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Evaluation of desalination and other strategic management options using multi-criteria decision analysis in Kuwait

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ABSTRACT

Water is essential to life sustainability and the development of industry and agriculture in Kuwait. Kuwait is faced with water shortages, because of the scarcity of the natural water resources; well-developed supply infrastructure; and the practice of expanding irrigated agriculture and industrialization. This paper describes how to evaluate different management options and policies on the strategic level that can lead to secure and sustainable water resources management in the future for all water users in Kuwait. Possible interventions/management options are identified and evaluated using a decision- support tool based on a multi-criteria decision analysis (MCDA) methodology. This paper is the first of its kind to use trade-off between different management options and strategic policies in Kuwait. The results showed that desalination using renewable energy technologies was ranked highly, despite its economic cost and environmental impact but there is also a need to implement widely other options. Wastewater Reuse for agriculture was ranked first overall in the MCDA. Most brackish water supply to the agricultural sector should be replaced by treated wastewater. Other options such as virtual water, water demand management and changes in agricultural policies should be prioritized because of their socio-economic and environmental benefits.

1. Introduction

Ensuring the availability of reliable water resources and the use of good quality water without threatening the public health in Kuwait has become a critical issue. Kuwait is faced with water shortages, because of the scarcity of natural water resources, population growth, higher standards of living, lack of well-developed supply infrastructure, and practice of expanding irrigated agriculture and industrialization without a proper link between livelihood and water security. In addition to that the nonconventional water resources in Kuwait are fragile and expensive. In countries like Kuwait water resources sustainability and security are interrelated and the main concern for socio-economic development. Both water sustainability and security are about providing viable access to sufficient quantities of tolerable quality water for sustaining livelihoods and socioeconomic development while ensuring protection against pollution and preserving ecosystems [1]. In this paper, the emphasis is on how to develop and evaluate suitable policies and management options in response to the economic, environmental, financial, and cultural conditions in Kuwait in order to secure water supplies for the future and achieve sustainable water resources management.

Water shortages, if not met in a timely and sustainable manner, will inevitably have serious adverse effects on socioeconomic and commercial development [2]. Water sustainability is essential to the population of Kuwait for its people to live in a healthy and productive manner while maintaining the natural environment [3]. Water plays a fundamental role in the security of food and energy as well as in economic growth, maintaining health, and reducing poverty. The challenges of water sustainability in Kuwait were addressed by Al-Otaibi and Kotwicki [4]; and Al-Qunaibet and Johnston [5]. Kuwait is ranked among the world's highest consumers of domestic water, with per capita water use well above international standards [6,7]. There is an ever increasing demand for brackish groundwater for oil processing/injection into oil fields to maintain reservoir pressure. The sustainable exploitation of brackish groundwater has become recently an issue in Kuwait [8]. The rapid increase in oil field-produced polluted water caused by the maturity of oil production wells has become a major disposal/pollution problem threatening the groundwater environment in in the country. Sustainability of oil production, including enhanced oil recovery, poses new challenges, as ever larger quantities of processed water will be needed, and more polluted oil-field water will be produced [9]. In Kuwait, water produced from desalination plants is pumped to blending stations, to underground reservoirs, and then to networks and elevated towers as an efficient means of maximizing the benefits from desalinated water [10]. However, this imposes a heavy fiscal burden of water subsidies that is presently 5.9% of the oil export revenues and 2.4% of Kuwait's

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gross domestic product (GDP) (Table 1), which is projected to increase to 10% in the near future [9]. As an example, the subsidies of the Government of Kuwait for the water sector may reach US$4 billion per year in the near future [9]. This is because the construction and operating costs of desalination plants are very high [11]. Despite all the environmental problems associated with desalination, such as brine discharges and carbon dioxide emissions, high cost, and elevated consumption of energy, there is an ever increasing demand for desalinated water in Kuwait. It is expected that the production of desalinated water will increase by 75% above the current level in the near future [9]. Also, in Kuwait, agriculture consumes 60 to 90% of the groundwater produced and provides a low contribution to the GDP. This practice has led to the rapid depletion of aquifers, and raises the question of whether it would be better to import food and embedded 'virtual water', thus releasing groundwater for more strategic use.

The concept of 'virtual water' is not well-recognized in Kuwait. This concept is about trade in embedded water when food or other commodities are imported/exported from one country to another. The concept was introduced by Allan [12] to support the idea that countries like Kuwait can save their scarce water resources for more critical needs by relying more on imported food. The virtual water includes by definition quantity of water needed to produce and to process a commodity. For example, If 3500 l of water is used by a person in the UK, only 150 l is used within the home, the rest in embedded (hidden as virtual water) in food and goods consumed. The idea (for countries that lack natural water resources) is to import food with its hidden (impeded) water (which is a large percentage of water needs) and leave the rest to be supplied by local water resources. Later, Zubari [13] envisaged that Virtual Water Trade should be adopted as a Policy Instrument to contribute to food security in countries like Kuwait.

Also, the reuse of treated wastewater in irrigation is still low at only 36% ([9]. Al-Jarallah [14] highlighted the potential of using grey wastewater to enhance water security in Kuwait. In addition, the rate of unaccounted- for-water (UFW) such as leakages is high. The World Bank [15] reported the level of UFW in Kuwait as 40%. However, Azrag et al. [16] gave much lower values for UFW in freshwater networks in Kuwait. The high values of UFW and excessive wastes have led to rising groundwater tables in urban cities, threatening the stability of building foundations and roads [8]. The lack of implementation of the principles of Integrated Water Resources Management (IWRM), including weak institutions and weak operational services, makes the water sector of Kuwait far from being sustainable. Moreover, using desalination as the prime development and management solution also requires an investigation of what other solutions can be offered in meeting the future water needs of Kuwait, as the gap between total water demand and renewable natural water resources is still large [17]. When these other solutions are planned for, there is an imminent need to evaluate and compare these solutions from the socioeconomic and environmental-technical points of view. This issue is addressed in this paper.

It seems that Kuwait is producing water as much as it is consuming. According to the records of the Ministry of Electricity of Water [7] about 630 Mcm/yr is generated from desalination plants and 8 Mcm/yr is generated from groundwater resources as freshwater. All other quantities of groundwater (about 89 Mcm/yr) are produced as brackish and used for agriculture and oil industry. Kuwait receives some 160 Mcm/yr as recharging water from rainfall to the aquifers which mix with brackish to saline groundwater resources. Also, Kuwait generates some 110 treated wastewaters for greenery use. Kuwait produces some 120 Mcm/yr as Reverse Osmosis Treated Wastewater for crops agriculture. In summary water supplies and resources in Kuwait without desalination are not sustainable because of the scarcity of natural water resources and because of the high rate of water consumption that Kuwait enjoyed throughout the past few decades. The concept of meeting water deficits in Kuwait through desalination while groundwater resources continue to be used for low value agriculture will not be a strategic solution. The objective of this paper is to highlight and evaluate the related strategic solutions/policies that might be used to achieve integrated and sustainable development and management of the water sector in Kuwait. These solutions/policies, when evaluated from the socioeconomic and environmental-technical standpoints using the multi-criteria decision analysis (MCDA) methodology presented in this paper, will help identify how water sustainability and security in the domestic and agricultural sectors can be achieved. This paper is the first of its kind to use such methodology to trade-off between different management options and strategic policies in Kuwait.

