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Managing disposal of water produced with petroleum in Kuwait

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Abstract

Disposal of water produced with petroleum has been of great interest in Kuwait for the last 20 years. The current problem arose when the Burgan oil field, which is the second largest field in the world, experienced successive increases in the water content of the produced oil. This study introduces a decision-making analysis of the considered alternatives for the disposal of the produced water. Four alternative solutions exist for the industry as practical solutions for the disposal of water produced in Kuwait. The first method utilizes a large number of pits to discharge water. The second alternative depends on discharging water into sealed pits. The third approach to dispose water is by injecting the water underground. The last method is similar to the previous one, but takes into consideration the recovery of reservoir pressure to maintain the rate of oil production. A questionnaire was distributed to 48 experts at the top management level of the petroleum companies and the governmental authority. The data collected considered cost, efficiency, and environmental parameters. Based on the data, a statistical analysis was conducted using the factor analysis method to reduce the number of investigated variables. The analysis concluded that the optimal solution is to use the effluent injection method to discharge water produced with oil in Burgan and similar fields in Kuwait.

Keywords: Produced water; Waste management; Petroleum production; Water injection

1. Introduction

The Burgan oil field is the largest of its kind in Kuwait and the second largest field in the world. Oil production started in 1948 from seven reservoirs at Burgan. For nearly 40 years, only a small amount of water accompanied oil production from Burgan. Initially, the oil was collected in tanks for a specific period of time depending on the type of oil. This phase allowed sedimentation of the solid waste found in the oil. In the second phase, the oil was passed through a series of pipes to reduce the salt content. The third phase helped to eliminate the remaining salt by two different processes: an electrostatic process and a physical process. At this stage, the oil would be compatible with exportation standards. Finally, the water produced was collected in seepage pits exposed to sunlight (Chaula, 1987; Al-Kandari and Rochford, 1997; Al-Yaqout et al., 2002). This process led to an efficient control of the quality of the oil and water produced. On the other hand, the environmental efficiency of this method was considerably low due to the solid waste remaining on the surface of the treatment areas. There was also a danger that the salinated water may penetrate the stratified soil, changing the chemical composition of the underground water. This chemical change could spoil the dulcet water, which is very precious in the desert areas of the Middle East (Koushki et al., 2000).

This study introduces a decision-making analysis of the alternatives under consideration for the disposal methods of the produced water. Four alternative solutions were proposed as practical solutions for the disposal of water produced in Kuwait.

2. Disposal experiences

Disposal of the produced water had, for 40 years, never been a problem for the petroleum industry in Kuwait. The large available desert areas surrounding the oil fields helped to ease the disposal process. In 1988, it was first noticed that the produced water was increasing incrementally. It increased to about 250,000 barrels per day (bpd), making

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it impossible to rely on the sunlight to complete the process of evaporation at the required rate (Al-Kandary and Rochford, 1997; Al-Yaqout et al., 2002; Koushki et al., 2000). Since that time, the national oil company began to move towards an appropriate solution that took into consideration the required discharge, the environmental standards, and the feasibility of the proposed method.

In 2000, the Kuwait Institute for Science and Research conducted research on the problem of the disposal of the produced water (Koushki et al., 2000; Salman et al., 2003). The proposed solution focused on the environmental impact and the cost of the process. The conclusion was to exchange the seepage pits by sealed pits to avoid the effect of soil permeability, which allowed the salinated water to flow through the different layers of the soil and reach the dulcet water (Brown et al., 1998). However, this method did not introduce a comprehensive solution to the impact of the remaining waste on the surface of the ground and the surfaces of the pits. In addition, the cost of this process was higher than the cost of traditional pits because of the added lining material, labor, and machinery.

The other proposed solution was to inject the produced water under the ground surface at specific locations. This method did not require large exposed areas of pits. It could also be controlled to minimize the effect on the stratified soil components. This method would also have less impact on the environmental balance of the atmosphere. On the other hand, the cost of the injection process is higher than the very low costs of excavating shallow pits, as carried out in the past.

In North America, more than 20 years ago, attention was given to the method of produced water disposal (Baker et al., 1999; Seureau et al., 1994; Srinivasan et al., 1997). A successive excavation method was used to separate water from the produced oil. It was noticed that these pits collected a large amount of waste. This waste included parts of the equipment used in the excavation, materials used in the excavation process, and other calcareous remainders as well as crude oil. In California, the waste collected from the oil production process, including produced water and other waste was injected into wells using the slurry fraction injection (SFI) method. This type of slurry was preferred due to its availability in North America, its minimal effect on the environment, and its low total cost.

