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The Third Gulf

Water

Conference

Muscat, Sultanate of Oman
29 Shawwal - 4 Dhol Qada 1417
8-13 March, 1997

Towards Efficient Utilization of Water Resources in the Gulf

Water Use in Agriculture and Irrigation Eficiency

Wastewater Treatment and Reuse

Environmental Protection and Public Awareness and Participation

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Towards Efficient Utilization of Water Resources in the Gulf

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Conference Proceedings

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Sultanate of Oman, 8-13 March, 1997

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Preface

Within the past decade, a considerable research and experiences have been developed and published on water resources assessment and development, water supply augmentation and maximization, and water facilities management in the Arabian Gulf countries. However, very little research was directed towards demand management, conservation, and efficient utilization of water in the different water consuming sectors. Thus the theme of the conference "Towards Efficient Utilization of Water Resources in the Gulf" was chosen to emphasize the role of conservation and demand management as an important and integral part in water resources management in the Arabian Gulf Countries.

As at the previous WSTA conferences (the first was held in Dubai, 1992, and the second was held in Bahrain, 1994), the overall goals of the conference are to encourage scientific studies and research in the different fields of water resources, to create a forum of open discussion, and to exchange experiences among the Arabian Gulf States that the WSTA engendered throughout the two previous conferences.

The objectives of the convening conference are: 1) Assessment of natural water resources and alternative sources in the GCC Countries; 2) Review methods of conservation and efficient utilization of water in different sectors, with emphasize on the agricultural and municipal sectors; 3) Review and exchange of local experiences in the field of water resources and sources planning and management; and 4) Review the latest research and advances in the assessment, development, and management of water resources.

The Third Gulf Water Conference is held under the patronage of His Highness Sayyid Haitham Bin Tariq Al Said, and is organized by the Water Science and Technology Association (WSTA) in cooperation with Sultan Qaboos University and the Secretariat General of the Cooperation Council (GCC) for the Arab States of the Gulf. The Conference is sponsored by the Ministry of Electricity and Water, Ministry of Agriculture and Fisheries, Ministry of Water Resources, Ministry of Regional Municipalities and Environment, Ministry of Commerce and Industry, and Muscat Municipality from the Sultanate of Oman, and the Arabian Gulf University (Bahrain), Ministry of Electricity and Water (State of Bahrain), Bahrain Center for Studies and Research, UNESCO Cairo Office (ROSTAS), UN-ESCWA (Jordan), International Desalination Association (IDA), and European Desalination Society.

This conference proceedings contains 84 papers assembled into 4 volumes, one volume in Arabic and the other three in English. The Arabic Volume contains Fourteen papers with most of them having English Summaries, in addition to the organizers speeches. The conference papers were selected by the Conference Scientific Committee from over 110 abstracts received from the call of papers. Many of these were modified to meet the standards of the Scientific Committee review. Conference sessions will be held on topics: Water Resources Planning and Management, Groundwater Resources, Water Desalination, Wastewater Treatment and Reuse, Surface Water and Artificial Recharge Experiences, Water Use in Agriculture and Irrigation Efficiency, Municipal Water Supply Systems, Environmental Protection and Public Awareness and Participation, and Domestic Water Quality.

Six papers are invited by the conference organizers. These are from the Secretariat General of the Cooperation Council (GCC) for the Arab States of the Gulf, Ministry of Water Resources, Ministry of Agriculture & Fisheries, Ministry of Electricity & Water, Ministry of Regional Municipalities & Environment, and Muscat Municipality from the Sultanate of Oman. In addition, Eight renowned international and GCC scientists were invited to give scientific presentations in respective technical sessions, and were supported by the WSTA, UNESCO (Cairo Office), and UNESCWA (Jordan).

The Scientific Committee wishes to express its deep appreciation to the Governments of the GCC Countries and the GCC Secretariat General and the sponsoring regional centers and organizations who kindly supported and endorsed this conference.

Organization of these conferences requires considerable time and effort. As in the previous WSTA conferences, individuals from various sectors (industry, Government and academia) have come forth and given generously their time. Special thanks are due to the members of the Organizing Committee, Scientific Committee, and Scientific Papers Coordinators and Reviewers.

Finally, we wish to acknowledge the immeasurable contributions made by the authors and their research associates who were not only willing to rework and modify their abstracts and manuscripts but also had to meet an extremely tight time schedule. Without their efforts this document would not have been possible. We sincerely hope that this conference will be both enjoyable and rewarding for you.

Dr. Waleed K. Al-Zubari
Head, Conference Scientific Committee
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Arabian Gulf University, Bahrain

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Lokman Zaibet and Abdulla Omezzine

A COMPARISON OF ECONOMIC AND ENGINEERING EFFICIENCIES IN MODERN IRRIGATION IN OMAN

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ABSTRACT

Irrigation efficiency as a standard engineering measure has been traditionally used to assess water use efficiency. Technical efficiency as applied in the microeconomics of production provides an alternative measure of irrigation performance. Both concepts are used in this study to investigate water efficiency levels for irrigated crops in the Batinah region of Oman under modern irrigation methods. Results show that on the average, technical efficiency is higher than irrigation efficiency. Larger size farms have high technical efficiency but low irrigation efficiency whereas smaller farms have lower technical efficiency and higher level of irrigation efficiency. These results raise the issue of improving farms irrigation efficiency. Efforts should concentrate on controlling water applications in terms of number and period of irrigations.

Keywords: Irrigation efficiency, technical efficiency, water, Oman

INTRODUCTION

The objective of increasing the productivity and the efficiency of agricultural resources in Oman is regarded as highly important for the development of the agricultural sector (JICA, 1990). Agricultural production is particularly dependent on water resources since most crops grown are irrigated and consume more than 94% of the national water available (MacDonald & Hawksley, 1991). Yet, Oman is characterized by an arid climate and limited water resources which precludes the potential for substantial horizontal expansion of cropped areas. Efforts, therefore, are being directed to vertical expansion, i.e., increase in water productivity and water use efficiency (MAF, 1995a).

Government efforts to rationalize the use of water resources as a component of national food self-sufficiency strategies have been substantial. Extensive programs have been implemented to introduce subsidized new irrigation systems in order to improve the management of water in agriculture. However, despite these substantial efforts it is recognized that water saving targets have not been fully achieved (MAF, 1995b). Recent assessment of water use in Oman reveals that the new irrigation techniques have not been able to achieve irrigation efficiency goals (Hundertmark and Al-Mamari, 1995). Hypothetically advanced irrigation techniques have the capacity of reaching an irrigation efficiency level of more than 90% (Bucks, 1993). This level, however, may remain sub-optimal if irrigation is poorly managed. Generally, the range of techniques for conserving scarce water resources would not be sufficient enough without a sound program to enhance farmers' managerial ability in water use.

In recent years, policy-makers and managers in developing and developed countries have emphasized the need for performance assessment and have sought to improve data collection that can provide feedback to management (Lenton, 1995). The efficiency of water use has been, traditionally, looked at from a technical or engineering point of view. Irrigation specialists have been interested in ways to improve irrigation scheduling and water saving techniques. Factors affecting irrigation efficiency include irrigation technology, environmental conditions and soil characteristics.

This paper develops a conceptual framework and provides empirical results on the efficiency of advanced irrigation techniques in Oman. It provides useful indices of irrigation performance based on efficiency field measures. It discusses the relevance of different concepts such as engineering-irrigation efficiency and technical efficiency. The information generated will be useful to farmers, extension services and to decision-makers for management strategies aiming at better use of water resources and higher agricultural returns.

MAJOR IRRIGATION WATER ISSUES IN OMAN

Water has been considered as the most important determinant of agricultural production in Oman. Nearly all crops grown are irrigated. The National Water Resources Master Plan estimated agricultural water demand at 1,170 million cubic meters (MCM)/year, representing about 94% of the total 1,250 MCM water demand/year. This important water demand has been beyond the limited available renewable water resources which are approximately estimated at 1,000 MCM/year (MacDonald and Hawksley, 1991). As a result groundwater levels have declined in some inland and coastal aquifers, and saltwater intrusion have appeared in the Batinah area.

Water demand projections by the National Master Plan for year 2010 show that the agriculture water win remain at the 1990 level, but the domestic and industrial demands are expected to reach about 280 MCM/year. Therefore total water demand will be approximately 1,450 MCM/year. A total of about 167,000 wells and 3,045 active falaj are and will remain the major sources of water supply for irrigation.

Remarkable efforts have been made by the Government of Oman to prevent further deterioration of the groundwater resources in the future. Considerable water conservation measures have been implemented including the introduction of new techniques to improve irrigation efficiency, public awareness, and water use regulations. Moreover, several water augmentation alternatives, such as artificial recharge schemes, desalination, utilization of brackish water, urban waste water reuse, runoff harvesting and monsoon precipitation harvesting have been adopted (Chebaane and Alesh, 1995). Currently desalinated water amounts to 52 MCM/year with 48 MCM/year in the Capital area, and is expected to reach 140 MCM/year in 2010. Water augmentation through recharge dams is about 7 MCM/year, and planned to attain 45 MCM in 2010. The newly discovered fossil groundwater aquifers, are an additional non-sustainable source of water which can be mined for a limited period.

The goal of efficient use of water at the farm level has also been recognized. An extension program has been implemented in order to rationalize water use through new irrigation systems, with a subsidy scheme ranging from 30 to 75% of total costs depending on farm size. Remarkable improvements have been reached but water saving targets are not fully achieved (MAF, 1995b). The introduction of new irrigation systems has been very slow. Recent agricultural census indicates that up to 1993 around 2,031 farms have introduced new irrigation systems and about 500 more were planned for 1994 and 1995. Currently, less than 6% of the agricultural area is equipped with these improved irrigation systems as shown in Table 1. Flood irrigation remains the most common irrigation system with an efficiency level of 30 to 65% (JICA, 1990). In general, it is recognized that at the farm level irrigation efficiency remains rather low even where advanced irrigation techniques have been adopted (Dutton, 1985; MAF, 1993).

Table 1. Use of new irrigation systems (sprinkler, drip, bubbler), 1993.

Crops	Areas equipped with new irrigation system (ha)	% of total area equipped with new irrigation system
Fruits	1,025	2.40
Vegetables	746	13.10
Animal Feed	1,818	11.00
Other Crops	122	2.30
Greenhouses	26.5	64.30
Total	3,711	5.23

Source: Assembled from 1993 Agricultural Census Reference (MAF, 1995).

Irrigation technologies have been developed and promoted in order to increase water application efficiency at the farm. Nevertheless, the key element to water conservation and water use efficiency is the proper management of these technologies (Deboer, et al., 1995). Developing appropriate and accurate irrigation scheduling is one way to improve water management and to maximize water use efficiencies. Estimation of crop specific irrigation scheduling (i.e., time interval between irrigation) is so important to minimize critical crop stress and improve yields.

IRRIGATION PERFORMANCE: CONCEPTS AND MEASUREMENTS

Irrigation performance measures have been tackled from different viewpoints. Irrigation performance is being used instead of irrigation efficiency which goes beyond the narrow engineering definition. Policy makers and managers in developing and developed countries are interested in more broad performance assessment measures. The emphasis has been on ways to improve data collection in order to provide useful feedback on water management and to develop better indicators for assessing irrigation system performance and methodology to use such indicators, improving our understanding of the factors causing good or bad performance (Lenton, 1991).

Irrigation efficiency

Irrigation efficiency is a standard engineering term that has been widely used to assess water use performance. It is defined as the ratio of effective water, i.e., the amount of water actually utilized by plants, to applied water (Lynne, et al., 1987). The difference between applied and effective water depends upon irrigation technology, environmental conditions, and land characteristics. For surface irrigation methods, efficiency is about 0.6, whereas drip or sprinkler technologies may increase irrigation efficiency up to 0.95 (Hanemann, et al., 1987).

Irrigation efficiency is defined as "the ratio of the volume of irrigation water required for beneficial use in the specified irrigated area to the volume of water delivered to this area" (Burrman et al., 1983). A computational formula is adopted from Norman et al. (1996).

$$IE = \frac{I_d}{I_s} \qquad (1)$$

where I_d is the estimated crop water demand at the field level and Is is the irrigation supply both in m^3.

Efficiency measures fall usually between zero and one where measures close to one are the most efficient. Equation (1) would yield values less than one ($I_d < I_s$) in case of surface or gravity irrigation. In case of drip irrigation, however, the following definition could be used:

$$IE = \frac{W_s}{W_R} \qquad (2)$$

assuming farmers supplying quantities (W_s) less or equal to crop requirements (W_R). In general any below or above one would suggest water use inefficiency.

With modern irrigation technologies, water losses from seepage, leaching and leaking are considered very low. Irrigation supply could be determined by measuring water delivery to the different plots. Water need depends particularly on cultivation period, irrigation interval and water flow. Crop water requirements were determined from maximum evapotranspiration values (FAO/MAF, 1993) and used to obtain an irrigation demand value for each crop.

Since the demand and supply components were determined at the field conditions, the irrigation efficiency measure reflects primarily water management practices of individual farmers, rather than the system as a whole. Management practices include irrigation scheduling (amount and interval) as well as irrigation methods.

Technical efficiency

Recently, there has been a great deal of attention on the effects of water use on crop yields and growth (Vaux, et al., 1981). Production frontiers have been, traditionally, used to relate input use and output. Caswell and Zilberman (1985, 1986) used this approach and incorporated physical features of irrigation systems into the following irrigation choice model:

$$y = f(w) \tag{3}$$

where **y** denotes the yield of a particular crop, and **w** denotes the quantity of water applied and used by the crop.

Technical efficiency is an economic criteria based on the concept of production frontiers. Inefficiencies, in this case, arise when the actual yield from a given input-mix, including water, is less than the maximum attainable yield.

The concept of technical efficiency is based on the fact that the production frontier can be viewed as composed of those parts of the farm's production functions that yield maximum output for a given set of inputs (including water). It is however, observed that some farms may not be able to reach that maximum (frontier). Farm specific technical efficiency would be defined by how close the individual farm production plans are to the maximum levels. This, of course, provides an indication on how efficient farmers are in terms of water use.

Theoretically this concept could be shown through two production frontiers, PF_1 and PF_2, relating the level of water used and the output level (Figure 1). At any level of water use, farmers operating on PF_2would be more technically efficient than those operating on PF_1. Thus, using the same quantity of water, any farmer operating on PF_1 could gain more by improving water management efficiency (moving on PF_2). Technical efficiency may result from management practices as well as the way water is combined with other inputs (labor, fertilizers, etc). A farmer may also gain more by moving from point C on PF_2 to point B where the profit maximization conditions are met. This gain results from allocative efficiency.