The development of a water sustainability strategy for Kuwait follows a strategic vision that each citizen has the right to a sufficient quantity of water of a required quality at an affordable cost for the purpose of use. However, when water resources are being developed, then the larger ecological system needs to be conserved. Water therefore has socio-economic and environmental values.

2. Desalination in Kuwait

Kuwait over the past half century has been fully dependent on the conventional steam -boiler-turbine-generator (SBTG) and the multi-stage flash (MSF) seawater desalination technologies for the supply of its needs for electricity and freshwater. This so-called cogeneration scheme was encouraged by the immediate availability of fossil fuel oils and the direct easy access to the Gulf seawater. This scheme helped Kuwait to grow and expand in different ways at different levels to continuously improve the standard of living for its people. The downside of this situation is the reckless attitude towards the natural resources (specifically, fossil fuel oils) and the environment as well as the irrational consumption of electricity and water. The latter may be attributed mainly to the lack of appropriate policies, sound codes of practice and proper decisions by the governing and legislative bodies in a way that would reward conservation and safeguard against misuse of such resources. Only lately; however, soaring fuel prices and rising concerns over global climate changes and increased atmospheric pollution made it impossible to continue turning a blind eye to this situation. On the supply side, the Ministry of Electricity and Water (MEW) has already started modernizing its technology base. Since 2005, projects for major power generation installations based on the open cycle gas turbine (OCGT) and the combined cycle gas turbine (CCGT) have either been completed or moving ahead. Construction of the first seawater reverse osmosis (RO) plant is already in progress. Furthermore, blueprints for construction of new mega capacity power generation and water desalination plants based on better and more efficient technologies continue to evolve. Prospects for adoption of alternative-energy-based power generation and water desalination technologies have better chances than ever.

Meanwhile; on the demand side, MEW conducted massive public campaign over the past few years aiming to create a culture of partnership with the consumers for the sake of encouraging and stimulating conservation of electricity and water. The last strategic aspect where MEW needed to work on in order to deal with the downside of the

Table 1
Water subsidies in the GCC countries (El-Sayed et al., [9]).

				Subsidies		
Country	Produced desalinated water (Mcm/yr)[a]	Cost ($/m^3)	Revenue ($/m^3)	1×10^6 ($)	% of GDP	% of oil export revenues
Kuwait	520	1.98	0.19	832	2.4	5.9
Saudi Arabia	2500	1.35	0.08	3175	1.7	7
UAE	831	1.16	0.13	856	1.2	2.1
Qatar	132	1.31	0.42	117	0.7	1.3
Bahrain	115	0.65	0.17	55	0.7	1.4
Oman	169	1.34	0.84	85	0.4	1.1

[a] Mcm/yr: million cubic meter per year.

present situation is to improve and make better utilization of its existing power generation and water desalination plants. The MEW started recently with Kuwait Institute for Scientific Research (KISR) a project to assess the existing electrical power generation and water desalination plants. The primary objective of this assessment was to identify problems affecting reliability and efficiency and to identify and rank possible enhancements with emphasis on operating practices and economics. The assessment focused on the steam-boiler-turbine-generator (SBTG) power generation and multistage flash (MSF) water desalination plants. The main outcome of the assessment showed that the desalination plants suffer from (1) inappropriate fuel is causing serious damages to different parts of the plants leading to some loss of power generation capacity (2) some plants suffer from poor welding quality, low grade materials of construction, poor design, and sponge ball cleaning system not in operation; and (3) improper water intake design and location brings in very low quality seawater feed, which is leading to sedimentations, erosion and excessive use of chemicals in the MSF plant, and subsequently restricting its top operating temperature and production capacity. (4) The overall cost of production is relatively higher than average; mainly due to high fuel cost. (5) Replacement of worn-out/obsolete electrical and control equipment is needed. (6) Some plants operate at low temperature, are heavily corroded. (7) The maintenance approach for some plants is good and for others is poor. Age is reflecting on the MSF plant, which is suffering from corrosion attacks. Improved and properly planned maintenance could keep the operational status of the MSF on an acceptable level without large replacement costs. (8) High sulphur content in the heavy fuel oil in some plants is causing heavy damages and corrosion in the flue gas ducts and other parts. The economic assessment of the water produced by desalination showed the total sum of all operating costs for water production during 2005 was ranging between KD 0.920 and 1.160 per 1000 imperial gallon for the plants powered by fuel oils (1KD = 3.3 $US). For the plants powered by low-price natural gas, this cost ranges between KD 0.860/1000 IG to KD 3.45/1000 IG. This shows the big difference between operating an MSF plant within a cogeneration scheme compared with one which is operated as standalone using auxiliary boilers.

3. Methodology

The methodology used in this study was a combination of pressure-state-response (PSR) concept (Fig. 1) and IWRM principles (Fig. 2), using the multi-criteria decision analysis (MCDA) methodology documented by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) [18].

Originally employed by the OECD [19] to characterize pressures on environmental systems using indicators, the PSR framework has more recently been used by the Global Water Partnership [20] as part of its approach to assessing water sustainability using indicators. The pressures (Fig. 1) can increase, either due to climate change, reflected in drought frequency, or due to increasing demand for water associated with population growth or growth in the agricultural, commercial, and industrial sectors in response to high-level socioeconomic conditions. Pressures act upon the states of the water supplies, which can be characterized in the economic, social, and environmental terms, to create impacts, e.g., on water scarcity, pollution, lack of equity in access to water, etc. The responses are the structural interventions/management options employed to relieve the pressures. To determine the appropriate responses, all the available water resources should be assessed first, both in terms of quantity and quality. Then, a strategic vision followed by the development of a long-term water sustainability strategy based on the most appropriate responses should be initiated; the responses will therefore need to be evaluated using suitable decision-making tools.

Here, the MCDA methodology [18] is used to evaluate the overall socioeconomic, technical, and environmental performance of a set of alternative management options (MOs) that could form the basis of a sustainable water security strategy for Kuwait. This is the core of this paper. Selecting the best strategy for water resources development and management from a number of alternatives is a complex decision-making process. The decision-making approach employed here seeks to achieve an appropriate balance between the multiple objectives of economic efficiency, social equity, and environmental sustainability. Achieving this balance requires the use of a multi-criteria decision-making technique, whereby the different alternatives can be evaluated in an objective way that is transparent to the decision-makers. This makes the decision-making process more explicit, rational and efficient [21]. Among the numerous multi-criteria decision-making techniques described in the water resources literature, Compromise Programming has seen widespread application ([22–27]). It is used to identify solutions that are closest to the ideal solution as determined by some measure of distance. The solutions identified to be closest to the ideal are called compromise solutions, since this is how conflicting objectives must be rationalized. Recognizing that, this technique had the potential for widespread application, UNESCO commissioned the preparation of a Methodological Guidelines Manual [18] for water resources applications and a software tool. This tool was developed further (in this study) into a Decision Support Tool for Kuwait (KDST). To develop a water sustainability and security strategy for Kuwait, multiple alternative MOs need to be evaluated using multiple criteria, involving multiple stakeholders. The KDST was adopted for this purpose for the aforementioned reasons. To evaluate the multiple MOs, indicators are needed which represent economic, social, and environmental criteria. The UNESCO MCDA approach is based on the use of a set of basic indicators (BIs) for evaluating the alternative MOs. Ideal and worst values of the indicators can be defined in absolute terms, or use of the best and worst values across the set of MOs. The BIs are then standardized to the range (0,1) using the ideal and worst values. They are then combined mathematically into second or third level composite indicators using numerical weights which reflect stakeholder preference as part of the balancing of conflicting objectives. The values of these third level indicators are then used to calculate the final overall indicator which can then be used to rank the MOs. Here, a set of possible MOs that could form the basis of a sustainable Water Security Strategy for Kuwait are evaluated using this methodology. The MCDA methodology [18] can be described mathematically as follows: Let a set of BIs represent the state of the system being analyzed. A hierarchy of several levels