In the water re-injection process, a complete water analysis of both the injection source water and connate water enables scaling, clay-swelling, and brine incompatibilities to be evaluated. Bacteria, suspended solids, oil, and dissolved oxygen and hydrogen sulphide levels should be established. Special attention should be given to the detection of any combinations of ions that may precipitate on being mixed (Reynolds, 2003). Unacceptable levels of these parameters must be addressed in the facility design and chemical treatment programs. In many major water floods, waters are isolated in the surface system and are injected separately into the reservoir (Bruno et al., 2000).

The Statfjord field, in Northern Europe, is one of the largest oil production locations in Europe. There are three platforms producing on average 125,000 m^3/day of oil mixed with salty water. The field includes a combined system to inject about 30,000 m^3 of water per day to recover the pressure at Brent field next to Statfjord field. The oil/water separation system passes through four stages based on a pressure separation method. The produced water is then collected in containers (Georgie et al., 1992, 2001).

3. Offered alternative disposal methods

Four alternatives for the disposal of the water produced during petroleum production process were investigated:

3.1. Seepage pits

For more than 40 years, seepage pits were the traditional procedure for disposing of the produced water in Kuwait. The method depends on the collection of water in small pits approximately $2.00\ m \times 2.00\ m \times 2.00\ m$. This follows the separation of water from oil through a process system consisting of multiple pipes that depends on the difference in density for liquid separation, as well as to allow for the sedimentation of salts in the mixture. The produced water is left in the pits exposed to the heat of the sun to be evaporated. This system was efficient for the small water content in the petroleum up to about 15 years ago (Al-Kandari and Rochford, 1997).

3.2. Sealed pits

This method can be considered as a modified version of the previous one. The added lining on the bottom and the sides of the pits solved the environmental problem to a considerable extent. The lining material should be impervious, so as to prevent leakage through the layers of the soil and damage to the underground water constituents. On the other hand, the lining process increases the cost per barrel of the disposal of the produced water. This increase in the cost of water disposal could be compensated through other processes of using underground water and maintaining environmental standards.

3.3. Underground effluent injection

The injection method does not require such large areas as the previous two methods do. The cost of excavation is also saved with this system. The environmental impact of this method is less than that due to the open pit system. The impact on the domestic facilities, green areas, and all surface issues is minimal. In addition, if the choice of the injected locations is well selected, the impact of the injected water on the underground conditions of water and soil can also be minimized. The only downside of this process might be in the direct cost of the disposal process. The equipment, operation, and maintenance costs of this process are usually expected to be higher than the cost of excavating pits for disposing of water.

3.4. Underground injection to recover reservoir pressure

The continuous process of pumping oil results in a pressure reduction in the reservoir. This reduction in pressure leads to a reduction in the oil production rate and/or an increase in the cost of oil production. The injection needs to be in the same area of the oil field as the pumping to prevent the composed oil from spreading into large areas, which may cause a reduction in the pressure. The required location may face local geological difficulties, or an increase in cost due to the distance that the water needs to be transferred. This method is an improved approach from the previous one.

4. Objectives of the study

The target of this study was to obtain the most appropriate method to dispose of produced water in Kuwait. The proposals for the disposal process included four alternatives according to the experience, research, field environment, geological nature, environmental standards, and cost of each alternative. The study was based on the opinions of practitioners in the petroleum industry in Kuwait. Forty-eight experts from the top management levels of oil firms participated in the study. The participants responded to the questionnaire that considered the problem, the alternative solutions, and the parameter measurements for each alternative.

5. Methodology

The questionnaire was planned to cover the requirement of water disposal at the largest oil field in Kuwait; the Burgan field; and fields with similar conditions. The issues considered in the questionnaire were discussed initially with experts in the national oil company. Hence, the main groups and the detailed questions were developed and discussed with academicians and professionals in the petroleum industry. The final form of the questionnaire comprised three groups of questions that addressed cost, pollution, and efficiency of the studied alternatives.