Once the maximum attainable level of outputs from different combinations of inputs (frontier of production) is constructed, technical efficiency of any particular farmer would be evaluated by comparing the position of that farmer relative to the frontier. Methods used to estimate the frontier functions are divided into two categories: parametric and nonparametric frontiers.

Parametric frontiers assume a specific functional form that describes the production function and is generally estimated using econometric methods (Forsund et al., 1980). Non-parametric frontiers proposed by Farrel (1957) require linear programming techniques for estimation. Estimations based on non-parametric frontiers were criticized on the base of their sensitivity to outliers and measurement errors (Timmer, 1971).

Previous studies on the estimation of production functions for irrigated crops have used different approaches. Hexem and Heady (1978) used field-experiment data to estimate functions relating plant yield to water. Other authors used the agronomic approach and estimated von Liebig response functions to explain the behavior of yield as a function of evapotranspiration (Stewart et al., 1974) or applied water (Grimm et al., 1987). Although these response functions are agronomically sound, they do not allow to capture the substitution opportunities such as between irrigation water and irrigation technology or between irrigation water and land (Moore et al., 1991).

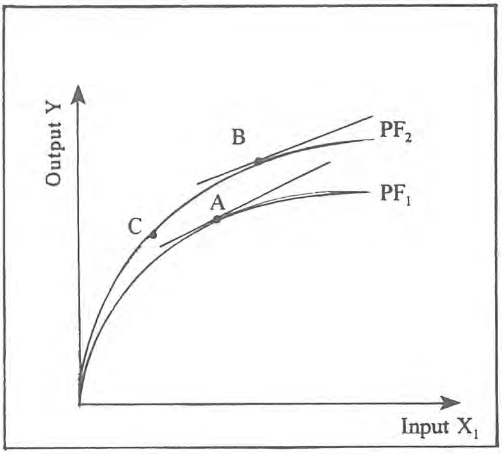

Figure. 1. Concept of technical efficiency.

The present study uses cross-section farm-level observations on crop-specific input and output quantities to estimate crop-specific production functions and derive corresponding farm-specific technical efficiency measures as an indication of water use performance.

DATA, SPECIFICATION, AND ESTIMATION PROCEDURE

The data used in this study were collected through a farm questionnaire prepared and conducted by the authors in the Batina region in Oman during summer

1996. Irrigation schedule (interval and period of irrigation) for each crop was obtained through interviews. Drip emitters on each farm however, are adjusted to deliver a flow rate of 4 liters per hour. This flow is assumed to be constant for all the farms in the sample. So, water supply was estimated based on this irrigation application design and farmers' irrigations schedule. Water use characteristics for selected crops are presented in Table 2.

Table 2. Water use characteristics.

	Irrigation method	Irrigation interval (days/month)		Irrigation period (hours/days)		Qty of water (m^3/feddan)		Crop Yield (tons/feddan)	
		mean	std	mean	std	mean	std	mean	std
Tomato	drips	24	8.26	1.66	0.65	2,224	753	6.96	2.69
Watermelon	drips	28.5	3.37	2.15	1.05	2,061	946	5.52	2.63
Alfalfa	surface	6.85	2.79	6.15	6.34	64,616	24,997		

Data, as described above, permit the estimation of per-feddan production functions. However, econometric estimation is done for tomato. The same methodology applies for other irrigated crops. The following Cobb-Douglas form is used:

$$y = Aw^{\alpha 1}L^{\alpha 2}e^{\Sigma\beta_i z_i + \varepsilon} \quad (4)$$

where y is output per feddan for a particular crop, w is the quantity of water applied per feddan (in m^3) during the cultivation period, L is the area of land cultivated in feddan, zi represent qualitative variables of water management, ε is an error term that captures any missed variables, and A, α1, α2 and βi are parameters to be estimated.

The introduction of the area (L) in the production function captures the effects of returns-to-scale. The omission of this variable assumes, implicitly, a constant-returns-to-scale (CRS) technology; i.e. we assume a production function that is multiplicatively separable in land. In particular, returns-to-scale from specification (4) is measured by the sum of exponents (α1 + α2). CRS would be indicated by a sum α1 + α2 =1.

Variables reflecting on-farm water management include irrigation scheduling, soil quality and irrigation technology. However, for tomato where estimation of production functions was possible, irrigation technology was drip irrigation for all farmers interviewed. Surface irrigation is widely used for alfalfa and other field crops, but it was difficult to assess the yield for these crops.

The error term ε measures the deviation from the production frontier and is assumed to have some specific one-sided distribution, such as truncated normal or exponential (Kumbhakar et al., 1991). The estimation procedure used in this study is the corrected ordinary least squares (COLS) suggested by Richmond (1974). This method consists, first, of estimating the production function and obtaining the residuals. Then, using the largest positive residual, one "corrects" the constant term by shifting it upward until no residual is positive. Technical efficiency is, then, computed as the ratio of the actual value of the output, y, and its predicted value, y* (TE=y/y*).

DISCUSSION OF RESULTS

Results of technical efficiency and irrigation efficiency will be discussed simultaneously in order to make comparisons. The Cobb-Douglas production function for tomato is estimated in linear-logarithms form using ordinary least squares method (Table 3).

Table 3. Estimates of the Cobb-Douglas production function for tomato.

	Intercept	Log water	Log land	Schedule	Soil
Parameter	-1.06	0.38	0.02	-0.01	0.43
T-value	-1.06	2.93*	0.80	-1.86*	4.45*

*Indicates parameter is significantly different from zero at 10% level.
Adjusted $R^2 = 0.90$

The estimated production function assumes that the quantity of water (log water), irrigation schedule (schedule) and soil characteristics (soil) represent major explanatory variables for irrigated crops in Oman. The adjusted R^2 is relatively high with three out of five variables showing statistically significant parameters. Other variables traditionally included in production functions such as labor and capital were not considered. Results show that irrigation water is a highly significant determinant of crop yield and indicate also the diminishing marginal productivity of water input[1]. The results also show a negative relationship between crop yield and irrigation interval (variable schedule) which is measured by the number of days per month. This means that frequent irrigation of the crop does not necessarily increase crop yield. Finally, soil quality shows significant positive effect on crop yield.

[1]The coefficient of irrigation water quantity is an elasticity measure. It also indicates the first derivative of water marginal productivity with respect to output (yield per feddan).

Based on these results, technical efficiency measures were estimated (Table 4) along with the estimated engineering-irrigation efficiency. An average technical efficiency indices are significantly higher than irrigation efficiency. Technical efficiency results indicate that farmers are relatively highly efficient with efficiency exceeding 70%. Based on irrigation efficiency, however, more than 50% of the farms fall below 60% efficiency level. This would suggest irrigation rates relatively low compared to crop requirements.

Table 4. Efficiency measures for tomato farmers in Al-Batina region.

Farm	Technical Efficiency	Irrigation Efficiency
1	1.00	0.42
2	0.99	0.84
3	0.77	0.60
4	0.87	0.84
5	0.90	1.00
6	0.94	0.58
7	0.81	0.33
8	0.94	0.33
9	0.82	0.45
10	0.87	0.67
11	0.93	0.39

Average efficiency levels for the farms in the sample, categorized by farm size as major characteristic of these farms, were also determined (Table 5).

Table 5. Average efficiency by farm size.

	Technical Efficiency		Irrigation Efficiency	
	<90%	>90%	< 60%	> 60%
Farm size (feddan)	15	8	4.7	15
Number of farms	5	6	4	7

Table 5 indicates that significant differences exist in the efficiency level (both technical efficiency and irrigation efficiency) between larger and smaller farms. In particular, farms with larger size (more than 15 feddan) are found to be more technically efficient but having lower irrigation efficiency (less than 60%). Smaller size farms, in contrast show lower technical efficiency but higher levels of irrigation efficiency.

These results suggest two major conclusions. First, irrigation deficiencies do not necessarily influence the level of technical efficiency. In fact estimates of technical efficiency are relatively high and even higher in larger farms than in smaller fires. Second, irrigation efficiency is relatively low although investigated farms are using modern irrigation techniques. Smaller farms were found to be more efficient than larger ones.

Modern irrigation methods used in the farms studied achieve a higher degree of control over water application and, consequently, can attain water management objectives. Major deficiencies, however, may come from irrigation scheduling that include both timing and the amount of applied water. These conclusions confirm the relatively high deviations among farms in terms of irrigation interval, irrigation period and the quantity of water applied suggested by the sample data (Table 2).

CONCLUSION

This study investigated water efficiency levels for irrigated crops in the Batinah Region of Oman under modern irrigation methods. It developed a conceptual framework and provided empirical measures of technical and engineering efficiency for individual farms using drip irrigation for tomato cultivation.

Results show that technical efficiency is generally higher than engineering efficiency for a majority of farms. Most farms have achieved a technical efficiency level of more than 90% while more than one-half of them have fallen below a 60% engineering efficiency level. The results also show that larger size farms have high technical efficiency but low engineering efficiency. Smaller farms in the contrast have low technical efficiency but a higher level of engineering efficiency.

The use of water quantity ratios such as water requirement to water supplied as a measure of efficiency is not sufficient to guide the proper use of irrigation water. An estimate of water quantity supplied may hide important features of water and irrigation management practices such as irrigation scheduling which could be decisive for optimal crop yields. Thus, future field studies should focus first on obtaining more accurate actual irrigation application rates in order to validate these estimates. Furthermore, production constraints and conditions controlling water application and irrigation scheduling in terms of timing and applied amount of water should be examined in closer details.

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New Technology for Variable-Rate Management of Center-Pivot Irrigation

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NEW TECHNOLOGY FOR VARIABLE-RATE MANAGEMENT OF CENTER-PIVOT IRRIGATION

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ABSTRACT

Center-pivot irrigation systems are capable of applying a relatively uniform depth of water over an entire field. However, it may be desirable to uniformly apply different amounts of water to different areas of the field because of variability in soil topography, crop growth, fertility and soil water content within a field. A system capable of variable application of water and chemicals would also enable different crops to be grown in the same circle in areas of any shape, including rectangular. A system with these capabilities is being developed in the USA in the form of an electronic control system which can be fitted to existing or new center-pivots. This paper reports on current progress of this technology which will likely become commonplace in the future.

INTRODUCTION

The area under continuously moving irrigation systems, such as center-pivot, continues to grow. For example, in 1982 in the USA, center-pivots accounted for 4.0 million ha (about 16%) of the total irrigated area of 25.0 million ha. By 1991 center-pivots accounted for 5.6 million ha out of a total irrigated area of 23.8 million ha (24%). There are also many center-pivot systems in the GCC countries producing a variety of crops. For example, Saudi Arabia has a large number of center-pivots irrigating wheat and forage crops using fossil groundwater. Oman currently also has several commercial farms based on center-pivot irrigation which produce fodder and vegetable crops, and has plans to expand production in the southern part of the country.

Center-pivot (and linear-move) systems are capable of relatively high application uniformities. A well designed and maintained system can achieve a coefficient of uniformity (CU) in the 85% to 90% range, which means it can apply approximately the same depth of water over the entire field. This is an important advantage in and areas with limited or non-renewable water resources. However, a high coefficient of uniformity (CU) is not always sufficient to ensure efficient irrigation because the fields themselves may not be uniform. Examples of variability within fields include non-cropped areas such as rock outcrops, slopes, soil texture and depth, and crop growth. Applying a spatially uniform amount of water or chemicals to a non-uniform field or crop is not the most efficient use of resources.

Technology development and decreasing prices are making it feasible to apply agricultural inputs, such as fertilizer, at appropriately different rates to different areas within a field. Site Specific Crop Management (SSCM) is one of the terms used to describe spatially variable inputs. Essential to SSCM are the abilities to locate the application equipment within a field and to automatically vary application rate according to a predetermined map. Much of the research in SSCM has concentrated on ground based machinery such as fertilizer spreaders, which require systems such as the Global Positioning System (GPS) to continuously determine equipment location in the field. Such equipment generally can not be used in the field once the crop has grown to the point that damage would occur. In contrast, center-pivot or linear-move machines have great potential for SSCM because it is relatively easy to determine their location within the field at any time, and they also operate throughout the season.

The latest programmable controls for center-pivots enable the speed of the machine, and hence the application amount, to automatically vary as the system rotates, thereby making it possible to apply different amounts to different 'pie slices' (sectors) of the field. However, field variability rarely matches sectors of a circle. In order to vary applications to an area of any shape within the field, the flow rate along the length of the lateral also needs to be variable. Figure 1 illustrates the concept.

There is currently much interest in SSCM, both from a research and a commercial perspective (e.g. Camp and Saddler, 1994, Fraisse et al, 1995a and 1995b, King et al, 1995). This paper describes some of the work which has been done at the University of Idaho in the USA and the potential for continuing work at Sultan Qaboos University in Oman.

SYSTEM DESCRIPTION

A series of prototype control systems to enable SSCM using center-pivots have been developed and tested. Wall et al (1996) describe the latest version of the control system. A typical prototype system, as shown in figure 2, consists of a microprocessor based controller, a location sensor, and solenoid valves under the control of individually addressable electronic modules. The controller includes digital input and output lines, digital to analog and analog to digital conversion, an RS232C serial communications port, keypad input and LCD display output, and sufficient system memory to contain the control program and required data. A typical sequence of operations is to:

- Determine the location of every sprinkler in the field
- Compare the sprinkler location with a map prescribing application amount
- Control the sprinkler to apply the prescribed amount
- Control the operation of associated equipment such as a chemical injection pump

The above sequence is repeated continuously. Additional details on the main components are given below.

To determine the location of every sprinkler in the field, the controller reads the output from the location sensor which, in the case of a center-pivot, measures the rotation angle of the first tower. Possible location sensors for a linear-move system include shaft encoders to count wheel revolutions or switches to count regularly spaced indicators on a guide wire. For any sprinkler on the system the combination of lateral location and sprinkler location along the lateral spatially locates the sprinkler within the field.

Individual or groups of sprinklers are electrically controlled using a solenoid valve which is operated by a control module. These control modules are connected to a single power cable which runs the length of the lateral and which carries both the current necessary to operate the solenoid valve and the signals necessary to operate the modules. The control signals are superimposed on the ac current carried by the power cable, and decoded by the modules. Each control module has an electronic address, and will only respond to control signals which are addressed to it. Thus, it is not necessary to provide each module with an individual signal cable. A control module responds to control signals by switching current on or off to the solenoid valve, thereby turning the water to the sprinklers on or off as required. Variable rate chemigation is accomplished by electrically controlling the chemical injection pump to maintain a constant concentration in the irrigation water regardless of the total flow rate in the system at any time. With a constant chemical concentration, chemical applications can be varied by varying the irrigation depth. Similarly, the output of the pumping plant can be matched to actual requirements if the pump is equipped with a variable speed drive. Various versions of the control system have been tested on full size commercial center-pivots with encouraging results.

