preference structure, and study about trade-offs and possible solutions. In the case of Zarqa River basin, simulation modelling is a powerful tool to assist decision makers and planners when confronted with water management decisions on system. The simulation results allow them to look at the response of the system under varying inputs and system configurations. This provides information about the interaction of the system components and allows decision makers to combine this information with economic and social consideration to design a system which provides the greatest benefit to society.

The DMC tool has two main analysis functions towards decision making:

- Discrete optimization: to find an efficient solution from a set of feasible and non dominated alternatives;
- Decision analysis for the individual optimization scenarios.

The two-analysis functions in DSS optimization approach particularly intended to facilitate a continuing stakeholder involvement. This is based on the feasible solutions that identifies all or as many as possible of the user expectations expressed in terms of constraints on performance criteria. The next step is a subsequent discrete multi-criteria decision-making that is oriented towards conflict resolution. DMC identifies the trade-offs between the conflicting objectives among different stakeholder preferences using a reference point methodology and the concept of Pareto-efficiency in order to arrive at an optimum and a generally acceptable solution. It also facilitates us to assess the application rates (AR) of the water technologies investment and the system performance of ZRB. This means; the use of a minimum and maximum set of assumptions, so that it provides itself to interactive use.

4. Results Analysis

Assessment of feasible solution sets with the DMC tool requires again a consideration of stakeholder and decision makers' priorities. They have agreed on maximizing criteria and minimizing others that are important for improving the basin performance. Accordingly, all optimization scenarios were re-evaluated through maximizing supply/demand ratio, reliability of supply and benefit/cost ratio criteria while keeping the water costs to a minimum. The basic constraints used in optimization are prescribed on the basis of stakeholder and decision makers' questionnaires and their votes where they were first put to define the significance levels of indicators on basin water management. Subsequently, stakeholders identified specific indicators to describe the overall performance of the basin.

Table 1 summarizes these specific indicators (constraints) and their ranges as dictated by the stakeholders and decision makers. In particular, the preference of decision makers (DMP), as it is the sole governmental planning agency that is responsible for water management in the basin. The decision makers specific indicators used for the DMC optimization are relaxed to reach a set of feasible results; that is, the supply/demand ratio and reliability of supply are set to 0.95 and 80% respectively, the benefit/cost ratio is taken as 1 and water shortfall is minimized to 0.5% while the economic efficiency is prescribed as 0 EURO/capita. Application of water technologies which are management at supply and demand nodes is a vital step to be performed for developing future scenarios specified by stakeholders. Once these technologies are evaluated for their economic efficiency, one can select best management practice and the "optimum" management plan from a number of alternatives.

Table 1. Values of Indicators for Optimization Identified by Stakeholders and Decision Makers

Indicators	Baseline Scenario Results	Min & Max Value Based on Stake-holders' Votes	Decision Makers Values-**RP**	Optimization Scenario Results-**Maximum Achievement**	Unit
Benefit/Cost	0.91	0.95- 1	>1	**1.034**	Ratio
Cost/Benefit	1.09				Ratio
Content Change	23.0			23.034	%
Economic Efficiency	-0.03	0	>0	**0.022**	EURO/m^3
Net benefit	-7				EURO/capita
Reliability of Supply	**58**	75- 95	>80	**84**	%
Supply/Demand	**0.90**	0.9- 95	>0.95	**0.996**	Ratio
Total Benefit	74				EURO/capita
Total Cost	81				EURO/capita
Water Shortfall	4.35	0.2- 0.5	<0.5	**0.274**	%
Unallocated	17				%
Water Cost	0.35				EURO/m^3

The stakeholders have identified reliability of supply and supply/demand as two of the priority problems so that the reduction of water demands and increased of water supply are essentially the objective to be optimized (Shammout et al., 2013). This addresses the reduction in the total amount of missing water from the total demand i.e. water shortfall. At this stage, decision makers can assess the use of water technologies that serve to reduce the demands and conveyance losses at the agricultural and municipal demand nodes identified in WRM. For the purposes of comparison of baseline scenario of 2001/2002, and the implementation rates of technologies, priorities in their application and relevant costs are selected for future scenarios.

