Multi-criteria decision approach for evaluation, ranking, and selection of remediation options: case of polluted groundwater, Kuwait

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Abstract

Freshwater groundwater resources at north Kuwait were contaminated by infiltrated oil as well as sea water that was used to fight the oil-well fires during the liberation of Kuwait in 1991. This paper investigates the feasibility of five remediation options to restore the polluted aquifers. These options include: (i) pump and treat of contaminated groundwater; (ii) cleaning the aquifer formation; (iii) construction of additional desalination plant; (iv) constructing additional storage tanks, and (v) development of artificial aquifer recharge schemes. The basis for this assessment study is to supply minimum basic drinking water to Kuwait City at a total rate of 50,000 m³/day in an emergency for up to one year based on essential basic need of 32 liters per capita per day. To compare these options, a decision matrix to select suitable remediation options using Multiple Criteria Decision Analysis (MCDA) approach is developed. The cost was given a relative weight of 20 whereas other criteria are given weight of 10. Based on these MCDA scores, it was found that option 3, namely, establishing an additional water desalination plant, is the most feasible option followed by option 5, artificial recharge of aquifers.

Keywords Water resources · Groundwater remediation · Pump and treat · Artificial recharge · Storage tanks · Desalination plant

Introduction

A decision support tool for groundwater remediation and pollution control is often needed to provide insight on the trade-off between water status and the cost to achieve such situation (Benedetti et al. 2010; Fragoso et al. 2010; Hajkowicz and Collins 2007; Lotov et al. 2005; Muleta and Nicklow 2005; Udias et al. 2011, 2014; Yihdego et al. 2017a; Zitzler et al. 2003).

Iraq's invasion and occupation of Kuwait in 1990 left a chronic legacy of damage and environmental contamination. Over one billion barrels of crude oil are estimated to have been deliberately released to the environment as a result of the Iraqi

invasion. The extent of contamination was such that vast lakes of oil were created in the desert and airborne petrochemical by-products from well fires initiated by the Iraqis resulting in dark days over Kuwait for months after liberation (Al-Damkhi et al. 2009). Seawater pumped from the Gulf to extinguish the many well fires, dousing the ecologically sensitive landscape with large quantities of saline water that also intruded into fresh groundwater aquifers (Al-Weshah and Yihdego 2016).

Freshwater is the most scarce, critical, and valuable natural resource in Kuwait. Surface water is generally absent and groundwater is limited and mostly non-renewable. The two main fresh groundwater fields in Kuwait are found in the north of the country, in Raudhatain and Umm Al-Aish as shown in Fig. 1. These aquifers are essential for the sustainable development of the country and served historically as huge underground reservoirs to secure freshwater demands during emergency situations. These aquifers were the only freshwater reserves available in Kuwait as active production fields prior to invasion. They form a strategic emergency supply if drinking water supplies from desalination of seawater ceased or were interrupted (Yihdego and Al-Weshah 2016a).

The two aquifers were contaminated by infiltrated oil and also by entrainment and dissolution of petroleum contaminants that subsequently leached with rainwater as well as

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Fig. 1 Location map of the two main strategic aquifers Raudhatain and Umm Al-Aish

saltwater, required to fight the oil well fires after liberation ultimately contaminated the freshwater fields.

Based on detailed monitoring and assessment to remediate Kuwait's freshwater groundwater resources, the State of Kuwait was compensated for the contamination and permanent loss of the freshwater aquifers at Umm Al-Aish and Raudhatain. The idea is to treat the contaminated fresh groundwater with the hope that treatment, coupled with the removal of oil contamination from the aquifer recharge catchments, might lead eventually to restoration of the aquifers (Yihdego and Al-Weshah 2016b, c).

The basis for assessment is to supply essential drinking water to Kuwait City (based on essential human need of 32 l per capita per day) at a total rate of 50,000 m³/day in an emergency supply for up to 1 year (Akber et al. 2009).