It was targeted to collect the responses of fifty participants. The sample was chosen to represent the top management levels in the petroleum industry in Kuwait. Participants who had 15 years of experience in the field of petroleum were chosen. The experts selected are currently serving in executive management positions with a technical or managerial background. This level of experts represented the decision support and decision-making personnel. This level of participants could assist in providing opinions in multiple disciplines as was needed for the study. Based on similar experiences in questionnaire response, eighty professionals were requested to participate in the study. Eventually, 48 experts actually participated in the study. A participation of sixty percent is considered fairly high compared with the common response rate for questionnaires in similar fields.

The questionnaire considered the following parameters:

5.1. Cost

The cost of each proposed method was considered, including labor, machinery, and any required material to be used in the disposal process. The cost of each system of the proposed methods included the whole life-cycle cost for each system including initial cost, operational cost, maintenance cost, and abandonment cost. The cost of each phase of each system was estimated in accordance with actual costs from the previous experience of the participants (Veil and Smith, 1999). The evaluation of the cost was evaluated on a scale from one to five, where one denoted the 'least expensive' and five denoted the 'most expensive' technique.

5.2. Pollution

The environmental effect of the disposal process was considered according to the compatibility of each system within the limits specified in universal standards. The environmental effects included in the questionnaire were the pollution of ground surface, underground conditions, underground water, surface water, atmosphere, health and safety, green areas, and domestic areas. The questionnaire was prepared so that the participants were required to rank the effect of each method on each of the aforementioned issues on a scale from one to five, where one denoted 'least affected' and five denoted 'extremely affected'.

5.3. Efficiency

The efficiency of each system was also considered in the questionnaire. The efficiency was measured against the general efficiency, operability, maintainability, accessibility, commonability, habitability, supportability, and life span of the system. The participants were required to rank the effect of each method on each of the mentioned issues on a scale from one to five, where one denoted the 'highest efficiency' and five denoted the 'lowest efficiency'.

6. Results of the questionnaire

As indicated before, all the items in the questionnaire were rated on a scale from one to five. The weighted average of the results of each item is hereafter referred to as the coefficient of this item. The following section presents the results of the collected and grouped data.

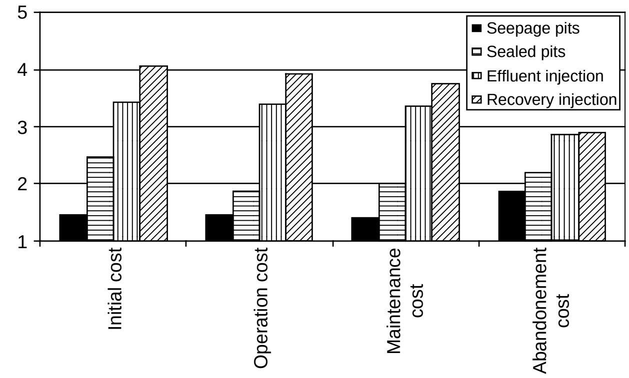

Fig. 1. Cost coefficients.

6.1. Cost

Fig. 1 presents a summary of the results obtained for the cost of each stage of the disposal process. The figure shows the increasing cost expectation starting from seepage pits, with the lowest expected cost, to recovery injection, with the highest expected total cost. It is clear from the figure that the estimated cost has the same trend for all the cost components as well as for the total cost.

(a) Initial cost: The seepage pit method is expected to have the least initial cost because the cost incurred is due to simple excavation operations, which are subject to minimum specifications and the least quality requirements. The sealed pit method has a higher initial cost than that of seepage pits due to the cost of the lining materials. Moreover, the excavation process in this technique requires a higher level of specification and quality control. For disposal of water produced by injection, there is the need to carry out well-established geological and physical studies in order to select an appropriate location to discharge the water. In addition, the feasibility of the selected locations should be optimized with respect to the total cost. Initial cost includes site preparation, importation of required machinery, as well as development of the necessary skilled labor. These costs justify the expected high initial cost of the injection methodology, especially if recovery is targeted.

(b) Operation cost: The operational cost for the sealed pits is low with respect to the initial cost, though still higher than that of seepage pits. Nevertheless, the expected operational cost for the two proposed injection methods is much higher, as shown by the results. The cost coefficients for the seepage pits and sealed pits are 1.45 and 1.87, while the same coefficients for effluent injection and recovery injection are 3.37 and 3.91, respectively.