One of the keys to implementing SSCM for irrigation systems is identifying and mapping the different management zones within a field. Some sources of variability do not change over time, such as soil type and slope. These therefore need to be mapped only once, and so perhaps grid sampling is appropriate. For sources of variability which may change during the season, such as nutrient status or pest infestation, periodic sampling or remote sensing are better methods. Management decisions can also result in the need for spatially variable application.

For example, it may be decided that rectangular blocks within the field should grow different crops or varieties, therefore requiring different irrigation management.

METHODS

The most recently completed test involved retrofitting a control system to a commercial 9 tower 354m long low pressure center-pivot in S.E. Idaho (King et at 1996). The primary objectives of the test were to evaluate techniques for developing a nitrate application map and to determine how well the irrigation control system could implement it by spatially varying nitrogen application through the system.

In 1995 the irrigation system was producing a wheat crop in a field characterized by short length moderate slopes under the outer third of the system. At the end of the previous season, the field was sampled on a 61m grid using a Global Positioning System to locate the grid points. At each grid point, four soil samples were collected to a depth of 0.6m in a 5m radius. The four samples were composited in 0.3m depth increments and analyzed for soil texture, organic matter, pH, phosphorus, potassium and residual nitrogen. To supplement this data, digital images of the field were obtained by measuring reflectance in the visible and near-infrared portions of the spectrum using remote sensing equipment mounted in an aircraft. A Normalized Vegetative Index (NDVI), which estimates biomass and yield, was derived from this data to determine yield potential within the field. A nitrogen application map of the field was then developed in which different parts of the field were assigned to receive one of 4 different levels of nitrogen, ranging from 0 to 90 kg/ha (figure 3). The variable rate nitrogen application was accomplished by varying irrigation depth while maintaining a constant nitrogen concentration in the water. Irrigation depth was assigned to be one of four levels, corresponding to relative application rates of 0%, 33%, 67% and 100% of the original unmodified application, using a pair of sprinklers with relative flow rates of 33% and 67%, as shown in figure 2. The four possible on/off combinations yielded the four relative application rates.

The field was divided into 8 sectors, of which 4 received variable rate chemigation and 4 received conventional management (uniform application). The total nitrogen requirement was applied in a single pass at the beginning of the season in the form of 6168 liters of Uran (which is composed of urea and ammonium nitrate and contains 32% nitrogen by weight). The performance of the system in applying variable nitrogen amounts was measured using groups of 4 catch cans at various locations within the field. These catch cans measured irrigation application and also provided a sample of irrigation water from which nitrogen concentration could be subsequently analyzed. Figure 4 shows the actual variable rate chemigation map which was used, together with the locations of the catch can groups. Each cell in the variable rate management sectors was assigned one of the four possible rates, depending on the chemigation requirement map shown in figure 3. A polar coordinate system was used, with each cell being a fixed length (38.1 m) in the radial direction and a fixed angle (6 degrees) in the rotational direction. This results in cells which are bounded by straight lines and arcs, and which increase in area the farther they are from the center. The outermost cells have an area of 0.13 ha.

RESULTS AND DISCUSSION

The measured irrigation depth at each location agreed very well with the target depth, with the exception of two locations which were below the target for unknown reasons. Excluding these two locations and those which occurred close to the boundaries between different targets, the average irrigation applications for the 33%, 67% and 100% target depths were 4.3 mm, 8.9 mm and 13.8 mm respectively.

The average nitrate concentration in the variable rate and conventional management sectors were 128.1 mg/l and 129.4 mg/l respectively. The coefficients of variation were 0.054 and 0.097 respectively. This shows that the chemical injection pump was successfully controlled to maintain approximately uniform chemical concentration despite the changes in total flow required for variable rate irrigation. The total nitrate application (kg/ha) is proportional to the product of nitrate concentration and irrigation depth. Therefore, it can be concluded that the system was able to apply step-wise variable rate chemigation with accuracy equal to or better dm a conventional system could apply a uniform amount.

We are planning to use a recently acquired 100m long linear-move irrigation system located at the College of Agriculture Experiment Station at Sultan Qaboos University to continue studies on the use and applicability of this system to Oman and other GCC countries. We expect center-pivot use to grow in Oman as new groundwater supplies are developed to ease the pressure on aquifers in the Batinah and Salalah regions. Production output per unit of water input is very important in areas such as this where the supply is non renewable or limited. If field variability is a problem then a system such as this can help ensure that water is used as productively as possible, and that contamination of groundwater by agricultural chemicals is minimized. Even if fields are uniform it may be desirable to grow more than one crop under a center-pivot at any one time. Farming operations generally favor rectangular shaped fields rather than sectors of a circle, and so there may be an advantage to a system such as this. Pest control is another area which this system could benefit. If the pests are initially located in discrete areas, then these areas alone could be targeted with pesticides rather than the whole field.

CONCLUSIONS

Additional research and operational experience is needed before this technology can be used effectively by commercial farms. However, the next major improvement in irrigated agricultural production is likely to be the adoption of SSCM technology. It should prove valuable to the Gulf countries as they seek to use their limited water resources in the most efficient way. Further study needs to be made of the current and projected areas under center-pivot irrigation in the Gulf to better determine its applicability.

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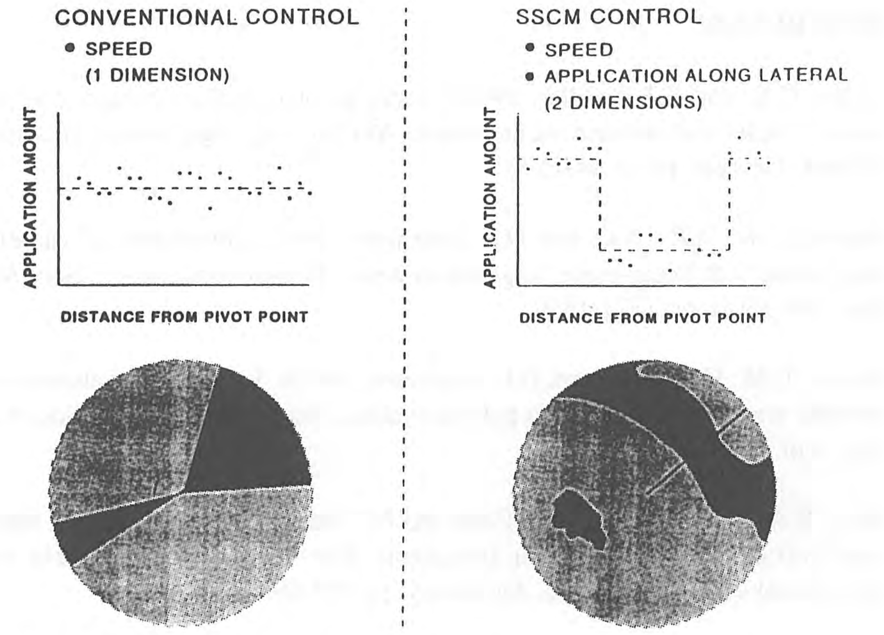

Fig. 1. Comparison of irrigation capabilities using currently available technology and Site Specific Crop technology.

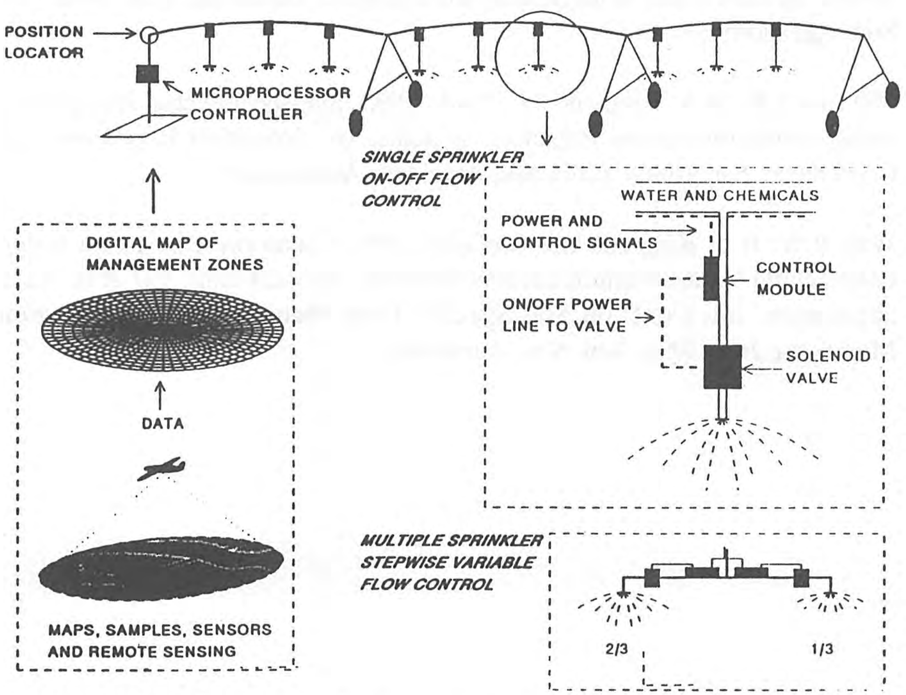

Fig. 2. General components of the system enabling Site Specific Crop Management.

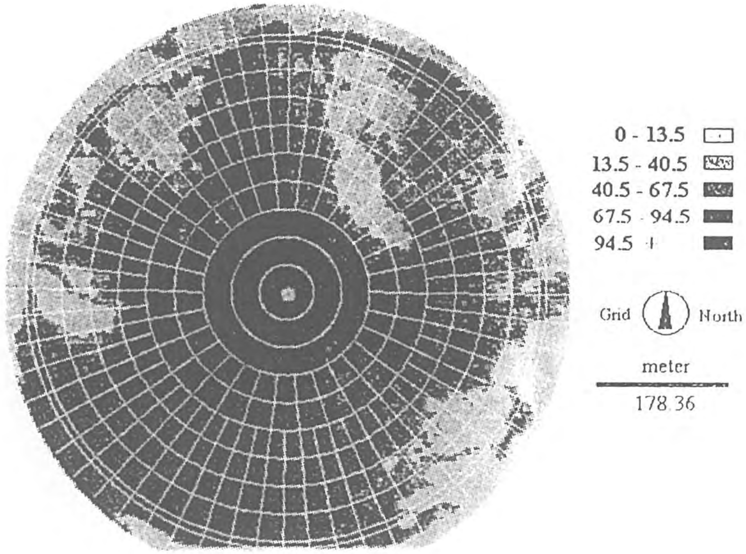

Fig. 3. Computed nitrogen chemigation requirements, kg N/ha, grouped by ratios of 0, 1/3, 2/3 and full.

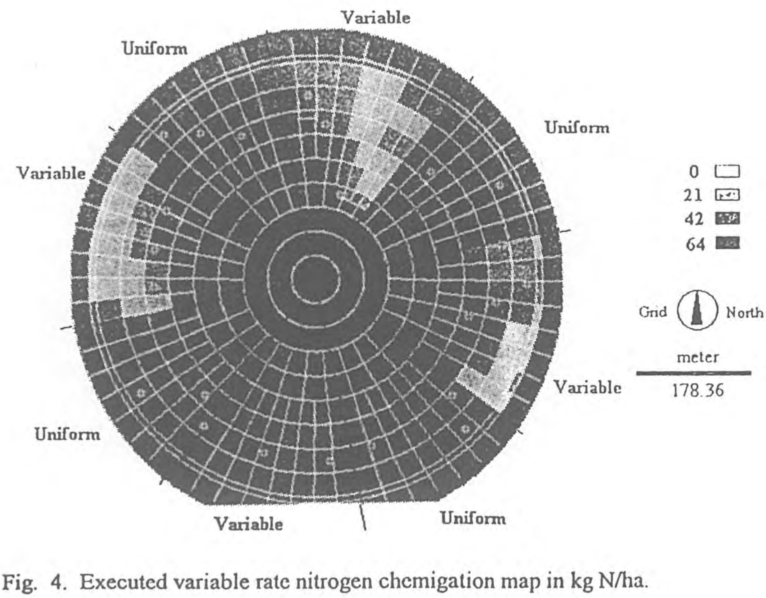

Fig. 4. Executed variable rate nitrogen chemigation map in kg N/ha.

Infiltration Rate reduction Prediction Under Surge Irrigation Using Management Variables and Soil Composition

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INFILTRATION RATE REDUCTION PREDICTION UNDER SURGE IRRIGATION USING MANAGEMENT VARIABLES AND SOIL COMPOSITION

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ABSTRACT

Four soils were tested under field conditions using duration of on-time and off-time combinations of surge and continuous flow. The combinations were 30, 60 and 90 minutes for the on-time and 0, 30, 60, 120, 180 and 960 minutes for the off-time. The effects of surge irrigation on the infiltration rate were determined and the reduction between the first and second surge were quantified. The infiltration rate reduction was significantly affected by the methods of irrigation which were surge and continuous flow. The soils tested were Fort Collins Nunn-Ulm soil (clay loam), Otero (sandy loam), Satanta loam soil, and the Table Mountain loam (sandy loam). The results of this study proved that the infiltration rate reduction increased with the increase of off-time up to the optimum off-time (Al- Saud et al., 1993), which was soil dependent. Each of the soils had a different optimum off-time. A model was derived to predict surge irrigation infiltration reduction using management variables and soil clay percentage. There is sufficient evidence to indicate that knowing the management varibales, including on-time, off-time and soil type, would provide a significant estimate of infiltration rate reduction due to surge at the 95 percent confidence level. This first degree model is useful at the farm level and gives good input for designing surge irrigation.

INTRODUCTION

Surge irrigation, the intermittent application of water to furrows or borders in a series of surges of constant or variable time spans, is shown to have advantages and benefits over conventional irrigation (continuous application of water). The advantages of surge irrigation are faster advance along the field and thus improvement in distribution uniformity along the length of the furrow or border. It also reduces tailwater and deep percolation losses, thus improving water application efficiency and so implying a reduction in total volume of irrigation water required. Furthermore, it provides a means of automating, managing and controlling the application of water to the field (Bishop et al., 1981; Podmore and Duke, 1982).

Several studies and theories have been proposed to explain the surge mechanism and its effects, known as the surge phenomena. These mechanisms include consolidation of the top soil matrix which reduces the hydraulic conductivity of the surface layer (Samani, 1983; Farahani, 1991) and surface sealing which is caused either by deposition of sediment on the surface or by migrating of soil particles into pore space which seals the surface, resulting of substantial reduction of the hydraulic conductivity of the thin surface (Stieb, 1983; Kemper et al., 1988; Trout, 1990). Other mechanisms such as air entrapment, in which air can be isolated in soil pores or as a layer between water layers, are believed to have great effects on infiltrations rate (Duke, 1988; Seymour, 1990; Lep, 1981; Farahani, 1991). Another explanatory mechanism is decreasing furrow roughness and more stable cross section during infiltration of water between surges (Coolidge et al., 1982; Trout, 1990). Other mechanisms include the redistribution of water during the off-time, which reduces the hydraulic gradient (Levin et al., 1979; Killen et al., 1987), and hysteresis (Izadi. et. al., 1988).