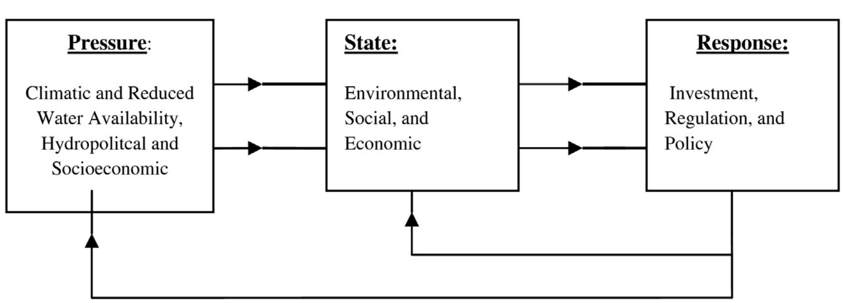

Fig. 1. The Pressure-State-Response (PSR) framework with feedbacks.

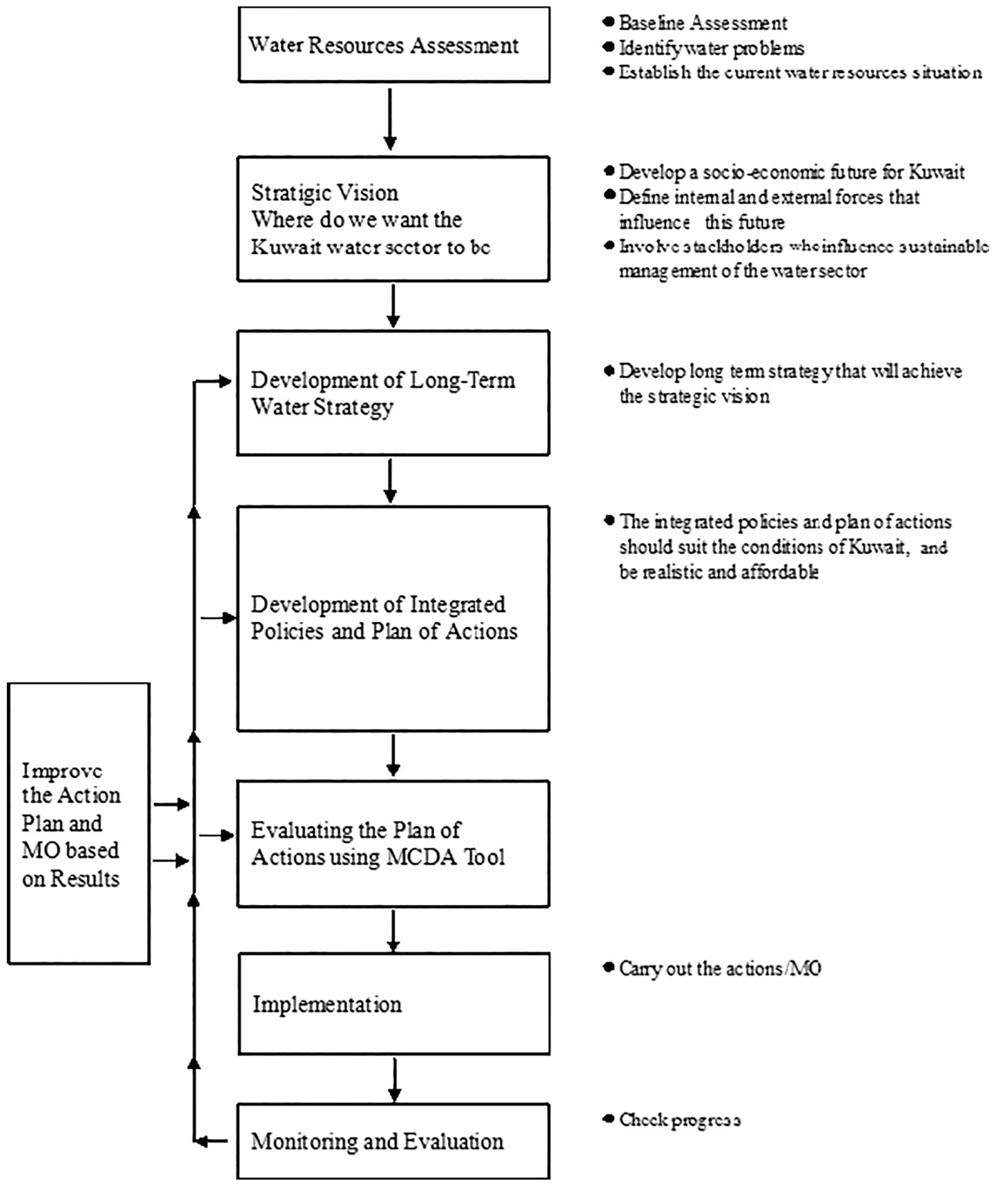

Fig. 2. Steps towards a sustainable water security strategy for Kuwait.

is used typically where the BIs are combined to obtain higher level composite indicators. In this methodology, the BIs are first standardized to the range 0–1. The second level involves the calculation of composite distances, Lj, from the ideal point using Eq. (1):

$$L_j = \left[\sum_{i=1}^{n_j} \alpha_{ij} S_{ij}^{p_j}\right]^{\frac{1}{p_j}} \quad (1)$$

where,

L_j = composite distances in group j from the ideal point;
S_{ij} = standardized basic indicator i in group j;
α_{ij} = weight applied to the ith indicated in group j;
n_j = number of indicators in group j;
p_j = balancing factor, As $pj \to \infty$, $Lj \to \max(Sij)$; normally $p = 1$or 2.