(c) Maintenance cost: Injection procedures need continuous maintenance and control to comply with physical, mechanical, and geological conditions. On the other hand, open pits need just minor maintenance activities. The cost coefficients for the seepage pits and sealed pits are 1.41 and 2.00, while those for effluent injection and recovery injection are 3.35 and 3.75, respectively.

(d) Abandonment cost: The abandonment of pits is a very simple process while it is more complex to uninstall the injection system, which may extend to hundreds of meters above and below the ground surface along with many connections that need to be unfitted and recycled according to environmental standards. The major cost of the pit technique is in the disposal of the waste remaining at the bottom of the pits without affecting the environmental requirements.

6.2. Pollution

The impact of the proposed technique to discharge the produced water on different environmental aspects was also considered in this study. The results of the study with respect to environmental pollution are presented in Fig. 2.

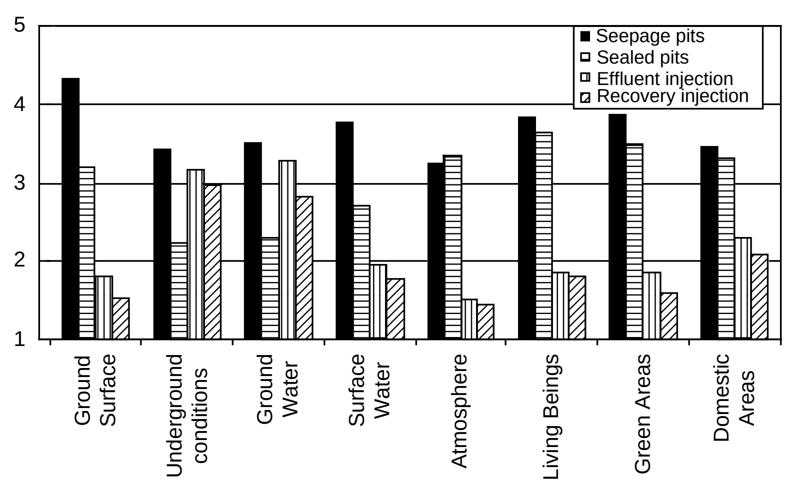

Fig. 2. Pollution coefficients.

(a) Ground surface: The expected pollution of the ground surface is affected greatly by surface disposal when using open pits to collect the produced water. On the other hand, the injection of the produced water eliminates the pollution of the ground surface. The results of the study showed average pollution coefficients of 1.52 for recovery injection versus 4.33 for the seepage pit method.
(b) Underground conditions: The participants' opinion on the pollution of underground conditions showed significant preference for the use of sealed pits. The other three techniques had similar expectations for their effect on subsurface conditions. The average coefficients range from 2.95 to 3.43 for the latter three techniques, while the expected pollution coefficient for the sealed pits is as low as 2.22.
(c) Underground water: The impact of the water discharge on the underground water is similar to the expectations for the effect on the underground conditions in general. The results of the study showed that the pollution coefficient of the sealed pit technique is 2.29 while the other three coefficients range from 2.81 to 3.52.
(d) Surface water: The expectations of the pollution of the surface water are similar to the expectation of the pollution of the ground surface but the range of the estimated pollution is smaller in this case. The pollution coefficient as obtained from the participants is 3.77 for the seepage pit technique but only 1.77 for the recovery injection technique.
(e) Atmosphere: Using the sealed pit technique has the highest impact on the pollution of the atmosphere as shown from the questionnaire. The technique of seepage pits showed a coefficient of 3.25 versus 3.33 for the sealed pits. On the other hand, the injection techniques have considerably lower coefficients of around 1.50. This obvious distinction between surface discharge and injection explains the current trend in the petroleum industry to use the latter technique to dispose the produced water.
(f) Living beings: The results of the study categorize the proposed techniques into two main groups with respect to the effect on living beings. The surface discharge group has high pollution coefficients of around 3.70 on a scale of five. The second group is the injection group, which has pollution coefficients around 1.80. These results were expected since the underground injection transfers the biological risks away from the living beings, which are primarily affected by the ground surface and by the atmospheric conditions.
(g) Green areas: The data collected concerning the impact of water discharge shows a similar trend to that noted for the previous two parameters. Green areas are greatly affected by the surface disposed waste in nearby areas. It should be noted that the injection process must consider conveying the waste to a depth that minimizes the effect on life at the ground surface.
(h) Domestic areas: The impact of disposing the produced water has a similar trend to the impact of the previous three parameters. The difference in the expected impact between surface discharge and injection is less in this situation. The domestic areas are affected by the underground water and underground condition in addition to their sensitivity to the surface conditions. This combination reduces the pollution coefficients of the surface discharge to about 3.40, while the pollution coefficients increase to about 2.20 for injection methods.