Based on the above, the sets of feasible 100 solutions are imported into the DMC tool to assess possible Pareto-optimal and non-dominated alternative solutions within the feasible sets. Figure 3 shows an example of 20 feasible alternatives that imported to the DMC tool. At this stage, the reference point (RP) used in comparison with alternative solutions in the feasible set is the maximum (Max) or the minimum (Min) value for selected criterion. Therefore, four derived solutions were selected out of 100 feasible solutions (alternatives) for the optimization scenario. Table 2 shows the levels of achievement of selected alternatives using DMC analysis. The alternatives selected for the optimization scenario represent four derived solutions out of the feasible set of 100 solutions. These alternatives are 6, 39, 45, and 61. This based on preferences of ZRB stakeholders and decision makers.

The selected alternatives foresee the possible steps that may be taken in the Zarqa basin in terms of water technologies for improvement of system performance. Stakeholders were invited for another round to select one optimal solution from the achieved four alternatives DMC analysis. Alternative 6 was selected because it has the highest economic efficiency and its profitability (Benefit/Cost) is marginal.

The analysis of DMC as shown in Figure 3 as well as the results from the selected alternatives (Table 2); show that alternative 6 is the most efficient and has a pareto-optimal solution. It was selected based on the concurrence of ZRB decision makers as it represents one derived solution out of the feasible set of 100 solutions under maximum/ minimum criteria. The optimal results from alternative 6 scenario show that the system reliability is 83.3%, and the Supply/ Demand ratio is 0.994. These two constraints were selected and discussed previously with decision makers to improve the system performance in the optimum condition as 0.411% for water shortfall, 1.034 for benefit/cost ratio, 0.022 EURO/m^3 for economic efficiency, and 0.654 EURO/m^3 for water cost. Figure 3 shows the achievement level of alternative 6 in DMC analysis.

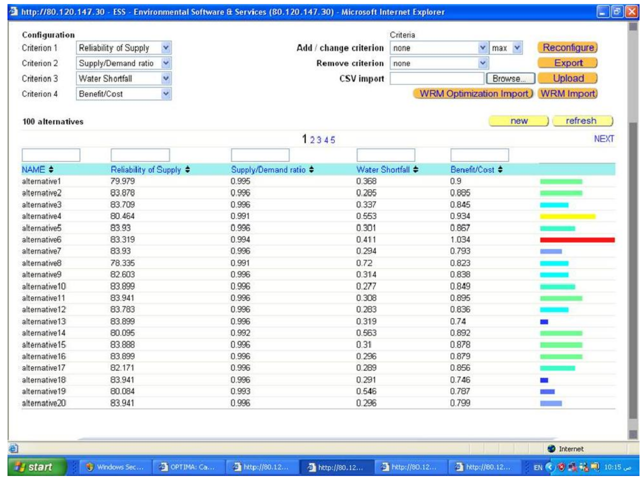

Figure 3. The List of Feasible Alternatives (1-20) Imported to the DMC (As An Example)

Table 2. Levels of Achievement of Selected Alternatives (Alt) Using DMC Analysis

Criteria	Alt 6	Alt 39	Alt 45	Alt 62	Max/ Min	Unit
Reliability of Supply	83.3	82	84	84	Max	%
Supply/Demand	0.994	0.955	0.996	0.966	Max	Ratio
Water Shortfall	0.411	0.324	0.274	0.289	Min	%
Benefit/Cost	1.034	0.908	0.955	0.954	Max	Ratio
Economic Efficiency	0.022	-0.058	-0.03	-0.031	Max	EURO/ m^3
Water Cost	0.654	0.631	0.677	0.675	Min	EURO/ m^3