The composite indicators are defined by Eq. (2):

$$Cj = 1 - Lj \quad (2)$$

The best value of Cj is 1 and the worst value is zero. Lj, therefore, represents a measure of the distance from the ideal point (Fig. 3), for which Lj = 0. For each group j, the weights must add up to one. Then,

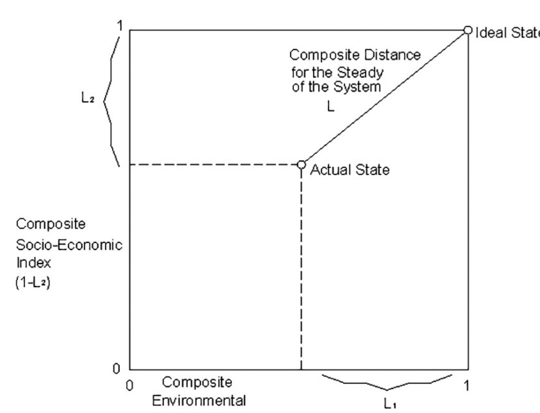

Fig. 3. Distances from ideal state [18].

composite distances at a third level can be calculated from Eq. (3):

$$L_k = \left[\sum_{j=1}^{m_k} \alpha_{jk} L_{jk}^{p_k}\right]^{\frac{1}{p_k}} \quad (3)$$

where,

L_k = composite distances at a third level;

k = 1: EQ (environmental quality);

k = 2: SE (socioeconomic);

m_k: number of elements in each third level group. Again, the weights for each group k must add up to one.

L_{jk} = composite distance in group k for element j.

The final overall composite distance can be calculated from Eq. (4):

$$L = \left[\alpha_1 L_1^2 + \alpha_2 L_2^2\right]^{\frac{1}{2}} \quad (4)$$

with the weights adding up to one. Then, a final composite indicator Eq. (5) is:

$$C = 1 - L \quad (5)$$

The alternative MOs are then ranked based on their C-values, with C = 1 representing the ideal point. The L – values represent the distances from the ideal point and can be shown on a graphical plot. Fig. 3 shows a plot of a composite socioeconomic indicator against a composite environmental indicator, and the distance L from the ideal point for a single MO.

Zones for Good, Acceptable, and Poor MOs can be defined using the following expression (Eq. (6)) for the boundary curves:

$$\beta = \left[\alpha_1 (1\text{-}x)^p + \alpha_2 (1\text{-}y)^p\right]^{\frac{1}{p}} \quad (6)$$

where, (x, y) = point on curve. Fig. 4 shows a plot of a hypothetical group of MOs, together with boundary curves separating Good, Acceptable and Poor MOs.

In using the aforementioned methodology, conflicts arising as to how best to achieve secure water supplies need to be addressed. For example, industrial activities can contribute to economic growth but may lead to aquifer pollution, resulting in potential health problems and longer-term water quality degradation unless investments are made in water treatment and desalination facilities. The weights applied to the different MOs allow compromise positions to be reached over some of these conflicts.

A participatory approach is adapted in this study to develop suitable interventions, management options and relevant indicators. A group of prominent water managers, experts and planners (stakeholders) in the disciplines of water/environment management, social and economic sciences, from Kuwait and the region met in a number of workshops, has proposed a set of MOs that could form the basis of an Action Plan (Table 2) and sets of BIs (Tables 3, 4, and 5). Some of these experts serve for many years in the strategic planning and management of the water sector in Kuwait. So, it was considered valid and reliable that an expert knowledge-based approach would provide a useful first evaluation of the MOs and BIs. The accuracy of this procedure can be accepted as first evaluation of the different strategic options which can be useful to direct countries like Kuwait towards a reasonable socio-economic future. The MO headings correspond broadly to the components of a Sustainable Water Security Strategy shown in Fig. 5. Table 2 covers a range of interventions that could be implemented under each MO heading. A selection of these BIs was then made for use in the evaluation.

The experts' input was combined through developing decision support tool software for Kuwait (KDST) as follows: Firstly, values of the BIs (based on the opinion of the experts) are input to the software for all of the MOs. Then, values of the standardized BIs are calculated using assigned best/worst values. Table 6 presents the values of the standardized BIs, coded from best to worst. The KDST software then takes the stakeholders through the steps previously described, whereby weights are first assigned to the BIs to obtain second level composite indicators (Table 7).

Weights are then assigned to these second level indicators to obtain the third level composite indicators (Table 8). Finally, third level weights are assigned to obtain the overall composite indicators which are used to rank the MOs (Table 8). The weights assigned to the basic, second and third level indicators are shown in Table 9. This also shows how the indicators were grouped under the Economic, Environmental and Social headings and then combined progressively through the different levels. For example, at the first level under the Social heading, the BIs are assigned to two subgroups of indicators, one dealing with Household Water (Water Connections, Water Quality, Water Usage, with weights of 0.1, 0.5, 0.4, respectively) and a second, dealing with Household Livelihoods (Agricultural Job Creation, Industrial Job Creation, Source Yield, and Livelihoods, Water Expenditure, with weights of 0.1, 0.4, 0.4, 0.1, respectively). These give two composite indicators at the second level, Household Water and Household Livelihoods, which are then combined (weights of 0.4 and 0.6, respectively)

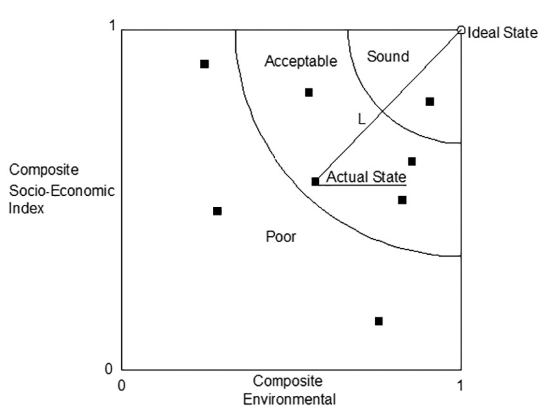

Fig. 4. Graphical representation of a set of ranked Management Options, showing distances from ideal state, and boundaries between Good, Acceptable and Poor MOs [18].

Table 2
Proposed MOs and related interventions.

MO	Description of related interventions
MO-1: Rainwater Harvesting	Construction of cisterns and dams; aquifer storage and recovery
MO-2: Desalination	New plants to be operated with renewable energy; small-scale brackish water desalination plants; small-scale Mobile Reverse Osmosis (RO) Units;
MO-3: Water Demand Management	Leak detection; household plumbing and maintenance of pipelines; saving of water devices; pressure control devices; metering and tariff systems with economic incentives;
MO-4: Environmental Protection/Conservation	Establish groundwater protection policy and guidelines
MO-5: Wastewater Reuse	Treatment plants for drainage from dewatering schemes, irrigation returns and from oilfield produced water; small-scale wastewater treatment plants; awareness on improved latrines, septic tanks, or dumping pits
MO-6: Sector Reallocation	Reallocate water from the agricultural sector to domestic/industrial sector
MO-7: Changes in Agricultural Policies	The implementation of virtual water policy; growing of water-efficient crops (more cash crops/less water consumption).
MO-8: Importation of Water	Importation of water from countries rich with water
MO-9: Administrative and Institutional Management	Establishment of water law and national water council with suitable regulations

Table 3
Social indicators.

Indicator number	Indicator description
SOC-1	Water connection
SOC-2	Water quality
SOC-3	Water expenditure
SOC-4	Percentage of reduction in per capita water use by households
SOC-5	Percentage of reduced Br_2O^{-3} to WHO limits in water supply networks
SOC-6	Percentage of households connected to sanitation networks
SOC-7	Percentage of reduced water-related diseases
SOC-8	Source yield and livelihoods
SOC-9	Industrial jobs
SOC-10	Agricultural jobs

Table 5
Environmental indicators.