6.3. Efficiency

The efficiency of the proposed methods for disposing of the produced water shows the most complexity with respect to determining a clear distinction in cost and pollution assessments. The efficiency fluctuates up and down for each method according to each item as shown in Fig. 3. Note that the higher efficiency is assigned a lower efficiency coefficient.

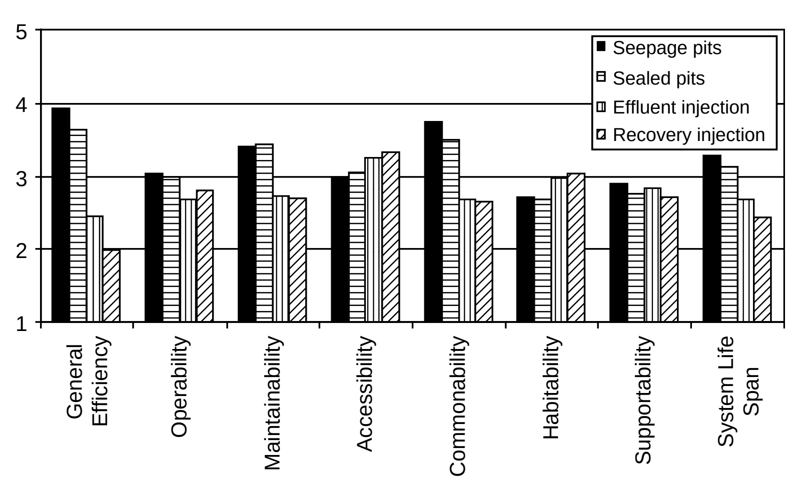

Fig. 3. Efficiency coefficients.

(a) General efficiency: This is the estimated rate at which the task is completed with respect to input power. The results show that the injection methods have higher efficiencies than the surface discharge methods. The efficiency coefficients for seepage pits and sealed pits are 3.93 and 3.64, while those for effluent injection and recovery injection are 2.45 and 1.98, respectively.
(b) Operability: This item measures the ability to operate the process of water disposal according to the required level of functionality and safety. The estimated operability for the four proposed methods are so close that it makes it difficult to assess whether there could be a preference for a specific method. All the efficiency coefficients range from 2.66 to 3.02, a small range from which to make a clear decision.
(c) Maintainability: The ability to maintain the discharge process according to the required functionality and target rate is termed the maintainability. The average efficiency coefficients for the seepage pits and sealed pits are 3.43 and 3.39 while those for effluent injection and recovery injection are 3.73 and 3.69, respectively. The injection processes show slightly better maintainability than that for surface processes.
(d) Accessibility: The ability to pursue the process promptly under all circumstances is the accessibility. The efficiency coefficients for all four methods are very close, with a range from 3.00 to 3.33. However, the preference in this case is also given to the injection processes over the surface processes.
(e) Commonability: This item measures the ability to keep the compatibility among the different items in the system in order to maintain the target level of efficiency, operability, maintainability, and accessibility. Since the commonability is a combination of different requirements, the preference for the injection methodology is again greater than the surface discharge methodology. The efficiency coefficients are 3.73 and 3.50 for seepage pits and sealed pits while they are 2.64 and 2.66 for the effluent injection and recovery injection methods, respectively.
(f) Habitability: Habitability is the ability of the staff and all system components to accommodate the process. The surface discharge methodology has the lead in this respect in Kuwait, since most of the disposal processes for water produced are done by surface discharge. The efficiency coefficients are around 2.70 for surface discharge systems and 3.00 for injection systems.
(g) Supportability: This item measures the capacity of the supporting technical system for each method. This item shows the narrowest range of all sections of the study. There is no actual differentiation among all of the four proposed methods for this parameter.
(h) System life span: This scale measures the life span of the proposed system in terms of operating hours. The recovery injection system has the highest efficiency coefficient of 2.43, while other coefficients for effluent injection, sealed pits, and seepage pits are 2.66, 3.12, and 3.29, respectively. The difference in life span supports the choice of the injection systems over the surface discharge systems.