Although there has been some progress in understanding the mechanisms of surge irrigation, the prediction of infiltration is still not completely understood. The effect of surge irrigation is soil type related and seems to be soil texture dependent (Alemi and Goldhamer, 1988; Saleh and Hanks, 1989). On the other hand, surge irrigation has responded to management variables (Al-Saud et al., 1993; Izuno et al., 1985, Blair, 1985). Moreover, surging caused soil properties to change (Senzanje, 1994; Saleh and Hanks, 1989; Farahani, 1991). Al-Saud et al. (1993) found that the surge effects increased with an increase of the off-time up to the optimum off-time. Senzanje (1994) tried to predict infiltration rate under field conditions using bulk density response surface for clay loam and sandy loam, but predictions obtained were too low.

Prediction of surge irrigation performance under a set of field conditions and management practices seems impossible. Yet the effectiveness of surge irrigation depends on the interaction between management and physical parameters such as soil bulk density, porosity, hydraulic conductivity, and others. The objective of this study was to use irrigation management and soil composition to predict infiltration rate reduction under irrigation so that farmers can use this method in designing their own surge irrigation systems. The underlying assumption was that change of infiltration rate due to surge irrigation is a result of complicated changes of physical and property of the soil. The purpose of this study was to use constant unchangeable physical predictor to account for these effects and to then use it to predict the reduction to infiltration rate.

MATERIAL AND METHOD

One objective of this study was to test a wide range of soil types with different soil compositions. The initial goal was to build a good database of information which reflected the actual soils found under surge or continuous irrigation and a wide range of possible on-time, off-time cycle ratios used by farmers. The soils were selected based on their distribution and popularity in the Fort Collins area from the soil survey and its soil map. Four soils were selected and tested between 1992 and 1995.

Clay Loam

The first experiments were performed at the Agronomy Research Center in Fort Collins, Larimer Country, Colorado in the summer of 1992. The field was ridged into 0.76 meter wide furrows 50 meters in length (Al-Saud, 1994). Tests were conducted in alternate furrows to allow for working space and to avoid walking in the test furrows. The test area was about 10 furrows from the edge of the field and about 10 meters from the head of the field. The soil was clay loam over a clay, and classified as a Fort Collins-Nunn-Ulm. Textural analysis revealed that the soil had 41 percent sand, 31 percent silt, and 28 percent clay. The source of water for all tests was city of Fort Collins water. The setup of the 1992 experiments is presented in Table 1. The comparisons were chosen to cover the possible realistic management combinations under which a farmer would operate under field conditions. Combination variations of on-time and off-time for surge simulations were selected as objectives of this study (Al-Saud, 1994; Senzanje, 1994). Three replications were performed for most of the combinations, and two replications were performed for the other. The number or replications for each treatment are also shown in **Table 1**.

Table 1. The experiment combinations and number of replicates for clay loam, 1992.

On - Time (min)	Off- time (min)			
	30	60	120	180
30	3	3	3	3
60	3	3	2	2
90	2	2	2	2

Otero Sandy Loam

Similar experiments were conducted at the Colorado State University Agricultural Research, Development and Education Center (ARDEC) in 1993. The soil was classified as Otero sandy loam. The soil was described as deep, well drained, and had low shrink-swell potential. The texture analysis revealed that the soil had 11 percent clay, 54 percent sand, and 35 percent silt. The field was irrigated before the experiment began (Senzanje, 1994). Six furrows were selected to eliminate its domination effects. For more information see Senzanje, 1994. The combinations of on-time and off-time for the 1993 experiment and number of replicates are presented in **Table 2**.

Table 2. The experiment combination and number of replicates for Otero sandy loam, 1993.

On - Time (min)	Off- time (min)			
	30	60	90	120
30	3	3	3	3
60	3	3	3	3
90	3	3	3	3

Satanta Loam

The first experiment of 1995 was performed at the Horticulture farm, Fort Collins. The soil was known as Santa loam soil. It consisted of deep, well-drained soils that formed in mixed and wind deposited material. This was a levelsoil with slope less than 0.01. The profile was described as seven inches of thick dark grayinsh brown loam in the surface layer. The subsoil layer was brown clay and pale loam about sixteen inches thick. The underlying material was very pale loam. The runoff was slow and the hazard of erosion is slight. The field was cropped of corn the previous season. The experiment setup was designed to minimize field variations. The soil analysis revealed that the soil had 23 percent clay, 39 percent sand, and 36 percent silt.

Table Mountain Loam

The second experiment of 1995 was performed on Table Mountain loam soil in a private farm in the Fort Collins area. The land was under grass. After harvesting the grass in late August of 1995, the experiment was conducted. The Table Mountain soils consisted of deep, well-drained soils which formed alluvium. In a representative profile the surface was grayish brown loam about 36 inches thick. The underlying material was brown fine sandy loam about ten inches thick and yellowish brown fine sandy loam about five inches thick. Below this was sand gravel materials. The permeability was moderate and the available water capacity was high. The series was used mainly for irrigated and dry farmed crops. This soil was suited to corn, sugar beets, beans, alfalfa, wheat and barley. The experiment setup was designed to minimize field variation and was the same for the Satanta soil 1995 experiment. The soil analysis revealed that the soil had 15 percent clay, 52 percent sand, and 33 percent silt. The combinations of on-time and off-time for the Satanta loam and Table Mountain loam experiments and number of replicates are presented in **Table 3**.

Table 3. The experiment combination and number of replicates for Satanta loam and Table Mountain loam, 1995.

On - Time (min)	Off- time (min)			
	30	60	180	960
30	3	3	3	3
60	3	3	2	2

A blocked furrow's infiltrometer was used to simulate surge and continuous irrigation on these soils and to assist with more accurate measurement of the data required. The equipment was a modified form of the blocked furrow as outlined in ASAE Standards (ASAE 1992). In order to simulate surge flow, the downstream plate had a hole seven centimeters at the bottom of the furrow to allow ponding and draining by using a removable rubber stopper. The blocked furrow was one meter long by 0.76 m. wide, thus giving a basin area of 7600 cm^2. The drawdown in the supply tank was converted to a volume of water per unit time then divided by the area of the blocked furrow in order to get the infiltration rate (cm/min). The average infiltration rate for the first surge was defined as the last five minutes of the surge one (i_1), The infiltration rate for the second surge was defined as the infiltration rate of the last five minutes of the surge two (i_2).

A reduction, or change was defined as a percentage, and was used to standardize the relation between the first and second surge because there was a large variation in the infiltration rate between treatments that had the same on time in the first surge due to special variability. **Equation 1** calculates the reduction of infiltration rate. The comparison would be the opportunity time as the on-time, and the off-time was zero in this case.

$$\mathrm{RIR} \; \frac{i_1 \; i_2}{i_1} \; 100 \qquad 1$$

Where:

RIR = reduction of infiltration rate (%)
i_1 = infiltration rate at the end of surge one (cm/min), and
i_2 = infiltration rate at the end of surge two (cm/min).

RESULTS

The soils showed surge irrigation reduced infiltration rate compared to continuous irrigation. These results are supported by early work in surge irrigation in the 1980's by Podimore, 1982 Izuno, 1985, Testezlaf 1987 and others. The infiltration rate reduction due to surge was higher than that of continuous irrigation by an average of 30-45 percent. Surge irrigation reduced the deep percolation of water and had good potential to reduce the total volume of water used in surface irrigation, thus, resulting in less use of total irrigated water, less environmental hazard and less use of chemicals.

The management predictors in the study of on-time and off-time had affected infiltration rate reduction due to surge. The on-time had no significance at the 95 percent level. In general, as the on-time increased the infiltration rate reduction decreased, and this was the case for all soils. The longer the on-time the larger the amount of water used and the closer it approximated the steady state infiltration rate. Thus the infiltration rate reduction would be less than that for a shorter on-time (Al-Saud et al., 1993). The off-time was a significant factor in infiltration rate reduction at the 95 percent level except for the Otero soil. Surge works perfectly in a fresh tillage soil, which was not the case in the Otero soil (Senzanje, 1994). While the experiments on the other three soils were performed in fresh tillage field as first irrigation, the Otero soil had been irrigated three times before the experiment took place. This soil was therefore excluded from the final analysis. The first irrigation had the greatest impact from surge, and as the season progressed its effects diminished rapidly and finally ceased. Therefore, a summary of the predictors and the response is presented in **Table 4**. It shows the minimum, the maximum, and the average. The off- time of zero suggests continuous irrigation.

The inflitration rate reduction, as the focus of this study, was the dependent variable or the response. The predictors were management, physicals, and the interaction between them. The management predictors were the on-time, off-time, and cycle ratio, defined as the ratio of on-time to the cycle (on-time + off-time), and the interaction among these predictors. The physical predictor was the percentage of clay in the soil which presented the soil texture factors. The underlaying assumption was that reduction of infiltration due to surge irrigation was the result of complicated changes of physical and property. However, it was not the objective of this study to quantify these changes. The purpose was to use a constant unchangeable physical predictor to account for these changes. (Senzanje, 1994; Onsted et al., 1984; Saleh and Hanks, 1989). There are conflicting reports as to whether surge irrigation works effectively in fine or coarse texture or between them, many reports claimed differing conclusions (Seymour 1990, lzuno et al., 1985; Samani, 1983).

Table 4. The variable predictors and the responses and their means, standard deviation, minimum and maximum

Variable	No	Mean	Std.Dev.	Minimum	Maximum
REDUCTION (RIR)	109[1]	41.00	18.60	4.30	76.80
ON-TIME	114	49.70	19.90	30.00	90.00
OFF-TIME	114	168.20	279.30	0.00	960.00
CLAY	114	22.30	5.40	15.00	28.00
CR	114	0.47	0.31	0.03	1.00

A multiple regression was performed for the soils using the infiltration rate reduction for surge and continuous irrigation. Standard diagnostic checking (Wesberg, 1985) did not reveal any gross violation of these assumptions underlying normal linear regression. The results of the multiple regression are presented below.

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	5	28917.7	5783.5	71.258	0.0001
Error	103	8359.9	81.2		
CTotal	108	37277.6			

Root MSE	9.0	**R-square**	0.7757
DepMean	40.97	**Adj R-sq**	0.7649
C. V.	21.99		

[1]5 observations had missing values.

Parameter Estimates

Source	DF	Sum of Squares	Mean Square	FValue	Prob>F
INTERCEPT	1	61.87	4.4978	13.756	0.0001
ON-TIME	1	0.06	0.05527	1.134	0.2596
OFF-TIME	1	-0.07	0.00952	-7.639	0.0001
CR	1	-64.19	3.65558	-17.560	0.0001
CLAY	1	0.54	0.16807	3.237	0.0016
ON/OFF	1	0.000825	0.0002	4.217	0.0001

The result of the Analysis of Variance (ANVOA) indicated that at P-value<0.0001 the knowledge of predictors provides a significantly better model than no knowledge of them. The fitted linear model is presented by **Equation 2**. It is a first degree linear model with three independent variables, cycle ratio, and interaction between on-time and off-time. The dependent variable or the response was the infiltration rate reduction. This model explained about 77 percent of the variation of infiltration rate reduction (See **Figure 1**).

$$RIR\ 61.87.062\ t_{on}\ 0.073\ t_{off}\ 64.19\ \frac{t_{on}}{t_{on}\ t_{off}}\ 0.544\ C\ 0.000825\ t_{on}\ t_{off}$$

Where:

- RIR = reduction of infiltration rate (%)
- t_{on} = on-time (min),
- t_{off} = off-time (min) and
- C = clay percentage (%)

All predictor coefficients were of significantly different from zero for on-time (p- value = 0.26). There is sufficient evidence to conclude that off -time, cycle ratio, clay percentage (soil type), and the interaction between on-time and off-time were significant predictors of infiltration rate reduction due to surge.

The model had some limitations for predicting infiltration rate reduction. The limitations are that the model predicts for soils with a clay percentage between 15 percent and 28 percent. Additionally, it only predicts the infiltration reduction for management predictors such as on-time and off-time. Such predictors must be in the experiment range, meaning that on-time should be between 30 and 90 minus and off-time between 0 and 960 minutes.

The infiltration rate reduction increased with the increase of the off-time up to optimum off-time. From the field data, the clay loam soil should be irrigated with a range of 120 minutes off-time. Furthermore, for shorter on-time, Satanta soil gave the highest reduction at 60 minutes off-time, while at longer on-time, on-time of the range of 120-180 gave the highest reduction. For the Table Mountain Soil, the longer the off-time, the higher the reduction. For example, 180 minutes gave the highest reduction at 30 minutes on-time and 960 minutes gave the highest reduction with 60 minutes on-tiine. In general, for these soils a range of 120 minutes off-time had the highest, or one of the highest, reduction rate, depending on the on-time and soil type. As a rule, farmers should operate at around 120 minutes off-time. However, the off-time should not exceed 180 minutes except for Table Mountain soil with a longer on-time of 60 minutes (see Figures 2 and 3). These results are similar to those obtained by Al- Saud et al., 1993.

Modeling the reduction of infiltration rate gives good results using the management and the clay percentages as predictors, which can be used at the farm level for hand designing of surge irrigation. An example of prediction reduction of infiltration rate by using the model is as follows: on-time = 60min, off-time = 180 min and clay = 15 percent; the cycle ratio is 0.25. Then by using Equation 2 the reduction = 53.6 percent. Another example is on-time = 30 min, off-time = 60 min and clay = 28 percent; the expected reduction is 54.5 percent.

CONCLUSION

The soils were tested using combinations of on-time and off-times. These soils were Fort Collins Nunn-Ulm soil (clay loam), Otero (Sandy loam), Santanta loam soil, and the Table Mountain loam (sandy loam). The soils tested showed a significant reduction of infiltration rate due to surge compared to continuous flow. This study indicates that the infiltration rate reduction is increased with the increase of the off-time, up to the optimum off-time, which is soil type dependent or soil texture dependent. In fact, soil type appeared to play a major role in the effects of surge irrigation and it differed significantly from 0. The on-time and off-time and the clay percentage provide a significant knowledge of infiltration rate reduction at the 95 percent level. The model was derived to predict surge irrigation infiltration reduction using management variables and soil clay percentage. This simple model is helpful in providing a useful information for designing surge irrigation at the farm level. This model should be further tested to determine how accurately it predicts the reduction of infiltration rate due to surge under other soils.