Indicator number	Indicator description
ENV-1	Aquifer water level
ENV-2	Reliability of supply from aquifer for irrigation
ENV-3	Aquifer water quality
ENV-4	Percentage of reduced UFW
ENV-5	Percentage of aquifer yield mixed with desalinated water
ENV-6	Water quality of brine discharged to the Arabian Gulf
ENV-7	Wastewater discharge on land
ENV-8	Wastewater discharge to the Arabian Gulf
ENV-9	Wastewater treated to tertiary/advanced standards
ENV-10	Use of agricultural pesticides
ENV-11	Industrial effluent

to yield a single Social Indicator at the third level. The third level Economic, Environmental, and Social indicators are then combined (weights of 0.2, 0.3 and 0.5, respectively) to yield a single Overall Indicator for each MO. As noted, the weights assigned to each subgroup must add up to one.

4. Analysis and discussion

Water supplies must be provided based on the sustainable management and development of all water resources. Fig. 2 shows that there is a need first to define a baseline reference State (in the PSR framework) for each of the resources to measure departures from this reference state at the beginning and end of the planning period. In Kuwait these departures from the reference state are expressed in severe water shortage [28]; [29]. The strategic vision requires the choice of strategic interventions (Plan of Action, see Table 2) to secure water supplies. The linkages between the different components of a Sustainable Water Security Strategy are shown in Fig. 5. Using the MCDA approach, the overall sustainability of water resources in Kuwait, can be evaluated by making trade-offs between the economic, social, and environmental costs/benefits of the different MOs using the weights. Then, the implementation of the Plan of Action based on the ranking of the MOs can be monitored, and as a result, decisions to improve the Plan of Action can be taken when necessary.

Fig. 6 shows a plot of the composite Economic, Environmental, and Social indicators, and the overall single composite indicator used to rank the MOs (the numerical values are presented in Table 8). The ranking of the MOs is as follows:

- Wastewater Reuse
- Desalination
- Demand Management
- Sectoral Reallocation
- Environmental Protection/Conservation
- Changes to Agricultural Policies
- Administrative and Institutional Management
- Rainwater Harvesting
- Importation of Water

Fig. 6 shows that when the social benefits (making water available to all households) are considered alone (Social Indicator), then the Desalination MO is ranked first. Desalination will continue to be the reality of life in Kuwait. However, water production through desalination is an energy-intensive process [30], and accounts up to 70% of electricity consumption in Kuwait from fossil fuel sources [31]. Therefore, it is critical for Kuwait to accelerate implementing desalination plants with renewable energy (such as solar and wind energies) in order to cope with such rapid expansion of electricity demand. The technology prices of renewable energy sources are declining significantly, thus, making this technology a valuable economic investment that reduces external, social, environmental, and operational costs. Furthermore, Kuwait enjoys high levels of solar radiation and sunshine duration that can provide good potential for solar-based generation of electricity; although, harsh weather conditions could negatively affect the performance of solar cells [31]. Moreover, the use of solar energy technology for desalination is still not applied on a large scale because of huge land requirements [30]. Policy makers need to support different technology choices for desalination in order to allow for more water to be produced with less seawater feed and less energy consumption per unit product of water. Also, the policy-makers should encourage an integrated approach for the development of the energy and water sectors [32]. Development of mobile reverse osmosis (RO) desalination units may be able to produce desalinated water at a significantly lower cost than the existing facilities especially if solar energy is used to operate them. Also, Mobile RO units can reduce the pressure on the central desalination plants that are very expensive. National regulations on brine disposal that support safe waste disposal should be promoted as a policy, the implementation of which would lead to the protection of the ecosystem of the Arabian Gulf.

When the overall social-economic-environmental system ranking is considered, Wastewater Reuse MO comes first. Wastewater is a valuable resource in a water- scarce region, and it represents a sustainable use of the water resource. Having been collected, it should be treated to acceptable standards for recycling/reuse in irrigation and recharge to the aquifers. The challenge is to make use of treated wastewater for agriculture while minimizing the health risk. Therefore, advanced membrane treatment technologies and suitable health measures should be implemented. Due to health and religious concerns, treated waste water through these advanced membrane technologies (although they produce high purity water) are not used in Kuwait for direct potable reuse. Small-scale wastewater treatment plants for schools, small communities, and farms should be encouraged to reduce the pressure on the central wastewater treatment plants and brackish water production for irrigation. Also, treated water from dewatering schemes should be considered as one of the reuse interventions [8].

Water demand management is third in the overall ranking. It is a key measure for controlling and managing the ever-increasing water demand in Kuwait and scores high on sustainability. Significant reduction in water consumption is normally associated with pricing and economic incentives. A better understanding of the factors responsible for the high rates of domestic water consumption in Kuwait is needed so that appropriate measures to encourage reduced consumption can be identified and implemented. The tariff schemes should be reviewed against full

Table 4
Economic indicators.

Indicator number	Indicator description
ECO-1	Internal rate of return (IRR)
ECO-2	Agricultural water production cost per unit of water
ECO-3	Public network production cost per unit of water
ECO-4	Agriculture/industrial water productivity

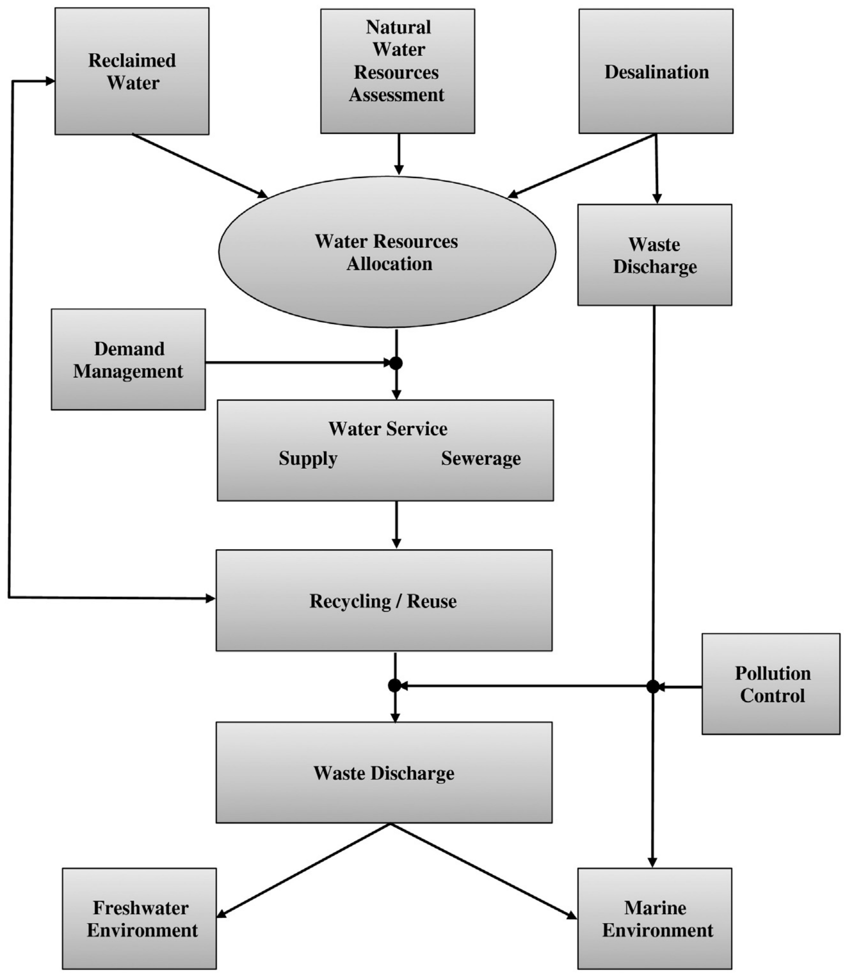

Fig. 5. Linkages between the components of the sustainable water strategy in Kuwait.