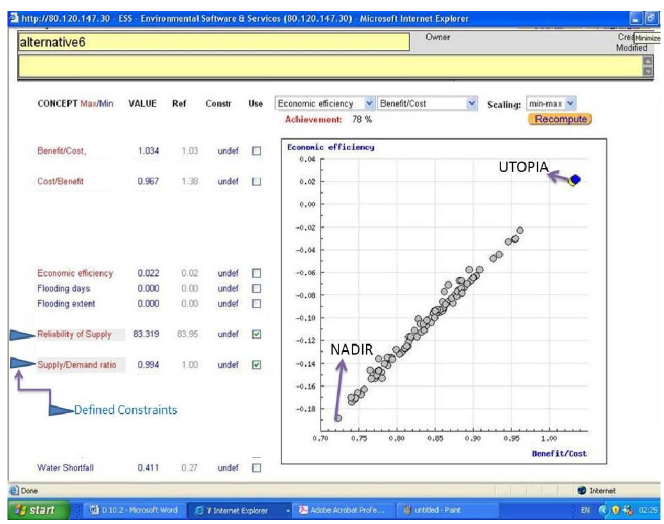

Figure 3. Achievement Level of Alternative 6 in DMC Analysis

5. Basin Evaluation in DMC Optimization Tool (Post Results Analysis)

The alternative 6 predicts the future step to be taken by decision makers for ZRB. Moreover, DMC optimization DSS tool enables decision makers to evaluate alternative 6 under application rates (AR), projected cost of water technologies that are addressed for functional nodes of WRM as shown in Figure 1. Table 3 and Table 4 show the application rates (AR) and projected cost of water technologies at water supply and demand nodes. These results were projected for the basin future and showed the following scenarios:

- The inter basin transfer (IBT) is the most effective water technology in meeting stakeholders constraints; where water from Disi aquifer will be transferred to Amman at a rate of 100 MCM/year (shammout et al., 2013), while the DMC optimization run has shown that 68 MCM/year is required to optimize ZRB constraints for the year 2010. This means that the application rate (AR) of this technology is 68% with an operational (OP) cost of about 37,400,000 EURO. Inter basin transfer technology would has the top priority in addressing functional Amman domestic supply node. It is important to note that Disi water was transferred to Zarqa River basin in 2013 at a rate of 50 MCM and increased gradually to 100 MCM in 2014.This means that this instrument was a valid approach to address water shortage in Amman area.
- Rehabilitation of pipe networks (RPN) is also an effective technology that followed inters basin transfer in the priority list of technologies. The DMC optimization results have also shown that this measure is important in particular for Greater Amman, Zarqa and Russiefeh areas. Thus, if a decision is to be made on rehabilitation of the existing networks, it would be reasonable to initiate such improvement in these areas. The operational cost is about 1.5 EURO/m^3 of water. The percentage of application rate ranges from 77% in Jerash domestic demand node to 83% in Amman, Zarqa, & Russiefeh domestic demand node. The operating cost of replacement pipe networks is evaluated at approximately 208 million EURO/Year.
- Irrigation water management (IWM) technology includes adaptation of micro irrigation, effective water scheduling, and optimal water cropping pattern is addressed at functional demand node of agricultural land that is near Khirbet es-Samra wastewater treatment plant; where 1700 ha need irrigation efficiency tools. DMC results have shown that this technology appears as the priority technology to be selected. The operating cost is about 285,600 EURO/Year with 84% application rate.
- Runoff harvesting (RH) and artificial groundwater recharge (GWR) technologies at catchment contribution (CC) of upper Dhuleil (supply node) appear in DMC optimization tool as priority technologies to be selected; where this catchment contributes about 6.53 MCM as runoff (shammout, 2003). DMC optimization results have shown that 3.5 MCM can be captured for irrigation purposes. Thus, the application rate is 54% with operating cost is about 350,000 EURO/Year. Whereas, 46% (3 MCM) can be used for groundwater recharge. The operating cost is evaluated at 300,000 EURO/Year.
- Water desalination (WD) technology appears in DMC optimization DSS tool as the priority technologies to be selected at Amman domestic supply node. Application rates of water technologies is 70%, whereas, their operating cost is evaluated at 1.4 million.
- Wastewater reuse (WWR) for irrigation appears as a high priority technology to be used on the supply node. This water is generated by wastewater treatment plant and requires 2.8 million EUROS to complete.
- Public awareness program (PAW) technology appears in DMC optimization DSS tool to have a part of the priority among other technologies considered. The application rate is 50% for the domestic demand nodes. This intervention is the responsibility of different institutions including NGOs.
- Total cost of water technologies at supply nodes is aproximately 42,250,000 EURO/Year and 208,216,060 EURO/Year at the demand nodes.