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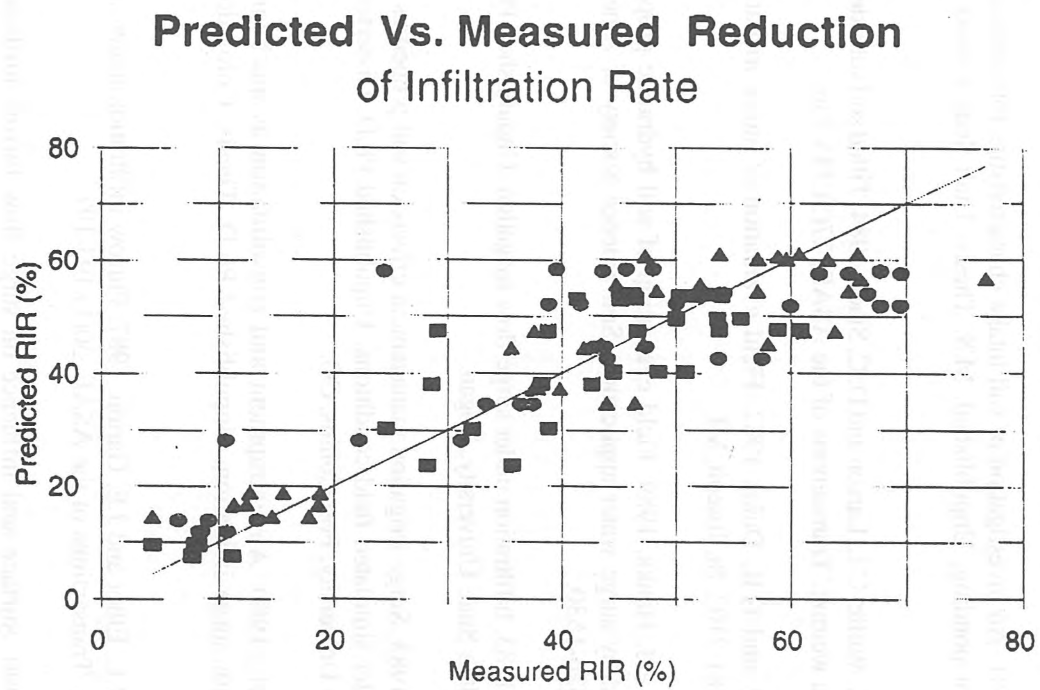

Figure 1 ▲ 28% Clay ● 23% Clay ■ 15% Clay

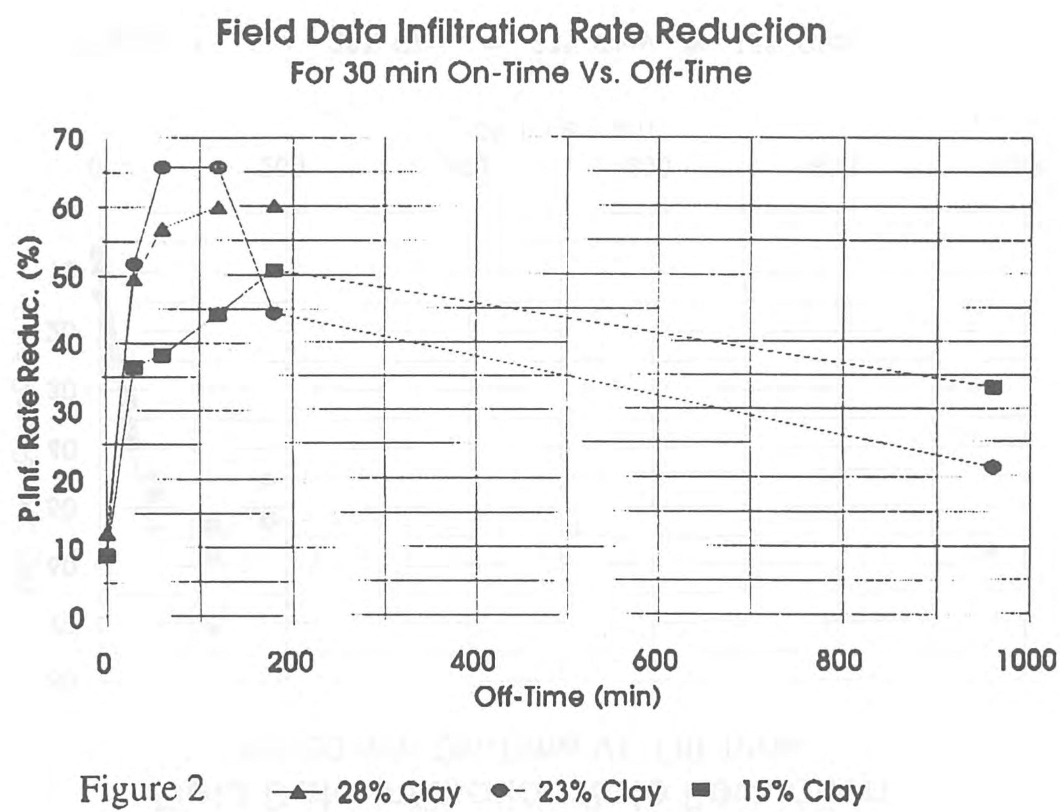
Field Data Infiltration Rate Reduction
For 30 min On-Time Vs. Off-Time
P.Inf. Rate Reduc. (%)
Off-Time (min)
28% Clay
23% Clay
15% Clay
0
10
20
30
40
50
60
70
0
200
400
600
800
1000

Figure 2

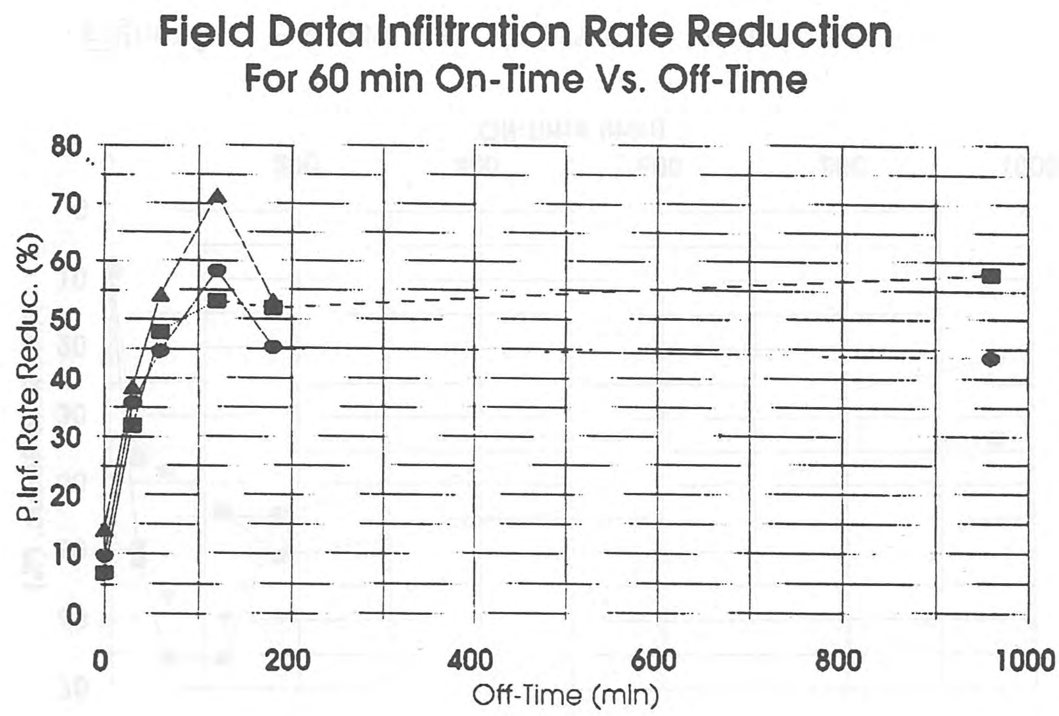

Figure 3 ▲– 28% Clay ● 23% Clay –■ 15% Clay

Aflaj Irrigation Water Management and Efficiencies: A Case Study from Northern Oman

W.R. Norman, W.H. Shayya, A.S. Al-Ghafri and I.R. McCann

AFLAJ IRRIGATION WATER MANAGEMENT AND EFFICIENCIES: A CASE STUDY FROM NORTHERN OMAN

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ABSTRACT

This paper reports on preliminary results from a case study on water management within a traditional, falaj irrigation system in northern Oman. In the planning and design of regional irrigation development programs, generalized assumptions are frequently made as to the efficiency of traditional surface irrigation systems. Although qualitative accounts abound, very little quantitative research has been conducted on on-farm water management within aflaj systems. Daily irrigation applications and crop water use was monitored during an 11-month period among 6 farm holdings at Falaj Hageer in Wilayat Al-Awabi. Contrary to the frequent assumptions that all surface irrigation systems incur unnecessarily high water losses, irrigation efficiencies were found to be relatively high. Based on actual crop water use, irrigation efficiencies among monitored farms varied from 64% to 107%, with a mean of 87%. Examination of the soil moisture budget indicates that during most irrigations of wheat (cultivated in the low evapotranspiration months of October-March) sufficient water is applied for the shallow root zone to attain field capacity. With the exception of temporary periods of high falaj delivery flows or periods of rainfall, field capacity is usually not attained during irrigations within the more extensive root zones of date pahn farms, The data presented in this paper should provide a better understanding of water use performance by farmers within traditional aflaj systems. Moreover, these data should also serve to facilitate more effective development planning for irrigation water conservation programs in the region.

Keywords: Irrigation, water management, efficiencies, traditional systems, aflaj, Oman.

INTRODUCTION

Most crop producing areas in the Sultanate of Oman receive only 100-200 mm of rainfall annually. Virtually all crop production is therefore dependent on irrigation. About half of the 62,000 ha cultivated in the Sultanate is irrigated from wells, while the remaining half is irrigated by traditional *aflaj* systems (Abdel-Rahman and Omezzine 1996, MAF 1995).[1] These indigenous, community-managed systems access ground water by gravity flow from underground galleries or surface springs on neighbouring mountain slopes. The *aflaj* of Oman, whose origins date back several centuries and more, have historically provided a secure and stable means of agricultural production in the region's dry, desert environment (Wilkinson 1983). They have also served as the foundation for settlement, community development and social structure among most interior communities of northern Oman (Wilkinson 1977).

The rapid social and economic changes which have occurred in Oman during the past 25 years have had a profound impact on the viability of *aflaj* systems. Today, lower-cost (although often environmentally unsound) access to water is available from wells in many areas. Among many *aflaj* communities, greater returns to labour are now available through non-agricultural and/or urban employment. These factors, among others, have contributed to labour shortages, decreased local investment in system maintenance and lower water tables (and, therefore, lower flow rates) among an increasing number of *aflaj* in the country (Dutton 1995).

Recent years have also seen a significant expansion in the cultivated area most notably, areas irrigated from wells. With agriculture's present use of 80%-90% of the nation's fresh water, water conservation in the agricultural sector has now become a priority for the government (George 1996, Adbel-Rahman and Abdel-Magid 1993). Measures are presently being sought by which irrigation water can be used more efficiently. Particular attention has been given to the improvement of "traditional", on-farm surface irrigation, since this method is employed in the majority of farms with wells and within all *aflaj* systems. In many parts of the world, including the GCC countries, the assumption is often made that high water losses are inherent in all forms of surface irrigation, with efficiencies often estimated at 50% or less (e.g. Ahmad 1996). Unfortunately, little quantitative work has been done to evaluate actual, on-farm water use among traditional systems in Oman. Among *aflaj* in particular, performance levels of on-farm water management have remained unknown. This form of baseline information is crucial in the search for (and evaluation of) solutions to the crisis facing many of Oman's *aflaj* and in the attempt to ameliorate water

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[1]*Aflaj* is the plural rendering in Arabic, while *falaj* is the singular.

conservation within irrigated, systems in the Sultanate.

This paper reports on preliminary findings from an on-going water management case study at Falaj Hageer in Wadi Bani Kharus, Wilayat Al-Awabi, in northern Oman. The objective of this paper is to provide a preliminary assessment of *falaj* on-farm water management through the evaluation of soil water management and assessment of irrigation efficiencies. Seasonal, on-farm water use data from 6 farm plots within the falaj system are examined and presented.

METHODOLOGY

Site Selection

The selection of Falaj Hageer for study was based several criteria. It is a medium to small-sized *falaj* system (under 10 ha) which is sustained by year-around spring *(ayn)* flow. It supports both date palm production and significant production in *awabi* land (primarily of wheat).[2] The system is still managed according to traditional methods of *falaj* management (including the sundial and star system for irrigation scheduling). Another reason for selecting this site is that the majority of farm labour is provided by Omani farmers, rather than by expatriate labour (greater than 90%). Finally, the site is within reasonable access to university research staff (1.5 hours driving time). The selection of farm plots within the system included: a) the identification of farmers willing to have their plots monitored on a long-term basis, and b) the selection of plots well distributed within different sectors of the system (e.g. at the head-end versus the tail-end of the channel delivery system).

Water Use Monitoring

During the period from October 1995 to March 1996, four wheat plots in *awabi* land were monitored for water use throughout the entire growing season. Water use within two date palm plots was also monitored during the period from October 1995 to August 1996. Direct water use monitoring and informal farmer interviews were employed in the assessment of on-farm water management. Flow measuring flumes were placed at the channel water delivery outlet at each plot, and water delivery times and flow rates were recorded during each irrigation. Soil characteristics and root zone development were also measured within each plot.

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[2]*Awabi* land is "excess" land where perennial date palms are not cultivated. Varying portions of it are used in the low evapotranspiration months (October-March) of most years when excess water allows for the supplementary cultivation of non-perennial crops.

During the same period a small climatological station was maintained on-site. Daily maximum and minimum temperatures, relative humidity, solar radiation and precipitation were recorded for the purpose of estimating crop water use.

Soil Water Budget

The SCS-Microcomputer Irrigation Scheduling Package (SCS-Scheduler) was employed for evaluating soil moisture budgets. SCS-Scheduler (Shayya and Bralts 1994) was developed for use by the Soil Conservation Service of United States Department of Agriculture and is widely used in the U.S.A. It is a versatile and user friendly general irrigation scheduling package for microcomputers. The program is suited for both on-farm irrigation scheduling and regional analysis. It can schedule irrigation based on either real-time or historical weather data for an unlimited number of fields simultaneously. The package is not specific to an irrigation system, crop, climate, or soil type.

SCS-Scheduler employs the computed root zone water balance method along with field-specific characteristics and local weather data for water budget updates and irrigation scheduling. The software can accommodate a wide variety of soil types and is applicable to any number of crops once crop-specific growth data are established.