Table 6
Values of standardized basic indicators for the different MOs based on the expert knowledge of a group of water experts in Kuwait. (High values close to best value of 1 and low values close to worst value of 0).

Basic indicator	Rainwater harvesting	Desalination	Demand management	Environmental protection	Watewater re-use	Sectorial allocation	Changes in agr. policies	Importation of water	Institutional management
Internal rate of return	0.6	0.7	0.8	0.5	0.9	0.8	0.9	0.5	0.7
Agricultural water production cost	0.9	0.4	0.6	0.7	0.8	0.8	0.9	0.3	0.8
Public network production cost	0.5	0.8	0.8	0.5	0.7	0.7	0.5	0.5	0.6
Public network production cost per benefit	0.5	0.7	0.7	0.5	0.7	0.6	0.5	0.5	0.5
Industrial/agriculture water productivity	0.8	0.6	0.6	0.5	0.7	0.7	0.7	0.4	0.6
Aquifer water level	0.6	0.8	0.7	0.6	0.8	0.8	0.7	0.7	0.6
Reliability of supply from aquifer	0.6	0.7	0.7	0.6	0.7	0.7	0.5	0.7	0.6
Aquifer water quality	0.6	0.8	0.7	0.9	0.9	0.6	0.6	0.5	0.6
Watewater discharge	0.5	0.6	0.7	0.7	0.8	0.5	0.9	0.5	0.6
Agricultre pesticide use	0.5	0.5	0.7	0.8	0.7	0.7	0.8	0.5	0.7
Industrial effluent	0.5	0.6	0.6	0.7	0.8	0.8	0.3	0.5	0.6
Water connection	0.5	0.7	0.7	0.5	0.6	0.5	0.5	0.7	0.7
Water quality	0.5	0.8	0.7	0.8	0.8	0.8	0.7	0.5	0.5
Water usage	0.7	0.8	0.8	0.8	0.8	0.7	0.5	0.7	0.8
Agricultural jobs	0.7	0.1	0.6	0.5	0.7	0.7	0.9	0.3	0.5
Industrial jobs	0.3	0.9	0.6	0.6	0.5	0.6	0.7	0.5	0.5
Source yield and livelihoods	0.6	0.7	0.8	0.8	0.8	0.7	0.7	0.8	0.8
Water expenditure	0.8	0.5	0.8	0.7	0.6	0.5	0.4	0.4	0.6

Table 7
Second level composite indicators for Kuwait MOs.

Second level of composite indicators	Rainwater harvesting	Desalination	Demand management	Environ. protection	Watewater re-use	Sectorial allocation	Changes in agr. policies	Importation of water	Institutional Management
Investment efficiency	0.57	0.73	0.78	0.52	0.77	0.74	0.66	0.48	0.65
Social vs productive benefits	0.68	0.64	0.64	0.50	0.70	0.66	0.62	0.44	0.56
Aquifer state: quantity	0.6	0.74	0.70	0.60	0.74	0.74	0.58	0.70	0.60
Aquifer state: quality	0.6	0.80	0.70	0.90	0.90	0.60	0.60	0.50	0.60
Pollutant pressures	0.5	0.58	0.66	0.72	0.78	0.66	0.64	0.50	0.62
Household water	0.58	0.79	0.74	0.77	0.78	0.73	0.60	0.60	0.64
Household livelihood	0.51	0.70	0.70	0.68	0.65	0.64	0.69	0.59	0.63

cost recovery to secure financial sustainability while maintaining a reasonable rate of subsidy for low-income citizens. Leakage reduction and improved agricultural technologies are parts of the water demand management approach in Kuwait.

Sectoral reallocation is fourth in the overall ranking. Any water saving due to the upgrading of the agricultural water supply system by the modification of agricultural practices, techniques, or cropping patterns will ultimately be reallocated to the domestic/industrial sector. Domestic/industrial water demand must be prioritized with regard to both quantity and quality.

Environmental Protection/Conservation comes second under the environmental criterion but is fifth, overall, reflecting lower economic and social benefits. In Kuwait, pollution control and waste discharge are so important for the protection of the seawater feed to desalination plants. A set of policies have to be developed and implemented based on the "Polluter Pays" principle. The extent of the impacts of industrial activities on the marine resources and the ecosystem of the Arabian Gulf is of great concern to the sustainable future of Kuwait's marine environment; special attention needs to be paid to pollution through oil refineries, petrochemicals, and industrial complexes. Safe disposal is a powerful strategy that can benefit all water purification and desalination processes if performed both in an economical and an environmental friendly manner. Safe disposal of wastewater requires treatment to eliminate biological, chemical, and physical hazards. Accumulation of heavy metals and salinity should be monitored, managed, and mitigated. Leaching of soils to reduce salinization should be advocated by the irrigation authorities. National standards for discharging industrial wastewater into sewers should be developed and implemented. National regulations for on-site sanitation need to be established and enforced as it is a potential source of pollution. The benefits of all of the aforementioned are to protect the environment and the quality of water resources, which means that the water supply/demand gap will not grow larger due to the pollution of the natural water resources.

Changes in Agricultural Policies are ranked sixth, overall. This is because the importance of this option is not yet promoted, as it should be among the stakeholders. Studying the water situation of Kuwait closely suggests immediately embracing policies to implement the Virtual Water concept and the use of treated wastewater in irrigation. Kuwait may consider establishing cooperation with countries rich in water and agricultural lands to cultivate major crops that can be transferred to Kuwait within a strategy of maximizing agricultural subsidies and minimizing the cost compared with cultivating these crops in Kuwait where water is hardly available. El-Sayed et al. [9] reported that the agricultural sector of Kuwait consumes about 320 Mcm/yr. Legal agreements should be promoted to regulate agricultural investments abroad [33]. Mechanisms are needed to expand the ownership base of existing agricultural companies in Kuwait alongside evaluations of investment and the provision of credit facilities and concessional funding for Kuwait investors outside the region. Special mechanisms are needed to regulate contracting with companies with investments abroad in order to purchase products that are tied to Kuwait food needs. International food companies should be attracted to Kuwait [33]. A possible cooperation with water and agriculture-rich countries abroad such as Hungary [34] and Italy [35] has been initiated by the Kuwait government. Under such cooperation, Kuwait would rent farm lands and the use of experienced farmers from Hungary and Italy, thus utilizing available freshwater resources from these countries to grow suitable crops for Kuwait. These opportunities are yet to materialize in agreements because this issue is complex and may include a lot of conflicts of interest, as the owners of Kuwaiti farms may be negatively impacted should those agreements be implemented.