Study objectives and assumptions

This paper investigates the feasibility of five remediation options to restore the polluted aquifers. The following facts and assumptions are considered in evaluating the feasibility of the proposed remediation options:

Kuwait's only strategic sources of fresh water at Raudhatain and Umm Al-Aish have been damaged as a result of Iraq's

invasion and occupation of Kuwait in 1990–1991. As a result of Iraq's destruction of the oil wells, the resulting fires, and the necessary firefighting activities, the groundwater at Umm Al-Aish is severely polluted with hydrocarbons and salts. It is anticipated based on the available evidence that the pollution of groundwater will increase over time (Yihdego and Al-Weshah 2016b).

Prior to 1990, Kuwait had planned to recharge the Raudhatain freshwater aquifer artificially to supplement natural recharge, preserve the availability of a sustainable productive field, and provide an emergency supply of drinking water (Mukhopadhyay 1992; Senay 1989). As a result of invasion-related surface oil spills and other impacts, natural recharge has been modified and resumption of pre-invasion production and artificial recharge have not been implemented because the soils in the natural recharge area, as well as the aquifers themselves, are polluted with hydrocarbons and salt. Currently, groundwater in Umm Al-Aish has the highest pollution levels of salts and hydrocarbons. Increased salt levels have been observed more extensively than hydrocarbon pollution in Raudhatain, but both types of pollution clearly are present (Yihdego and Al-Weshah 2016b, d). Kuwait does not have a replacement of this natural strategic reserve that would have continued to exist if oil pollution had not occurred; implementation of a strategic artificial recharge scheme with enhanced

production has not been practical given the presence of the contamination (Mukhopadhyay 1992; Fadlilmawla et al. 2008; Yihdego and Al-Weshah 2018). Replacing the strategic reserve in the shortest possible time will require an alternative source of fresh water or the treatment of water from the two aquifers.

Groundwater treatment options

To achieve the strategic objective and supply drinking water at a rate of 50,000 m³/day in an emergency year, the government of Kuwait and other partners identified the following possible remediation options:

Option 1: “Pump and treat” groundwater to restore the groundwater aquifers

Pump and treat the groundwater from the Raudhatain and Umm Al-Aish aquifers allowing capacity for an emergency year supply, including the treatment necessary to address the increasing salinity in these aquifers, allowing for natural attenuation of residual pollution (Yihdego 2017; Yihdego et al. 2017b) and restoration of the aquifers over an extended period of time. The option calls for the establishment of two treatment plants to carry out treatment of hydrocarbon-polluted groundwater pumped from the Raudhatain and Umm Al-Aish aquifers, with treatment designed to achieve the standards of drinking water quality (Al-Weshah and Yihdego 2016).

Under the current option, costs of the following components are considered:

- (i) The establishment of two groundwater treatment plants (one at Raudhatain and one at Umm Al-Aish) to treat groundwater from Umm Al-Aish and Raudhatain freshwater aquifers over the next 30 years, including operation and maintenance costs.
- (ii) Treatment process includes
 - a. pre-treatment of the groundwater for parameters such as calcium, iron, manganese, magnesium, nickel, and vanadium that may be toxic and foul air strippers and activated carbon surfaces,
 - b. air stripping of volatile hydrocarbon contaminants, and
 - c. treatment via activated carbon to remove longer chain hydrocarbons.
- (iii) The treatment plants were sized to be able to treat water in the 15th year at a rate up to 41,000 m³/day from Raudhatain for 1 year as an emergency supply and at least 4300 m³/day from Umm Al-Aish for 1 year as an emergency supply and up to 9000 m³/day for an unspecified peak period (Akber et al. 2009).

This option includes costs for salt treatment by reverse osmosis, assuming up to 50% of the total flow (i.e., 25,000 m³/day) is treated. Costs also allow for disposal of all residuals in a secure hazardous waste landfill. Additionally, over the limited timeframe of 30 years of pumping and treating groundwater from the Raudhatain and Umm Al-Aish aquifers, it is expected that this option will not restore a secure strategic groundwater for Kuwait.