7. Analysis

The analysis of the data was carried out using the commercial statistics package SPSS® (SPSS Inc., 2002). Factor analysis was used to identify the underlying variables, which explain the pattern of correlations within the set of the observed variables. Factor analysis is often used in data reduction to identify a small number of factors that explain most of the variance observed in a much larger number of manifest variables (Johnson and Wichern, 2002).

The principal component method was used for the extraction process of the obtained data. The principal components method of extraction begins by finding a linear combination of variables (a component) that accounts for as much variation in the original variables as possible. Then, it finds another component that accounts for as much of the remaining variation as possible and is uncorrelated with the previous component. It continues this way until there are as many components as original variables. The detailed mathematical processes can be found in statistics references such as that of Johnson and Wichern (2001).

Table 1 presents the sum of the averages of the coefficients as obtained from the questionnaire (Fig. 1–3). The correlation between the expected cost and the expected pollution can be noticed in the relationship plotted in Fig. 4. The vertical axis of the figure represents the sum of the four averages of the cost components as per the collected data from the questionnaire responses. The horizontal axis represents the sum of the averages of the eight items

Table 1
Sum of the averages of the coefficients

	Cost	Pollution	Efficiency
Seepage pits	6.2083	29.4790	25.9791
Sealed pits	8.5416	24.1667	25.1667
Effluent injection	13.0001	17.6668	22.2501
Recovery injection	14.6250	15.9582	21.6249

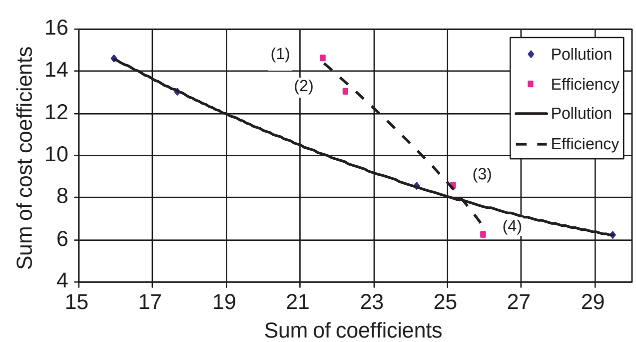

Fig. 4. Correlation between cost against pollution and efficiency.

Table 2
Total component variance

Component	Parameter	Variance	Variance %
1	Environment	1.536	51.201
2	Cost	0.861	28.709
3	Efficiency	0.603	20.091

investigated for pollution and efficiency coefficients. Each of the proposed four methods to dispose of produced water is represented in the figure by two points. One point is for the pollution and the corresponding cost and the second point is for the efficiency of that method and its corresponding cost. The diagram shows the large range for pollution versus the range for efficiency of the proposed methods. In Fig. 4, the highest expected cost is for the recovery injection method, point (1), with the sum of average cost coefficients of 14.62. The same sum for the effluent injection method, point (2), is 13.00; it ranks second. The cost coefficients for the surface discharge methods sum to 8.54 and 6.20 for sealed pits, point (3), and seepage pits, point (4), respectively. The relationships in Fig. 4 emphasize the numerical results obtained from the component matrix.

The SPSS® package was used to manipulate the collected data using the factor analysis method. Table 2 presents the variances for the three extracted components. Table 3 presents the component matrix, illustrating the correlation between the components and the studied parameters: cost, pollution, and efficiency. The first component was found to be highly correlated with the environmental pollution. Pollution is a better representative of this component. The second component is most highly correlated with the efficiency of disposing of produced water. The third component is most highly correlated with the cost of the disposal process.