Not all of Kuwait's food needs could be met through external agreements with agriculture and water-rich countries. All produced wastewater should be treated to a quality suitable for safe and productive reuse in agriculture, in line with national standards, and the distribution and productive reuse of treated wastewater in irrigation should be supported. Crops to be irrigated by effluent- treated using advanced membrane treatment technologies should be selected to suit the irrigation water, soil type, and chemistry, and the economics of the reuse operations. Most brackish water supply to the agricultural sector should be replaced by advanced-treated wastewater mixed with brackish water. Although agricultural water needs should not be increased as a policy, any increase in the agricultural demand for water should be satisfied by reclaimed wastewater. To encourage the switch towards using reclaimed water, metering of agricultural wells and the implementation of different tariffs for water use are recommended. For the agricultural sector to become more able to bear tariffs, small farms must become more profitable.

Continuing with national policies on food self-sufficiency in Kuwait may result in the high cost of domestic food production and in wasting

Table 8
Third level and overall composite indicators for Kuwait MOs.

Third level of composite indicators	Rainwater harvesting	Desalination	Demand management	Environ. protection	Watewater re-use	Sectorial allocation	Changes in agr. policies	Importation of water	Institutional management
Economic	0.64	0.68	0.70	0.51	0.73	0.69	0.64	0.46	0.60
Environ.	0.55	0.68	0.68	0.74	0.80	0.67	0.62	0.55	0.61
Social	0.54	0.74	0.72	0.72	0.70	0.68	0.65	0.59	0.63
System overall	0.56	0.704	0.701	0.669	0.733	0.676	0.638	0.55	0.619

Table 9
Weights assigned to the basic, second level and third level indicators by a group of experts in water resources/supply in Kuwait.

Basic indicator	Weight	Second level Indicator	Weight	Third level indicator	Weight
Internal rate of return	0.3				
Agricultural water production cost	0.1	Investment efficiency	0.4		
Public network production cost	0.6				
				Economic	0.2
Public network production cost per benefit	0.4				
		Social vs productive benefits	0.6		
Industrial/agriculture water productivity	0.6				
Aquifer water level	0.4				
		Aquifer storage quantity	0.25		
Reliability of supply from aquifer	0.6				
Aquifer water quality	1.0	Aquifer storage quality	0.25	Environmental	0.3
Watewater discharge	0.4				
Agricultre pesticide use	0.2	Pollution pressure	0.5		
Industrial effluent	0.4				
Water connection	0.1				
Water quality	0.5	Household water	0.4		
Water usage	0.4				
Agricultural jobs	0.1			Social	0.5
Industrial jobs	0.4				
Source yield and livelihoods	0.4	Householdlivelihood	0.6		
Water expenditure	0.1				

a lot of water (maybe to crisis levels) that may be used for domestic purposes with some treatment. Nonself-sufficiency in food means importing essential foods at remarkably advantageous terms of trade. The cultivation of the high water-consumptive crops of low economic values should be avoided. Farmers shall be encouraged to determine the rate of water application needed for different crops, taking into consideration the value of nutrients in the treated water and other parameters. They should also be encouraged to use modern and efficient irrigation technologies. The protection of on-farm workers and crops against any impacts from polluted wastewater should be ensured.

The Administrative and Institutional Management option is so crucial in Kuwait for the efficient management of water resources, yet it has emerged behind the more traditional technical measures in its ranking. This may be because; it is perceived that achieving major institutional changes can be difficult and slow, albeit, there is much that can be done to create a more efficient institutional setup. The Government should comprehensively manage Kuwait's water resources; execute the water policy; monitor water projects; and initiate coordination between the parties affected by water management. The environmental regulations on the discharge of treated wastewater and on-site sanitation should be developed. The Ministry of Energy and Water (MEW) should be in charge of the overall regulation of water producers and service providers, including tariff setting and resolving conflicts between service providers and users. Institutional strengthening through permanent capability and capacity building of agencies responsible for water policies, programs, and infrastructure should have high strategic priority. Legislation is perhaps the most important mechanism to underpin decision-making in the management of water resources in both the medium- and long-terms.

The responsibilities for water resources governance, being a regulatory function, and water services management, being an operational function, should be separated institutionally. Regulatory functions comprise monitoring and enforcement of established laws, rules, standards, and agreements, which should be professionally based and as independent as possible to protect rationality. The management of Kuwait's water sector will remain fragmented until a National Water Council is implemented. It will include representatives of the main stakeholders in the water and sanitation sector. The Council's role would consist of approving the overall allocation of water rights to the different sectors, approving the overall allocation of investments to various subsectors, and ratifying proposed improvements to sector regulation.

Kuwait needs to consider involving the private sector in the management, operation and conservation of Kuwait's water resources. On the water resources development front, there will be a continuous search for new water resources for Kuwait, which can be summarized to be improved schemes for desalination plants/units for seawater and brackish groundwater, in addition to utilizing flash floods, rainwater harvesting, treated wastewater, and urban effluents. The IWRM principles require that water resources development and management should be based on a participatory approach, involving all stakeholders at all levels. Flexible strategies to deal with the impact of climate change on water resources are needed [36] [37]. An integrated component of the water

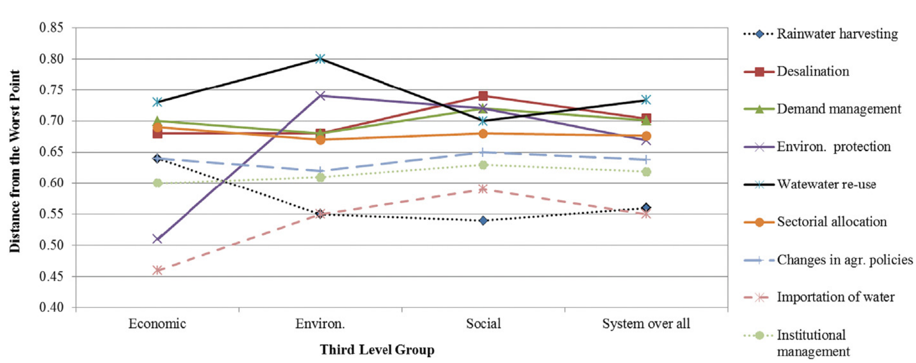

Fig. 6. Results of the evaluation of the Kuwait MOs using the MCDA methodology (leave this figure in colors).

security plan in Kuwait is the tariff structure for water and sanitation services. The water supply service providers should be considered to become commercially oriented, providing quality service to the consumers, establishing progressive tariffs, and collecting revenues to cover their costs. The service levels should be controlled by the MEW so as to recognize affordability while appreciating the right to adequate water for health and prosperity. In this context, an important strategic direction is to separate the institutional responsibility of policy and regulatory functions from the service delivery function.