Option 2: Alternate remediation of the aquifer formation

Clean-up of the contaminated aquifers using bioventing and other remediation techniques to restore conditions that existed prior to the Iraqi invasion, thus restoring these aquifers as a strategic freshwater resource, is recognized as a longer-term option requiring an additional short-term supply of water while clean-up is being effected (SMEC 2006). Any alternative that allows contamination to remain in place will fail to achieve protection and remediation of the groundwater resources. Moreover, removal of these materials is only proposed to extend to shallow depths and does not account for oil or salts that are already entrained in the soil profile and that have penetrated below the oil lakes and other impacted areas of the soil, or for ongoing leaching of dissolved hydrocarbons and salts through the soil profile towards groundwater.

Remediation of the aquifer to pre-invasion conditions would therefore require not only treatment of all contaminated groundwater but also treatment of all impacted zones beneath the thin surface soil removal zone, to depths of up to 30 m of the soil profile in Raudhatain and up to 20 m in Umm Al-Aish (Al-Weshah and Yihdego 2016).

Some available to remediate the contaminated soil profile includes

- (i) Natural attenuation via aeration to biodegrade hydrocarbons and leaching of salts via natural rainfall infiltration through the soil;
- (ii) Bioventing to aerate the soil horizon and stimulate bacterial breakdown of the hydrocarbons in the soil profile;
- (iii) Enhanced leaching over an extended period to wash salts (and possibly some dissolved hydrocarbons) from the soil profile,

whereas techniques that are available to remediate the contaminated groundwater include

- (i) Natural attenuation of hydrocarbons in groundwater due to biodegradation and dispersion processes, and discharge from the freshwater basin of salts due to ambient groundwater flows to the north and east;
- (ii) Air sparging to aerate the groundwater to strip any residual volatile hydrocarbons, but principally to enhance bacterial breakdown of the longer chain hydrocarbons;

- (iii) Reactive barrier walls downgradient of the plumes to treat mobile contamination as the plumes migrate eastward, and create a reactive zone to halt further expansion of the area of groundwater pollution;
- (iv) Hydraulic containment (e.g., slurry or bentonite) walls from ground surface to the depth of the low permeable strata below the water table (Yihdego 2016), surrounding areas like the oil lakes and other oil/salt-impacted areas to inhibit movement of polluted groundwater outside the affected areas;
- (v) Recirculating wells to allow in-well treatment of hydrocarbons, and aeration of groundwater for recirculation to enhance hydrocarbon biodegradation within the aquifer;
- (vi) Pumping of groundwater and treatment of produced groundwater for hydrocarbons and salts (this is already considered under option 1 above).

A combination of these techniques would need to be employed to remediate the soil and groundwater, and a combination would be needed to address salt and hydrocarbon pollutants. Natural attenuation processes will lead to some dilution, biodegradation, and leaching of hydrocarbons and salts from the soil and groundwater. This process is likely to take many decades, as evidenced by the remaining ponded oil in oil lakes and salinity in groundwater more than 20 years after liberation.

In summary, clean-up of the contaminated aquifers using bioventing and other remediation techniques to restore conditions that existed prior to the Iraqi invasion, thus reestablishing these aquifers as a strategic freshwater resource, is recognized as a longer-term option requiring an additional short-term supply of water while clean-up is being effected (Al-Weshah and Yihdego 2016).

Option 3: Establishment of additional desalination plant

Establishment of additional desalination capacity using seawater or brackish groundwater as water sources to simply meet the freshwater supply objective while failing to achieve any restoration of the strategic reserve capacity. This option would provide an alternate water supply by establishing a new desalination plant for seawater, and by blending the desalinated water with water drawn from the brackish aquifers in southern and western Kuwait. It would not restore a strategic freshwater reserve to the State of Kuwait (Fadlilmawla et al. 2008).

For this option, it is assumed that the desalination plant will be commissioned to run at full capacity (50,000 m³/day) for 2 years. Then be placed on standby for emergency.