The theory used as the basis for the development of SCS-Scheduler was discussed in several publications (Shayya et al. 1990, Shayya et al. 1991, Shayya and Bralts 1994). Consequently, only a brief review will be presented here.

The soil water content is determined daily by adding rain and irrigation amounts and subtracting evapotranspiration as follows (Shayya and Bralts 1994):

$$SM_{i+1} = SM_i + RAIN_{i+1} + IRR_{i+1} - ET_{i+1} - DP_{i+1} \quad (1)$$

where SM_i is the soil moisture in inches on day *I*, Sm_{i+1} is the soil water in inches on day *I+1*, $RAIN_{i+1}$ is the effective rainfall in inches on day *I+1*, IRR_{i+1} is the irrigation in inches on day *I+1*, ET_{i+1} is the evapotranspiration in inches on day *I+1*, and DP_{i+1} is the amount of deep percolation in inches on day *I+1*. The *ET* is defined as the total amount of water lost to the atmosphere through transpiration, or removal of water through the plant tissue, and evaporation of water from the surrounding soil surface.

Soil water characteristics required by the program are site-specific and must be provided by the user. Weather data may be entered manually into the computer or transferred directly from a local weather station. Rainfall and irrigation measurements must also be supplied by the user.

To predict soil water for a given field, SCS-Scheduler requires an initial estimate of the available water capacity (AWC) of the soil, daily climatic data to determine crop evapotranspiration (ET), and daily precipitation records. These parameters are discussed below (Shayya and Bralts 1994).

1. Soil Water

The principal measure of soil water used in SCS-Scheduler is the available water capacity, AWC, which is the difference between the amount of water contained in the soil at field capacity and the amount of water held in the soil at the permanent wilting point. This quantity may be expressed in terms of total depth of water in a column of soil or as a percent of the maximum AWC.

2. Root Growth

SCS-Scheduler calculates soil water available in the root zone. Rates of root growth are established for each crop to be scheduled. As the rooting depth increases, SCS-Scheduler uses the available water in each added soil increment. The available water capacities of these soil increments are defined by the user.

3. Evapotranspiration Estimation

Most methods for computing crop ET involve the basic equation:

$$ET = K_d (K_c ET_0) \tag{2}$$

where ET_0 is the reference evapotranspiration, K_d is a coefficient that depends on the available water capacity of the soil, K_C is the crop coefficient that varies with the growth stage of the crop, and ET is the crop evapotranspiration.

Daily weather data are used by SCS-Scheduler to estimate crop ET. Future ET predictions are based on historical or estimated weather data.

4. Precipitation Records

Irrigation and rainfall events are incorporated into the farm file for a given field at each scheduling session.

Irrigation Efficiency

Irrigation water supply and the respective crop demand for water constitute two principal components in irrigation water use evaluation. These components are often combined to provide the standard measure for irrigation efficiency. For the purpose of this study, actual irrigation efficiency (EFF_a) is defined as the ratio of (actual) crop water demand to irrigation supply and is expressed as

$$EFF_a = 100 \frac{ET_a}{(IRR + P_e)} \tag{3}$$

where, ET_a is the actual crop evapotranspiration (mm), IRR is the total irrigation supply (mm), and P_e is the effective precipitation (mm). Conveyance seepage losses are assumed to be negligible within the plot. When applied to an individual plot, EFF_a provides a measure of actual farmer water use performance.

However, irrigation efficiency values which are frequently used to compare performance among systems and/or between geographic regions are often based on a theoretical or design evapotranspiration value for crop water needs (as opposed to actual evapotranspiration, ET_a). Generally, a maximum evapotranspiration value (ET_{max}) is used to establish this design limit or requirement for each crop type, and it is usually obtained by applying crop coefficients to potential evapotranspiration (ET_0) for various stages of crop development (i.e. assuming $K_d = 1$ in equation 2). A "design" efficiency (EFF_d) can therefore be obtained by replacing ET_a in equation 3 with a value for ET_{max}. Although EFF_d values are also derived in this paper, it should be understood that design demand values (ET_{max}) are frequently used in system planning and for (generalized) comparative purposes among irrigation systems. But they may be less useful in measuring farmer irrigation performance, particularly in cases where farmers may view optimal production at evapotranspiration rates below design crop demand (Norman and Walter 1993).

RESULTS AND DISCUSSION

Figures 1-6 depict the available soil moisture regimes for all monitored plots, as generated by the soil moisture budget model. It should be noted that Figures 1-4 depict the entire cropping cycle for wheat, while Figures 5 and 6 depict 11 months of soil water management for perennial date palms. All water within *aflaj* systems is owned by participant farmers in the form of water shares. These shares are usually divided into half-hour time units *(athars)* and farmers have access to their shares on a fixed rotation interval (the *dawran*). At Falaj Hageer, the *dawran* is 7 days. Thus, all plot irrigations are spaced at 7 or 14 day intervals, according to farmer choice or crop need.

The period of highest reference ET (ET_0) occurs during the 7 months from April to October. Average daily ET_0 during the remaining 5 months from

November to March may be as low as half of that of the high ET_0 months. During this period, the cultivation of non-perennial crops (usually wheat) is practised in *awabi* land. In most years, this occupies 20%-30% of the total cultivated area of the *falaj*. The extent of cultivated area in *aflaj* is generally a function of the base flow of the main *falaj* delivery channel. At Hageer, rainfall within the system's catchment watershed may result in a significant, yet short-lived, increase of delivery flow of the source spring (usually lasting a week or less).[3] When this occurs, farmers may have no choice but to apply excess amounts of water within their plots during their weekly water share delivery period. This is because farmers have no means for storing large, excess volumes of water. Irrigations for date palms occurring on 13/3, 20/3, 5/6, 12/6 and 18/7 in Figure 5 are exemplary of this practice. One finds that among plots whose owners have a number of other holdings within the system, these excessive irrigation applications are less pronounced because farmers can divide the "excess" among a greater number of plots. Figure 6 is an example of such a plot where the farmer's water shares must be (or can be) divided among four or more plots within the system.

At Falaj Hageer, most rainfall events within the system's contributing watershed occur just after the growing season for wheat. This can be noticed by comparing rainfall and high irrigations that occur before and after March, 1996 in Figures 5 and 6. For this reason, the evaluation of irrigation water management practice among wheat plots may provide a better assessment of farmer water use performance since periods of "excess" *falaj* delivery flows are infrequent.

Table 1 provides a summary of the components of seasonal water use for monitored plots as well as measures of irrigation efficiency and yield, Actual irrigation efficiencies (EFF_a) range from 64%-107%, with a mean of 87%. EFF_d values are approximately 10% higher. There is probably a significant variation of EFF_a among plots throughout the system, due to the aforementioned variance in the extent of demand (i.e. the total number of system holdings per farmer) on the farmer's water shares. Nevertheless, the mean on-farm EFF_a for the system as a whole is probably relatively high (80% or greater).

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[3]These temporary "surge" flows are more pronounced in *"ghayli" aflaj* systems (whose source is wadi base flow), while they are less pronounced in *"daoudi" aflaj* systems (whose source is a mother well).

[4]This excess water is applied directly to the field plot, even if it will eventually be lost as excess subsurface drainage or as surface runoff. Traditionally, it is considered unsuitable practice among farmers at Falaj Hageer to allow water (including "excess water") to discharge directly from the *falaj* channel into uncultivated areas or outside of the system.

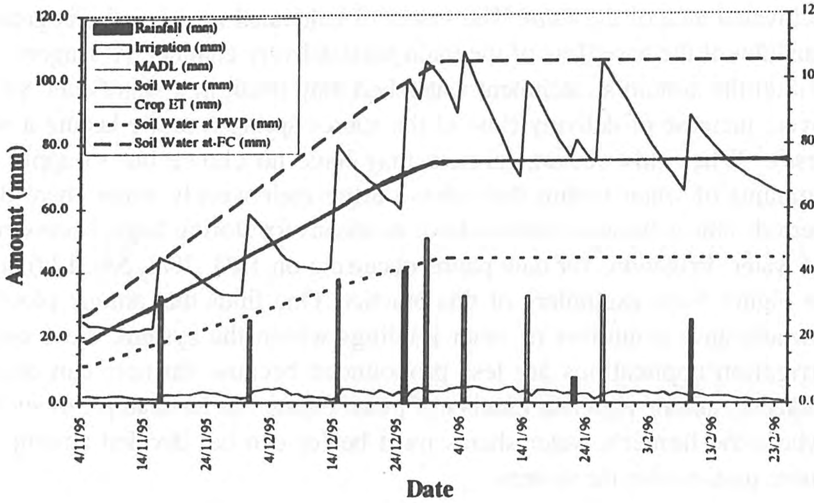

Figure 1. Soil moisture budget for wheat in plot W1.

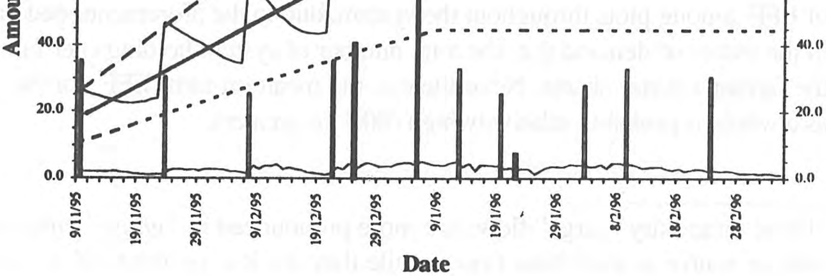

Figure 2. Soil moisture budget for wheat in plot W2.

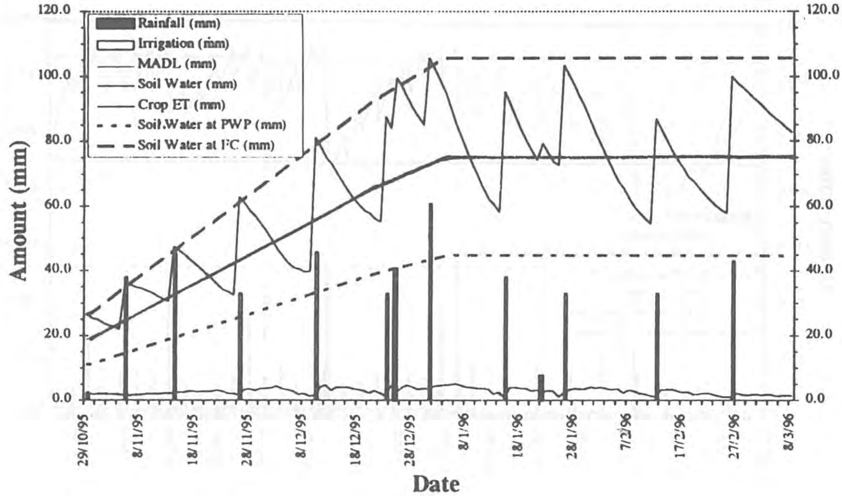

Figure 3. Soil moisture budget for wheat in plot W3.

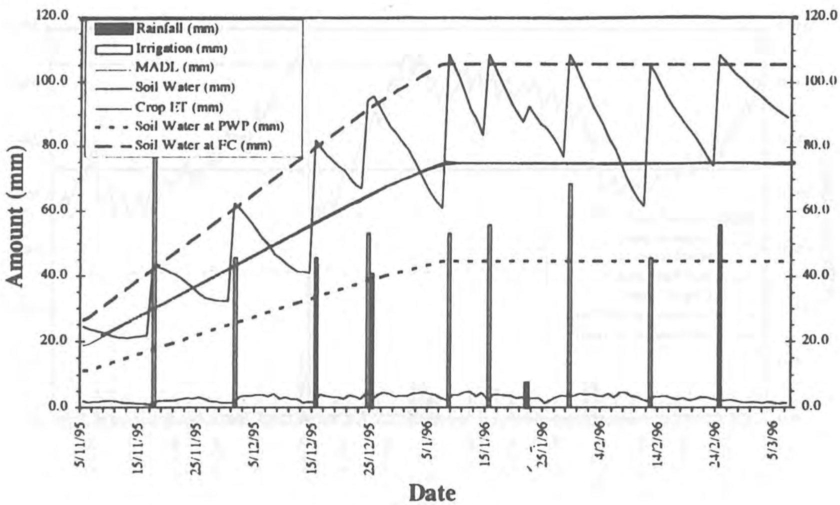

Figure 4. Soil moisture budget for wheat in plot W4.

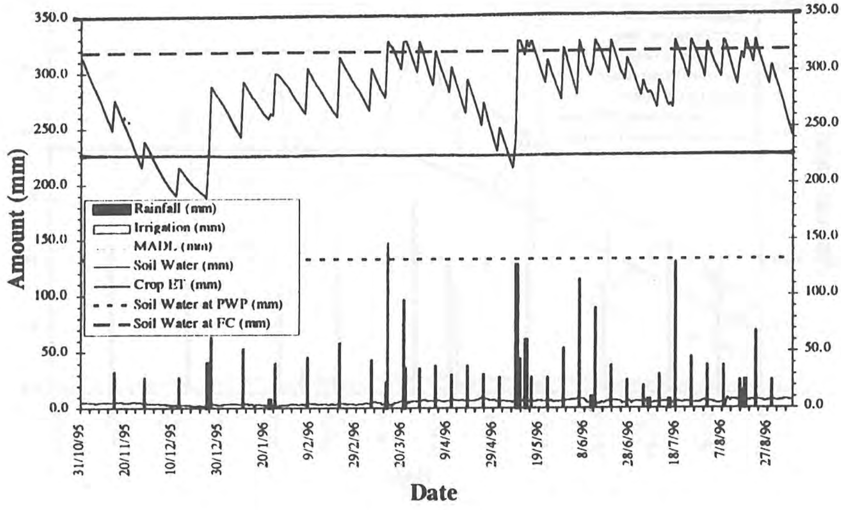

Figure 5. Soil moisture budget for date palms in plot D1.