Table 2. Application Rates (AR) and Projected Costs of Water Technologies (Tech) at Supply Nodes

Water Tech	Invest-ment Cost EURO/m^3	OP Cost EURO/m^3	% Min to Max **AR-DMP**	MCM	OP Cost EURO/Year million	% AR DMC Run	WRM Supply Node Name
RH	1	0.1	45-55	3.5 out of 6.53	0.35	54	CC of Upper Dhuleil
GWR	1	0.1	40-50	3 out of 6.53	0.3	46	CC of Upper Dhuleil
Disi IBT	0.72	0.55	60- 70	68 out of 100	37.4	68	Amman Domestc Supply
WD	0.5	0.25	60-75	8	1.4	70	Amman Domestc Supply
WWR	0.3	0.2	60-75	20	2.8	70	Agri. Supply
Total					42.25		

Table 3. Application Rates (AP) and Projected Costs of Water Technologies (Tech) at Demand Nodes

Water Tech	Invest-ment Cost EURO/m^3	OP Cost EURO/m^3	% Min to Max **AP- DMP**	MCM	OP Cost EURO/Year Million	% AP DMC Run	WRM Demand Node Name
RPN for Amman, Zarqa and Rusifh	1.0	1.5	70-85	161.89	200.58	83	Domestc Demand Node
RPN for Suileh	1.0	1.5	70-80	4.52	5.42	80	Domestc Demand Node
RPN for Jerash	1.0	1.5	70-80	1.45	1.68	77	Domestc Demand Node
Total OP Cost of RPN					207.68		
IWM	0.15	0.15	80-85	1700 ha	0.286	84	Agri. Land Demand Node
PAW	.05	0.1	35-50		0.25	50	Domestc Demand Nodes
Total					208.216		

6. Conclusions

The use of computer-based interactive optimization and simulation models with related databases embedded into a discrete multi-criteria (DMC) decision support system (DSS) have shown that, specified constraints can be met successfully engaged in evaluating water technologies of Zarqa River Bain management plans. These technologies are managed on supply and demand nodes including their cost and application range. DSS has allowed comparing various water management scenarios where the values of optimizing criteria are varied to evaluate basin baseline, and its future management scenario.

Results have pointed out that the water technologies (instruments) and specifying constraints are needed for management water resources for Zarqa River basin future. Stakeholders within OPTIMA have identified Zarqa River basin issues and its problems, as water supply, water demand, and reliability of supply of the main challenges have to be coped. Hence, DMC enables decision makers to obtain the pareto-optimal solution. From the results of the DMC optimization DSS analysis, four feasible solutions were selected and could be specified in having high achievement levels of optimizations solution under maximizing and minimizing values of specified criteria (indicators). Nevertheless, one efficient pareto-optimal solution is selected and agreed by decision makers and it also represents one derived solution out of feasible set of 100 solutions. The optimal results showed that the reliability of supply improved from 58% in baseline scenario to 83.3, supply/demand ratio increased from 0.90 to 0.994 and water shortfall is minimized to 0.411%. Moreover, the benefit/cost ratio had been modified to 1.034 while the economic efficiency improved from -0.03 to 0.022 EURO/ capita and the water cost reached 0.654 EURO/ m^3.

The discrete multi- criteria optimization DSS evaluation has shown that Disi aquifer inter-basin transfer, rehabilitation of pipe networks, irrigation water management, wastewater reuse, and water desalination are the most effective instruments in obtaining high achievement levels of optimization. Whereas, runoff harvesting, artificial groundwater recharge, and public awareness program as it appeared in DMC optimization tools have the second priority to be considered.

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