Reverse osmosis (RO) treatment technology is proposed. Location of the RO plant shall be located to ensure connections to Kuwait City's water main network and power supply. The standby mode assumes minimal production to protect the membranes of the RO plant. This option establishes an alternative above ground infrastructure, rather than a more secure

Table 1 Summary of strategic options comparison

Option	Estimated cost (capital + O&M)	"Construction period" (average)	Technology used
1. Pump and treat	US\$ 365M	5 years	Cost of treatment plant includes capital + O&M for pre-treatment for metals; hydrocarbon removal; salt removal artificial recharge and plant required up to 30-year cost basis assumed.
2. Clean aquifer formation	High to very high US\$ 500M > US\$ 1000M	20 years	Remediation would take time, and in the meantime an alternative water supply from new desalination plant is included.
3. Desalination plant	Moderate US\$ 234M	2 years	No artificial recharge needed.
4. Storage tanks	Very high US\$ 1230M	3 years	Includes supply of water from new desalination plant.
5. Artificial recharge	High US\$ 300M	6 years initially but consider as pilot project to develop a long-term strategic groundwater resource	Source of supply will be excess potable water from desalination plants or from new plant. Plant to provide potable water for artificial recharge.

subsurface supply. The desalination plant established for this emergency supply would have the same vulnerability as Kuwait's other desalination plants.

Option 4: Establishment of storage tanks as a water reserve

Provision of alternative water storage facilities for a reserve using a water supply of (i) surplus desalinated water in winter or (ii) water from a newly constructed and dedicated desalination plant.

The option seeks to establish water storage tanks around Kuwait City, capable of supplying 50,000 m³/day for the 15th year of a 30-year period (Akber et al. 2009).

This option considers 180 tanks each with a water capacity of 100 ML distributed across the Kuwait City metropolitan area, and plumbed into the City water distribution system.

Table 2 Summary of evaluation criteria and weight

Criteria	Weight	Option 1	Option 2	Option 3	Option 4	Option 5
Cost (M US\$)	20	365	1000	234	1230	300
Construction period (years)	10	5	20	2	3	6
Sustainability	10	Very good	Acceptable	Excellent	Good	Very good
Risk/security	10	High	Moderate	High	Moderate	Low
Environmental impact	10	Moderate	Low	Moderate	High	Low

Allowance is made for mixing and disinfection to maintain water quality over non-emergency years, and for maintenance of the structural integrity of the reservoirs. The option assumes an initial supply of water from a new desalination plant to initially fill the tanks with potable water.

Option 5: Establishment of artificial aquifer recharge

Artificial groundwater recharge is a common practice in arid and semi-arid zones (Abboushi et al. 2015). This option seeks to establish an artificial aquifer recharge system as an alternate freshwater aquifer that would be capable of supplying emergency water to Kuwait City at a rate of 50,000 m³/day for one year (Fadellmawla et al. 2008).

Prior to invasion, Kuwait had planned to recharge the Raudhatain aquifer with up to 45,500 m³/day for 10 years so that the aquifer would be sustained as a productive field and configured as an emergency supply capable of withdrawal of up to 34,000 m³/day (Senay 1989). Continued artificial recharge of about 50,000 m³/day would allow a long-term sustainable withdrawal from the aquifer of up to 23,000 m³/day but possibly higher rates could be sustainable since recharge is into a freshwater aquifer giving greater efficiency of recovery of recharged freshwater compared to saline aquifers (Mukhopadhyay 1992). This option, however, restricts consideration to the establishment of a supply in a new location capable of sustaining the extraction of a volume of 50,000 m³/day for one emergency year, in accordance with the claims, even though a long-term sustainable yield of at least 23,000 m³/day has been lost.

Few alternate sites exist in Kuwait that are suitable for artificial recharge and “creation” of a freshwater field. This is because all the aquifers in Kuwait are brackish to saline, apart from those at Raudhatain and Umm Al-Aish, and

injection of freshwater into a saline aquifer gives a lower recovery during re-extraction (Senay 1989).