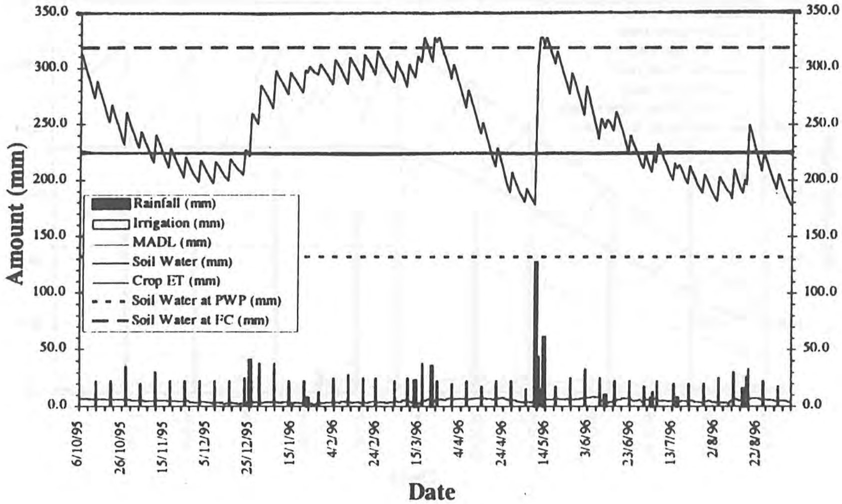

Figure 6. Soil moisture budget for date palms in plot D2.

Table 1. Soil Moisture Balance Components, Irrigation Efficiencies and Yields from Monitored Plots

	Plot Number						
	W1	**W2**	**W3**	**W4**	**D1**	**D2**	**Mean**
Crop	wheat	wheat	wheat	wheat	dates	dates	—
Area (m^2)	419	520	365	249	465	299	386
Et_{max} (mm)	344	358	411	377	1599	1754	—
ET_a (mm)	305	332	358	345	1577	1592	—
P_e (mm)	48	28	24	10	262	337	—
IRR (mm)	272	333	406	531	1666	1148	—
EFF_d (%)	108	99	96	70	83	118	96
EFF_a (%)[5]	95	92	83	64	82	107	87
Yields (T/ha)	3.7	3.7	4.3	3.9	25	29	—

Plots W1 and W2 had the highest efficiencies for wheat, with W1 incurring a deficit (i.e. EFF_d in excess of 100%) with respect to potential crop demand. For both plots, water may be the limiting factor which resulted in the slightly lower yields than plots W3 and W4. Where water delivery to the root zone is not as limiting (e.g. W3 and W4, with lower EFF_d values) other factors may have a greater effect on yields (e.g. fertilizer levels, etc.). A comparison of Figures 1-4 indicates that W3 performed better in the first half of the crop cycle than the other wheat plots. With the exception of W3, which has the highest yield, most deficits below the 50% MADL (management allowed depletion level) occurred before plant maturity (i.e. before early January). However, some depletion of readily available soil moisture during the post-maturity period does not seem to have adversely affected crop yields.

As indicated earlier, excess irrigations may occur more frequently among perennial date palm plots than for non-perennial wheat, cultivated when rainfall events are less frequent. However, the extent of the occurrence of excess irrigations may be dependent on the water demand (of other plots) on the water shares of the plot owner. This is particularly evident between D1 (EFF_a = 82%) and D2 (EFF_a = 107%), where D2 has considerably more demand (in terms of the number of other plots) on allotted water shares than D1 (also compare Figures 5 and 6). The EFF_a of 107% in D2 also indicates that soil moisture is usually being maintained at a level which results in some water savings. This may not be optimal for obtaining maximum potential yield, but D2 nevertheless

[5]Perhaps it should also be noted that the lower EFF_a of 64% for W4 is due primarily to a single "excess" irrigation on 18/11 in which more than twice the usual irrigation dose was applied. Had a normal irrigation depth been applied on this day, EFF_a and EFF_d would have been 72% and 79%, respectively.

had a higher yield than D1 - which indicates that factors other than water may be involved (e.g. disease, pests, tree spacing, date variety, and etc.).

A review of the soil moisture regimes for dates in Figures 5 and 6 indicates that soil moisture levels are brought up to field capacity only when a rainfall event occurs which affects the cropped area both directly and indirectly. While the direct effect is obvious due to an additional precipitation event in the field, the indirect effect of a rainfall event results in a significant increase (although temporarily) of *falaj* delivery flow and a subsequent increase in irrigation water. The indication is that in a dry year it is possible that soil moisture in many date palm plots may be maintained below MADL's of 50% when there is little rainfall in the cropped area or in the *falaj* watershed. This is demonstrated when the soil moisture budget is generated for D2 *without* rainfall.[6] Figure 7 depicts this soil moisture regime where it is evident that soil moisture would not exceed 70% MADL during most periods.

Although it is beyond the immediate scope of the field research program at Falaj Hageer, it should be added that the relative cost or value of water to the farmer has an impact on the way he uses it. Data from a related study among farmers using wells in northern Oman indicate that there is an inverse relationship between the cost of irrigation water and the way in which it is managed (Norman et al. 1996). Among surface irrigation systems (in which wells are used) it was found that, when the cost to the farmer for irrigation water is low, there is a tendency for it to be used excessively. When water costs are relatively high and greater value is associated with it, water is used more conservatively. For most farms, only when the volumetric cost of water exceeds about 0.04 RO/m^3 (1 RO = 2.6 USD) would irrigation efficiencies (EFF_d) attain a level of 80% or better (Norman et al. 1996). Indigenous, traditional irrigation systems, such as those found in parts of Asia and Africa, are often very effective at minimizing risks, providing equitable access of water to users and assuring the efficient use of water (Coward 1977, Norman and Walter 1993, Norman 1995). The *aflaj* of Oman, in their historical traditional setting, apparently had most of these characteristics. And, in spite of the present-day threats to *aflaj* sustainability, these inherent strengths warrant closer study. Among the *aflaj* of Wadi Bani Kharus, the cost of water in 1995-1996 was about 0.10-0.15 RO/m^3 (when considering water share, system maintenance and labour costs). Given the data presented in Table 1, it is evident that mean efficiencies (EFF_d) are 90% or higher. Furthermore, due to the traditional importance of *aflaj* on community structure and organization, a better assessment of the *social* value of *aflaj* water among rural communities would perhaps also be warranted. It is probable that

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[6]Plot D2 was used to demonstrate this due to the absence of "excess" irrigation applications during temporary periods of high *falaj* flows.

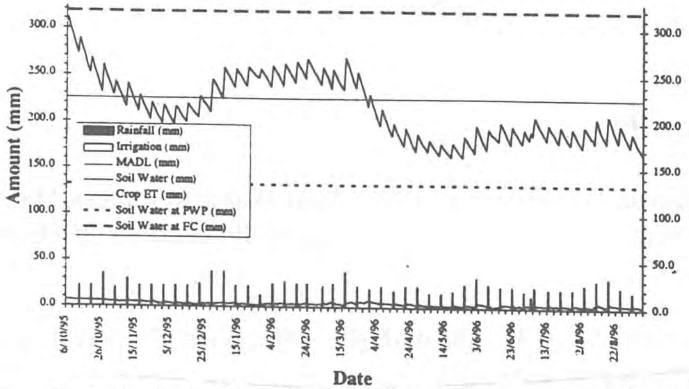

Figure 7. Hypothetical soil moisture budget for date palms wheat in plot D2, with supplementary rainfall removed.

the monetary value of *aflaj* irrigation water, alone, does not adequately reflect its full value within and among rural communities.

CONCLUSIONS

This study has demonstrated that on-farm irrigation efficiencies are relatively high in Falaj Hageer. Mean efficiencies which reflect farmer practices (EFF_a) are in excess of 80%, for both wheat and date palm crops. When "design" irrigation efficiencies (EFF_d) are considered, the values are even higher (considerably higher than the often-quoted efficiencies of 50% or less for traditional surface irrigation methods). It is likely that an important portion of surface-irrigated farms in the region do operate at low irrigation efficiencies, particularly those which have been developed in more recent years. But the case study at Falaj Hageer indicates that rural *aflaj* systems, in which traditional Omani management methods continue to be employed, may be operated at efficiencies considerably higher than presumed.

The data indicate that farmers understand how to manage water carefully when using traditional surface irrigation methods, in so long as flow rates (in particular, base flow rates) can be anticipated and remain within their control. Brief periods of "excess" flow resulting from periodic rains are, in a sense, beyond the control of the farmer. Consequently, high irrigation applications do not necessarily reflect a lack of management ability or a poor grasp of crop water need by farmers. More accurately, such "excesses" reflect a technical problem brought on by natural, environmental processes which are quite beyond local farmer capacity to control.

Finally, both the monetary and social value of water need to be given more adequate attention when considering water use performance levels within *aflaj* systems. For regional development planning, the relative value of water to the user should perhaps be given equal (if not greater) consideration to the methods(s) or technology used for on-farm irrigation.

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Effect of Soil Amendments and Water Quantity and Quility on Cumulative Evaporation and Moisture Distribution

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EFFECT OF SOIL AMENDMENTS AND WATER QUANTITY AND QUALITY ON CUMULATIVE EVAPORATION AND MOISTURE DISTRIBUTION

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ABSTRACT

Soil amendments are used to improve the water holding capacity of coarse textured soils and alleviate problems of infiltration and percolation in fine textured soils. The effects of peat moss and a cross linked gel-forming absorbent copolymer as soil amendments, on intermittent evaporation and moisture distribution through columns of a saline-sodic fine loamy soil, were investigated. Two water qualities (560 and 3,600 μScm^{-1}), two intervals (5 and 10 days) and two water application rates (3 and 6 mm day^{-1}) were used. After a threshold period which was longer for the lower rate of water application, cumulative evaporation (E) increased with the decrease in irrigation intervals and the type of amendment added in the order control> peat moss > the absorbent copolymer. The absorbent copolymer reduced evaporation by 18.4% and 10.2% over the control and peat moss respectively and conserved 30% more water over the control. Cumulative evaporation, E was defined as: $E = C, \sqrt{t}$, where C was largely determined by the water amount per irrigation and the soil amendment type. Soil water distribution was governed by the amount of water conserved. The quantity of water applied per irrigation, rather than the cumulative amount, seemed to affect water conservation. The quality of water applied, however did not significantly affect evaporation from the soil. Soil amendments studied reduced evaporation and conserved moisture.

INTRODUCTION

The addition of organic matter to the soil, either to the surface or incorporating in it, has shown to improve the soil structure and water holding capacity, and increase infiltration rates (Miller and Donahue, 1990). Top dressing with 10% or less by volume organic matter can improve infiltration, in poorly structured soils, and internal drainage in fine textured soils (Carrow et al., 1990). Applications of excessive organic matter (> 20%) could, however, produce an excessive wet soil by retaining considerable moisture, and soluble salt contents can hinder plant growth or be washed into the ground water (Andrian et al., 1971). Peat, a general name for many types of partially decomposed plant residues, is widely used in the desert sandy soils to improve their water holding capacities (Abdel Rahman and Abdel Majid, 1993). The most important peat forming plants are *sphagnum* spp. when subjected to climatic conditions of high precipitation and low evaporation, solar radiation and temperatures (Wallach and Chen, 1993). Synthetic polymers that absorb 40-500 times their own weight, developed from baby diaper technology, have been used to alleviate problems of water holding capacities of different soils, and were the subject of study by many researchers. Addition of water soluble polymers such as polyacrylamide (PAM), polyvinylalcohol (PVA), or bitumen emulsions to the soil surface tend to increase its aggregation and aggregate stability and reduce evaporation from the soil (Cheshire, 1979; Tisdall and Oades, 1982; Chaney and Swift, 1986). Johnson (1984) found that polyacrylatnide (PAM) reduced evaporation and increased available water of coarse sand, and the effects varied with type of commercial produced used. Tayel and El-Hady (1981) reported an increase in water supply to growing plants with an improvement in water use efficiency when using polymers as soil amendments. A hydrolysed starch polyacrylonitrile graft copolymer (super slurper) increased soil swelling and decreased infiltration. Hemyari and Nofziger (1981) reported a 38, 18, and 11% reduction in sorpitives of sandy loam, clay loam and loamy sand soils treated with 0.4% super slurper, respectively, with little effect on clay loams. Al-Omran et al. (1987) reported a significant increase in aggregation indexes (AI) and relative swelling indexes (RSI) of loamy sand, sandy loam, and clay loam soils with addition of an organic supergel at the rate of 0.4%.

In this study, the effects of a gel-forming copolymer and peat moss on intermittent evaporation and moisture distribution under different water qualities and quantities were investigated, in an effort to reduce evaporation from the soil and hence conserve soil water.

MATERIALS AND METHODS

A 150-cm profile was dug in a fine textured saline-sodic soil of the Batinah area in the Sultanate of Oman. Field methods of feel and appearance were used to classify the profile into four horizons: 0-20, 20-44, 44-95, and 95-150 cm. Soil horizons were identified by the systematic analysis of their main characteristics using methods described by Klute (1986). The soils were classified as typic salorthid, fine loamy, mixed, hyperthermic soils. The bulk densities were determined using the core method and the resultant bulk densities of the four horizons were 1.19, 1.26, 1.32, and 1.37 Mgm-3, respectively. Soil samples were collected from the four horizons, air dried, thoroughly mixed, crushed, and passed through a 2-mm sieve. Forty-eight columns, each 5 0 cm long, were assembled from PVC sections 10 cm long and 8.5 cm in inside diameters, held together with adhesive tape. Each column was closed at one end with a firmly held piece of cloth. The four samples were then packed uniformly in the same sequence they occur in the soil profile, so that each layer occupied 10 cm of the column length. Packing was done by adding the soil in small aliquot and dropping the column a known number of times over a vertical distance of 5 cm on a levelled support to give the bulk densities representing field conditions.

The top layers (0-10 cm) of 32 columns were treated with peat moss (< 2 mm) and cross linked polymer (Water Works, produced by Water Works America, Inc., Cleveland, OH)[1], amendments, 16 columns each, before packing. Peat moss was added at the rate of 45 tons per hectare (25 grams per column), whereas the recommended rate of the polymer (2 pounds per cubic yard) was applied, amounting to 0.6 grams per column. The last 16 columns were left untreated (control).

Saline water (EC = 3,600 μS/cm) and non-saline water (EC = 560 μS/cm) was applied at two rates (R), 3 and 6 mm day^{-1}, and two intervals (I), 5 and 10 days. The total amount of water actually applied on the day of irrigation was the product of the rates times the irrigation interval. Treatments were replicated twice and the soil columns were maintained in a vertical position and arranged randomly in an open but protected area. Water was applied gently over a glass rod to prevent soil puddling. Mean daily temperatures of 26.6^{o}C, average daily humidity of 66.3 %, average daily wind speeds

[1]The use of trade and firm names is for the information and convenience of the reader. Such use does not constitute an official endorsement of the product.

(U_2) of 2.0 m/sec and Piche evaporation of 8. 4 mm/day prevailed during the period of study. Soil water evaporation was determined by daily weighing of each soil column. Gravimetric measurements of the soil water distribution were made at the end of the total irrigation periods, 35 and 40 days.

At the given time each of the appropriate columns was sectioned and the soil of each section was transferred to a weighing can to determine its moisture content.

RESULTS AND DISCUSSION

The results of the physical and chemical analysis of the soil samples collected from the profile are given in Table 1.