Fig. 5 presents the score coefficients for each of the disposal techniques as concluded from the analysis of the collected data. The effluent injection method has the best expected score as noticed in the histogram of Fig. 5. The recovery injection method is the second best. The sealed pits and seepage pits methods came at the third and fourth place, respectively. This rank order differs from the expectations in many countries other than Kuwait. Experiences in the petroleum industry in western countries recommend using the recovery injection method, as discussed earlier in this paper. In Kuwait and the Arabian Gulf area, the

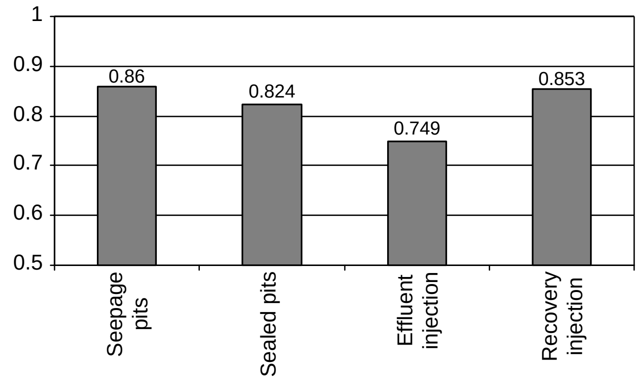

Fig. 5. Score coefficients for disposal techniques.

practitioners feel that there is no fear of recovery problems at the present time.

A general coefficient is introduced to provide a unique measurement for the results of the analysis. Eq. (1) is used to determine the general coefficient C, of each proposed technique. The general coefficient is a simple weighting function that considers three variables. These variables are the score coefficient as given in Fig. 5, the percentage variance as given in Table 2, and the sum of the averages of the coefficients for each category and each alternative, as given in Table 1. The equation can be written as:

$$C = s \times \left(\sum_{i=1}^{3} V_i \times \mu_i \right) \tag{1}$$

where,

- C general coefficient that describes the risk of the technique
- S score coefficient for each technique (Fig. 5)
- V_i percentage variance for each technique as per the component matrix (Table 2) and
- μ_i mean value for each technique as calculated directly from the sums of the coefficients obtained from the questionnaire results (Table 1).

The results of the implementation of Eq. (1) are summarized in Table 4. The results are governed primarily by the impact of the score coefficient for the alternative techniques. The traditional seepage pits have the highest general coefficient. This result points to the rising general sense of practitioners that cost alone is no longer the governing parameter. The impact of pollution and procedure

Table 3
Component matrix

	Component		
	1	2	3
Pollution	0.805	−0.104	−0.584
Cost	0.720	−0.524	0.455
Efficiency	0.608	0.759	0.234

Table 4
General coefficients of disposal techniques

	Technique general coefficient
Seepage pits	19.0033
Sealed pits	16.3838
Effluent injection	12.9193
Recovery injection	14.2575

efficiency has their important contribution in the decision-making process. The proposal for effluent pits is considered a better solution from the point of view of pollution and efficiency. Both injection methods have better environmental and efficiency expectations but the effluent injection is preferred from the participants' perspective. Although the recovery injection method is expected to be better than effluent injection with respect to pollution and efficiency, the effluent injection is recommended in Kuwait because of its lower cost, in addition to the observed effective pressure in the reservoirs, for the time being. It is worth mentioning that effluent injection is currently being used in many of the wells in the Burgan field and other smaller fields in Kuwait.

8. Summary and conclusions

The traditional method of discharging water produced during petroleum production in Kuwait is no longer sufficient. The national company for petroleum is seeking the best alternative for the existing conditions. Four alternatives were investigated for making the proper decision; traditional seepage pits, sealed pits, effluent injection, and recovery injection.

A field study was carried out through discussions with 48 senior practitioners who had extensive experience within the petroleum industry in Kuwait. The analysis was based on a questionnaire that comprised 20 items concerning the cost, environmental pollution, and efficiency for each of the proposed alternatives. The following conclusions can be deduced from the analysis of the data collected:

- The traditional method of seepage pits is the cheapest method to discharge the produced water. On the other hand, it is the worst method from environmental and efficiency perspectives.
- Using sealed pits enhances the environmental efficiency and the efficiency of the discharge process but increases the overall cost of the system.
- Injection of the produced water at deep levels has better environmental and efficiency expectations than those for surface discharge methods provided that contamination of ground water is avoided.
- Injection of the produced water with consideration of the reservoir recovery is the most expensive method but it is the most compatible method with the environmental requirements. It is also the most efficient method among the proposed alternatives.
- The participants preferred the effluent injection method rather than the recovery injection method because of the lower cost and the current sufficient reservoir pressure in Kuwaiti fields. This is different from the situation in most of the fields in other countries such as in the North Sea and the United States.
- The current conclusions need to be re-evaluated periodically based on the changes in the conditions of the reservoirs in Kuwait, on the proposed solutions, and on other suggestions from international consulting experts.

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