Post-liberation, artificial recharge studies were carried out by Mukhopadhyay (1992) in the Sulaihiyah and Shigaya fields well field areas in the shallow Kuwait Group and in the Dammam aquifers. The study focused on injection and recovery efficiencies through wells and concluded that injection of water to the two aquifers was technically feasible, but with a recovery efficiency of approximately 20% for the Dammam. Costs for establishment of a 45,500 m³/day production resource (with injection/recharge of 230,000 m³/day were estimated at 150 million USD for the recommended design including the cost of water (Mukhopadhyay 1992).

This is a long-term option requiring an extended period of aquifer recharge over 10 years prior to extraction. Over those years, Kuwait would still lack a strategic emergency reserve. For this option, an alternate fast-track strategic reserve may be needed. If this is provided by construction of an additional desalination plant, the costs outlined in option 3 need to be substituted for the costs of water included above (SMEC 2006).

Feasibility and cost analysis of new options

The feasibility and cost of various options are based on set of assumption that each option need to provide an emergency supply for 1 year at full capacity (365 days @ 50,000 m³/day = 18 Mm³ per year). The elements that are considered in the feasibility are:

- Financial and economic viability: cost of making the project
- Construction period

Table 3 MCDA matrix of option's scores

Criteria	Weight	Option 1	Option 2	Option 3	Option 4	Option 5
Cost (M US\$)	20	13	5	20	4	16
Construction	10	4	1	10	7	3
Sustainability	10	8	5	10	7	8
Risk/security	10	3	6	3	6	9
Environmental	10	7	9	7	3	9
Sum	60	35	26	50	27	45

- c. Sustainability: ability to continue getting water up to the total renewable capacities of the aquifers.
- d. Risk and social viability including public acceptance
- e. Environmental impacts on the physical and natural environment.

Comparison of options

Based on the feasibility of the discussed options, Table 1 shows the comparison of these options based on their present value cost of each option.

Development of multiple criteria decision matrix

A decision matrix to select the most suitable remediation options using multiple criteria decision analysis (MCDA) approach is developed (Abudeif et al. 2017; Benedetti et al. 2010; Mendoza and Martins 2006). The five options are evaluated against the comparison criteria.

Table 2 shows the summary of the evaluation criteria for each option with proposed weight for each criterion. These weights are taken based on the researcher judgment. A matrix of scores for each option using MCDA is developed based on the weights given in Table 2.

A matrix of scores for each option using MCDA is developed based on the weights given in Table 2. The high score present the most feasible option. The results of MCDA are presented in Table 3.

Discussion of results

Based on these MCDA scores, it was found that option 3, establishing an additional water desalination plant, is the most feasible option followed by option 5, artificial recharge of aquifers. Other options are less feasible especially options 2 (treatment of aquifers formation) and 4 (constructing additional storage tanks).

The above analysis and results were presented and discussed with the respective stakeholders in Kuwait. They are technically and economically the most feasible and sound options. The study recognized that the MCDA approach is very sensitive to subjectivity by given a certain relative weight for each criterion or options. However, the presented approach is flexible as it gives the decision makers a tool to revisit this analysis and change the relative weight for each criterion if new conditions would developed in future. It has been found that establishing an additional water desalination plant is the most feasible option. The design of this plant is beyond the scope of this paper.

The research findings will help the State of Kuwait to better decide on the best remediation options for their groundwater

aquifers given the fact that they recently received compensation funds of about 40 million USD for this purpose from Iraq through the UN system.

Conclusions

Prior to Iraqi invasion to Kuwait in 1990, the Raudhatain and Umm Al-Aish aquifers were the only fresh water aquifers in Kuwait. There were supplying 50,000 m³/day in an emergency situation.

Five remediation options are investigated in this study against five evaluation criteria. A decision matrix to select suitable remediation options using multiple criteria decision analysis (MCDA) approach is developed. The cost was given a relative weight of 20 whereas other criteria are given weight of 10. The study found that establishing an additional water desalination plant is the most feasible option followed by option 5, artificial recharge of aquifers. Other options are less feasible.

The research findings will help the State of Kuwait to better decide on the best remediation options for their groundwater aquifers given that they received compensation funds from Iraq through the UN system.

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