The decentralization of water services to financially autonomous utilities should be encouraged. The privatization of water utility services to promote capital efficiency should be promoted. The involvement of the private sector in the management of these operational services needs to be considered as a policy. It is envisaged that this will improve the technical and managerial expertise, increase operational efficiency, reduce public expenditures on subsidies, and especially, make the water services sector faster and more responsive to its users and their demands. Private sector participation in the operation of water and wastewater utilities is growing worldwide. The legal separation of service provision from policy-making as well as independent regulation and supervision is important for greater transparency and accountability of service providers.

Rainwater harvesting will provide a legitimate and cost-effective option for household water supply, but it will never be a major resource as reflected in its overall seventh ranking. In particular, farmers could use the captured storm water to feed their animals and irrigate their farms. Urban residents could use the harvested water to irrigate their gardens. This would help reduce the gap between water supply and demand. Dams can be built on intermittent Kuwaiti wadis to capture and retain storm runoff for the purpose of artificial recharge, cattle use, or irrigation.

Importation of water is a strategic option in the long run. Kuwait will study in detail the prospect of importing water from countries with rich sources of freshwater such as Turkey through pipelines. However, it should be understood that the hydro-transport of water over long distances is very costly, vulnerable, and it may lead to failure, but the decision-makers in Kuwait are encouraged to study different options in detail about the importation of water from countries other than Turkey and how to implement this water importation option.

5. Conclusions

It is clear that Kuwait lacks national water sustainability and security in all sectors of water use. Water is essential to human life and crucial to the development of industry and agriculture in Kuwait, which in turn depends on secure and sustainable access to water. Therefore, reliable strategic water plans and policies are necessary for the protection, conservation, sustainable management, and development of water resources, water supplies, and wastewater services. The utilization of the available water resources needs to be optimized for economic, social, and environmental benefits using developed policies. These policies at the moment are neither well-developed nor integrated in Kuwait. In order to develop a water sustainability and security strategy for Kuwait and an Action Plan to implement it, choices have to be made between the alternative MOs to ensure that those chosen for implementation will be sustainable from the social, economic, and environmental terms. An MCDA Decision Support Tool has been developed to support this process, and a group of MOs have been ranked using a set of environmental, social, and economic indicators. Assigning relative weights of the different indicators is a very essential part of this process, and these were estimated by a group of prominent experts in water resources/supply in Kuwait and the region. The final ranking enables the MOs to be prioritized; while, under each MO, a set of actions has been identified that can provide a basis for implementation. Following the extensive review of the ranked MOs as carried out, a summary of recommendations are made in the next section.

6. Summary of recommendations

6.1. Desalination

- Relevant policies about desalination should be developed to take advantage of the latest innovative hybrid process schemes and to promote utilizing renewable energy such as solar and wind technologies that allow water to be obtained with less seawater feed and less energy consumption per unit product of water.
- New desalination power plants should be based mainly on the combined cycle gas turbine technology with natural gas firing.
- Mobile RO units should be used widely.
- Modern state of the art steam-based technology can be considered to make use the residues from the refineries as fuel.
- Membrane-based desalination/pretreatment technologies as well as multiple effect distillation technology side by side with the MSF could offer solutions to site limitations in Kuwait and also could offer major technical and economic advantages over the existing single-technology base.
- High-tech power plants should be foreseen for future installations and advanced fuel cleaning/treatment processes should be considered at the refineries or at the plants.
- It is highly recommended to develop governmental regulations to meet at least the World Bank (WB) standards for the emission of unburned particles, tar, NOx, and SO2.

6.2. Water demand management

- Appropriate measures to encourage reduced domestic consumption need to be identified and implemented.
- Kuwait should start metering water consumption in all sectors of water use.
- Tariff schemes should be developed and reviewed against full cost recovery to secure financial sustainability while maintaining a reasonable rate of subsidy for low-income citizens.
- Leakage reduction, improved agricultural technologies, and treatment of dewatered water should be parts of the water demand management measures.

6.3. Wastewater Reuse

- Wastewater Reuse should be prioritized in Kuwait, particularly for agriculture.
- Most brackish water supply to the agricultural sector should be replaced by treated wastewater mixed with brackish water.
- Small scale wastewater treatment plants should be encouraged to be reused on farms scale.

6.4. Changes in agriculture policies

- Virtual Water concept should be embraced. It is strongly recommended that Kuwait should consider establishing cooperation with countries rich in water and agricultural lands to cultivate major crops that can be transferred to Kuwait within a strategy to maximize agricultural benefits and minimize cost when compared to cultivating these crops in Kuwait where water is hardly available.
- National food self-sufficiency in Kuwait should not be a rigid policy, but the use of advanced-treated wastewater in irrigation should be widely encouraged.
- The cultivation of high water-consumptive crops of low economic value should be avoided.
- All agricultural wells should be metered.
- Farmers should be encouraged to use modern and efficient irrigation technologies.

- The protection of on-farm workers and crops against pollution with wastewater should be ensured and relevant policies should be developed.

6.5. Regulations, Administrative and Institutional Management

- Government should comprehensively manage the water resources; execute the water policy; monitor water projects; and initiate coordination between the parties involved and affected by water management.
- Institutional strengthening through permanent capability and capacity-building of agencies responsible for water policies, programs, and infrastructure should have high strategic priority.
- The responsibilities for water resources governance, being a regulatory function, and water services management, being an operational function, should be separated institutionally.
- Regulatory functions comprise monitoring and enforcement of established laws, rules, standards, and agreements, which should be professionally based and as independent as possible to protect rationality.
- A Water Law and a National Water Council should be established.
- The water supply service providers should become more commercially oriented, providing quality service to the consumers, establishing progressive tariffs, and collecting revenues to cover their costs.
- Private sector participation in the operation of water and wastewater services should be considered widely.
- The decentralization of water services to financially autonomous utilities should be encouraged. The privatization of water utility services, to promote Capital Efficiency, should be promoted.

6.6. Pollution control policies

- The “Polluter Pays” principle should be implemented.
- Safe disposal of wastewater or polluted water should be developed as a powerful strategy that can be economically beneficial while also protecting groundwater resources and the Arabian Gulf environments.
- Accumulation of heavy metals and salinity should be monitored, managed, and mitigated.
- Leaching of soils should be advocated by the irrigation authorities.
- National standards for discharging industrial wastewater into sewers and discharging wastewater into the Arabian Gulf should be developed and implemented.
- National regulations for on-site sanitation should be established and enforced as it is a potential source of pollution.

Finally, the outcomes of this study were discussed with officials in Kuwait who are in charge of water, environment, agricultural and industrial sectors. Some results such as metering water consumption, implementing tariffs and other water demand measures are being used by the government of Kuwait for ensuring a sustainable supply–demand balance. Based on the recommendations of this study, the ministry of Electricity and Water (MEW) is working with Kuwait Institute for Scientific Research (KISR) to (1) make substantial breakthrough in desalination systems' efficiencies in terms of footprint, energy, raw materials and environment, to respond to needs for new desalination capacity and to support the economic development of the State of Kuwait; to (2) improve sustainability and competitiveness of freshwater supply from the commonly used thermal desalination technologies by radically improving efficiency, economics, and flexibility, while minimizing environmental impact; (3) to augment the overall water availability by improved technologies for wastewater reclamation; (4) to assess the robustness of implementing different management options scenarios to combat future climatic and socioeconomic uncertainties.

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