Table 1. **Physical and chemical properties of the soil samples**

Depth cm	Particle-size distribution, %			pH paste	$EC^{1:5}$ MS/cm	SAR (meq/L)'
	Clay	Silt	Sand			
0-20	12.2	51.7	36.1	7.8	16.83	92.1
20-44	8.2	67.4	24.4	8.0	7.91	57.9
44-95	28.1	53.0	18.9	7.8	7.06	57.8
95-150	37.7	38.7	23.6	8.1	3.99	20.8

These results reveal the problematic nature of these soils which were rendered saline-sodic by sea water intrusion into the ground aquifers due to over pumping of the groundwater in the Batinah area of Oman (Abdel Rahman et al., 1993).

Intermittent evaporation

The cyclic cumulative evaporation (E) versus time relationships as affected by the soil amendments, water quality, and the interactions of the application rates and intervals, are given by Figures 1-4. At the end of the 7th drying cycle the cross-linked polymer reduced evaporation by 18.4 and 10.2 per cent over the control and peat moss, respectively (Figure 1). Peat moss reduced evaporation by 9.1 % over the control. Regression analysis showed that for each drying cycle, E was a function of the square root of time: $E = C\sqrt{t}$. The values of C and hence E was in the order control > peat moss > the absorbent copolymer (Figure 2). During the early cycles, the values of the cumulative evaporation constants C were closer for all treatments. The differences in C values, and hence evaporation, between treatments became progressively greater with the drying cycle. It can be seen that C values increased with time and approached a constant value at the end of the drying cycles. With time, swelling of peat moss and the absorbent copolymer granules might have allowed water to penetrate deeper, reducing evaporation. This seemed to be more pronounced with the absorbent copolymer than peat moss. The water quality had no profound effect on water evaporation from the soil as illustrated by Figure 3. Similar behaviour of the cyclic trend was obtained from all treatments irrigated with saline water (3,600 μScm^{-1}) and non-saline water (560 μScm^{-1}) with almost identical C values. The slight variation could be attributed to the improved penetration of the saline water into the soil, hence marginally decreasing evaporation. Figure 4 shows that the higher water application rate (6 mm per day) gave more evaporation than the lower rate (3 mm per day) all the time for the lower interval (5 days). With the higher interval (10 days), the 6 mm per day yielded more evaporation than the 3 mm per day only for the first eleven days, after which a reverse trend emerged. The longer the interval the greater was the quantity of water applied per irrigation and made readily available for evaporation. At first, the water apparently did not penetrate deep enough and thus remained within reach of the evaporating surface. With the advance of time, the water penetrated deeper and the reverse trend emerged, indicating an increase in E with decrease in the rate after the 11th day. With the lower application rate (3 mm per day), E increased with an increase in the interval for the first 26 days, after which the reverse trend was established. With the higher application rate (6 mm per day) the reverse trend was established only after 5 days. More water was added per application with increased intervals, and more water was thus conserved because of deeper penetration into the soil. The soil developed more and more relatively deeper cracks that facilitated water penetration and hence reduced evaporation. It can be stated that E increased with a decrease in irrigation interval after a threshold which was longer for the lower rate of water application; 26 days for 3 mm per day applications and 5 days for 6 mm per day.

Soil water distribution

The cumulative evaporations at the end of the drying cycles and the percentage of water conserved under different experimental conditions are given in Table 2.

Table 2. Cumulative evaporation (E) and percentage of water conserved (% WC) at the end of (N) drying cycles as affected by soil amendments and irrigation interval and water application rate (1 x R)*.

	1_1R_1			1_1R_2			1_2R_1			1_2R_2		
	IxRxN mm	E mm	% WC	IxRxN mm	E mm	% WC	IxRxN mm	E mm	%WC	IxRxN mm	E mm	% WC
Control	105	65.7	37.4	210	96.9	53.9	120	65.3	45.6	240	49.6	79.3
Peat Moss	105	59.8	43.0	210	88.8	57.7	120	57.5	52.1	240	45,8	80.9
Absor-bent copolymer	105	54.1	48.5	210	79.9	62.0	120	51.0	57.5	240	40.6	83.1

I_1= 5d, I_2= 10d, R_1=3 nun day^{-1}, R2=6 mm day^{-1}, N=7 for I_1 and 4 for I_2.

The cross linked polymer conserved more water than peat moss which in turn was better than the control. The higher the amount of water applied, the higher was the amount of water conserved, but the lower was the percentage of water conserved by the absorbent copolymer over peat moss and the control. The absorbent copolymer gave 29.7, 26.1, 15.0, and 4.8% increase in water conserved over the control when a total of 105, 120, 210, and 240 mm of water were applied, respectively. The higher the total amount of water added, the deeper it penetrated into the soil, and the amendments being applied to the top soil become less effective in water conservation. Soil water distribution was governed by the amount of water conserved. Factors that reduced E caused more soil water conservation and consequently more soil water distribution. The analyses of variance of the main effects on soil water distribution are depicted in Table 3.

Table 3. Soil water content as affected by soil amendments, water quality, application rate and interval, and its distribution through the profile for different amendments.

Treatment	Water Quality μScm^{-1}		Application Rate (mm day^{-1})			Interval (days)			Depth (cm)				
	560	3600	3	6	L.S.D.	5	6	L.S.D.	0-10	10-20	20-30	30-40	L.S.D.
Control	A 19.7 b	A 21.8 b	B 16.7 c	A 24.8 b	6.0	B 17.5 b	A 24.0 b	6.1	D 9.0 c	C 16.2 c	B 23.6 c	A 34.1 b	6.0
Peatmoss	A 27.3 a	A 27.4 a,b	B 23.5 b	A 31.3 a,b	6.9	B 21.9 b	A 32.9 a	6.6	D 11.7 b	C 22.2 b	B 32.4 b	A 43.3 b	5.8
Absorbent copolymer	A 34.4 a	A 34.5 a	B 29.5 a	A 39.3 a	8.6	B 28.9 a	A 40.0 a	8.5	D 15.0 a	C 28.3 a	B 40.1 a	A 54.4 a	7.2
L.S.D	7.5	7.5	55	8.6.		6.0	8.0		1.0	5.4	6.6	9.5	

The effects of the irrigation interval, rate, amendments, and their interactions were found to be highly significant, whereas the water quality made no significant difference. Differences in the soil water content with depth were also found to be highly significant. As the application rate and interval decreased, the moisture content increased. The absorbent copolymer resulted in higher moisture retention, and hence higher water conservation. The higher the application rate and/or irrigation interval, the higher was the soil water retained, which significantly increased with depth for all treatments,

As revealed by Table 4, the amount of water applied per irrigation, however, seems to have made the significant difference, rather than the total amount of water applied.

Table 4. Soil water content as affected by the interactions of the application rates and intervals.

	MC %		
	R_1	R_2	LSD
I_1	B 19.6 b	A 25.9 b	5.1
I_2	B 26.9 a	A 37.7 a	6.7
LSD	4.7	7.0	

Figures followed by the same letters are not significant at the 5% level. Capital letters for rows and small letters for columns.

Applying 60 mm per irrigation(I_2R_2) significantly increased the moisture conserved in the profile, but applying 30 mm per irrigation either as I_1R_2 or I_2R_1, gave the same results whether a total of 210 mm was applied in 7 irrigations with I_1R_2 or 120 mm was applied in 4 irrigations with I_2R_1, without any significant differences (Table 4). The water quality had no significant effect, and irrigating with water having an EC of 560 μScm^{-1} gave similar results of evaporation losses and moisture conservation as irrigating with water having an EC of 3600 μScm^{-1}.

CONCLUSION

Cross linked polymers proved to be efficient in soil water retention and water conservation. These findings are in agreement with those of Al-Omran et al. (1987) who reported that a similar product improved aggregate stability of the surface treated layers, suppressing evaporation. Peatmoss, however, was significantly effective in leaching salts, down the soil profile, than the copolymer. This is in line with the reports by Miller (1979) who found that super slurper increased soil swelling and decreased infiltration, and those of Al-Omran et al. (1987) who indicated that the pronounced swelling of the organic super gel reduced the size of macro pores, limiting infiltration. In contrast to reports by Reeve and Bower (1960) and Vander Pluyan et al. (1973), moderately saline water did not enhance leaching, possibly because the predominant salt in the irrigation water was sodium. As reported by Dahab et al. (1988) salt leaching was improved as time progressed and the amount of water applied increased. The soil water conserved, however, was dependent on the amount of water applied per irrigation. Cross linked polymers proved to be efficient in soil water retention and water conservation. Laboratory and field investigations may prove to be useful in understanding the performance of synthetic and polymer gel-forming soil amendments. The second part of this study investigates their effects on salt and SAR redistribution.

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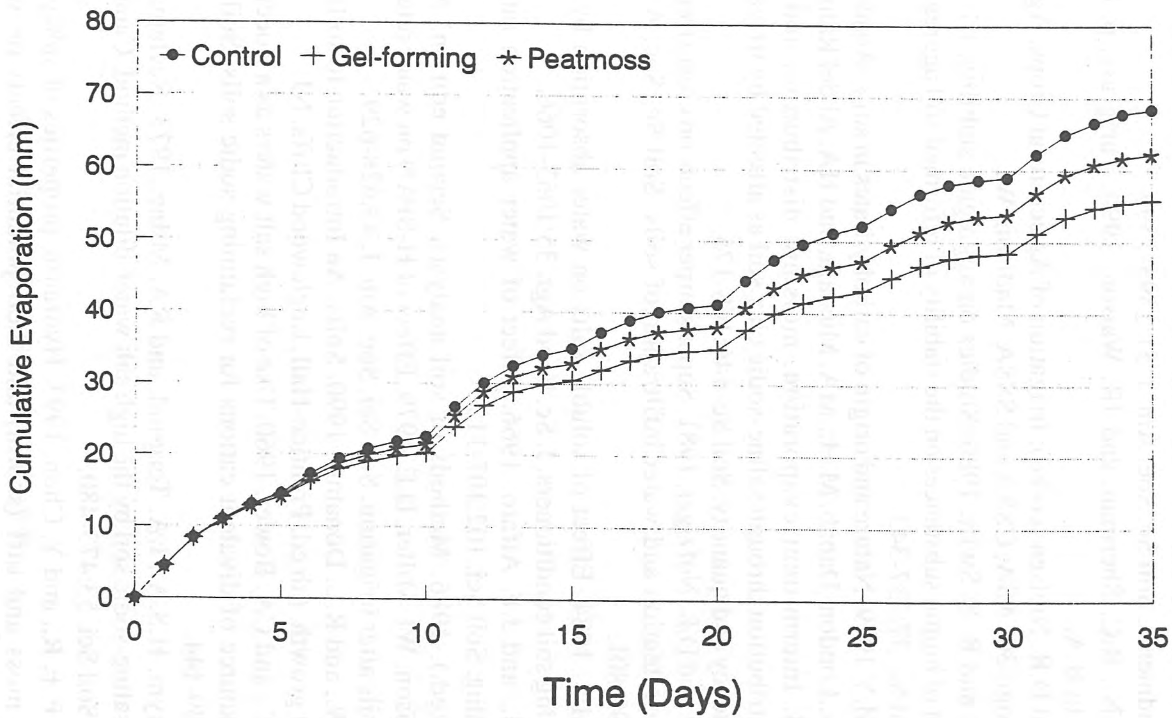

Figure 1. Cumulative evaporation versus time as affected by soil amendments. Each point is the mean of 16 determinations.

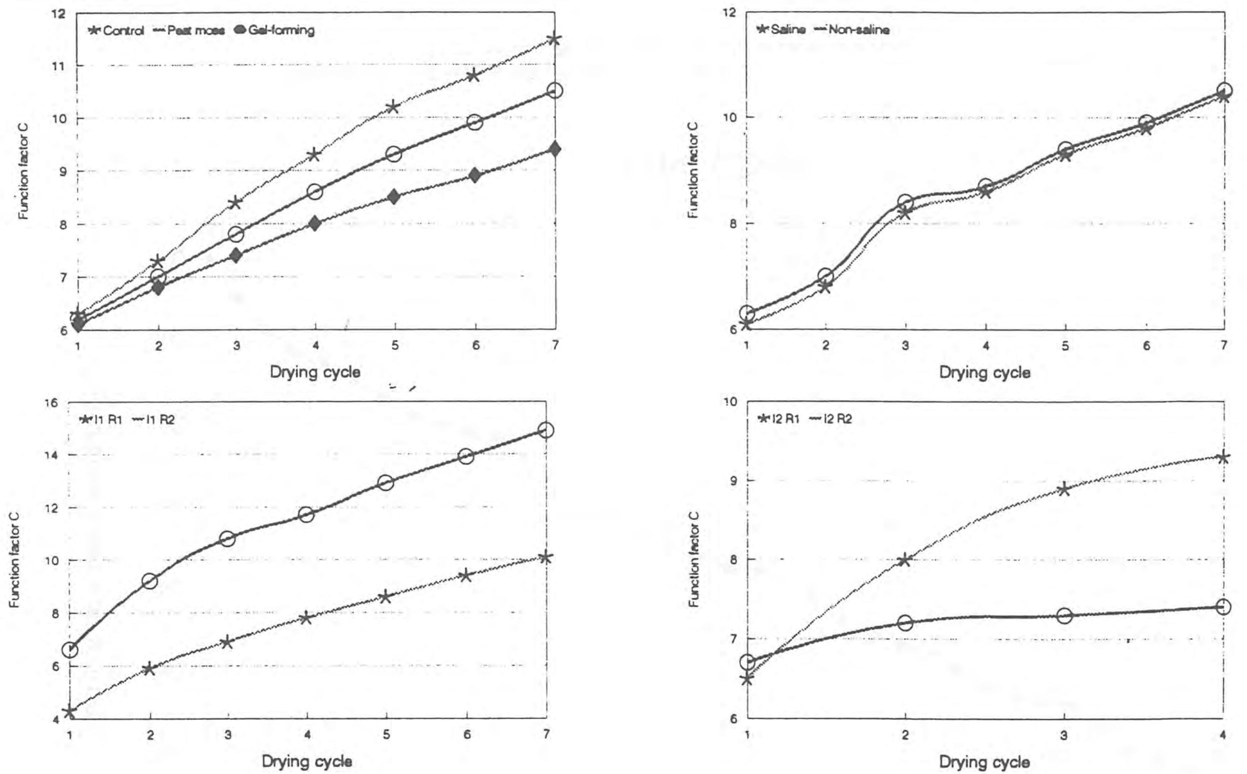

Figure 2 . Regression analysis function factor (C) depicting cumulative evaporation (E) versus square root of time ($E = C\sqrt{t}$).

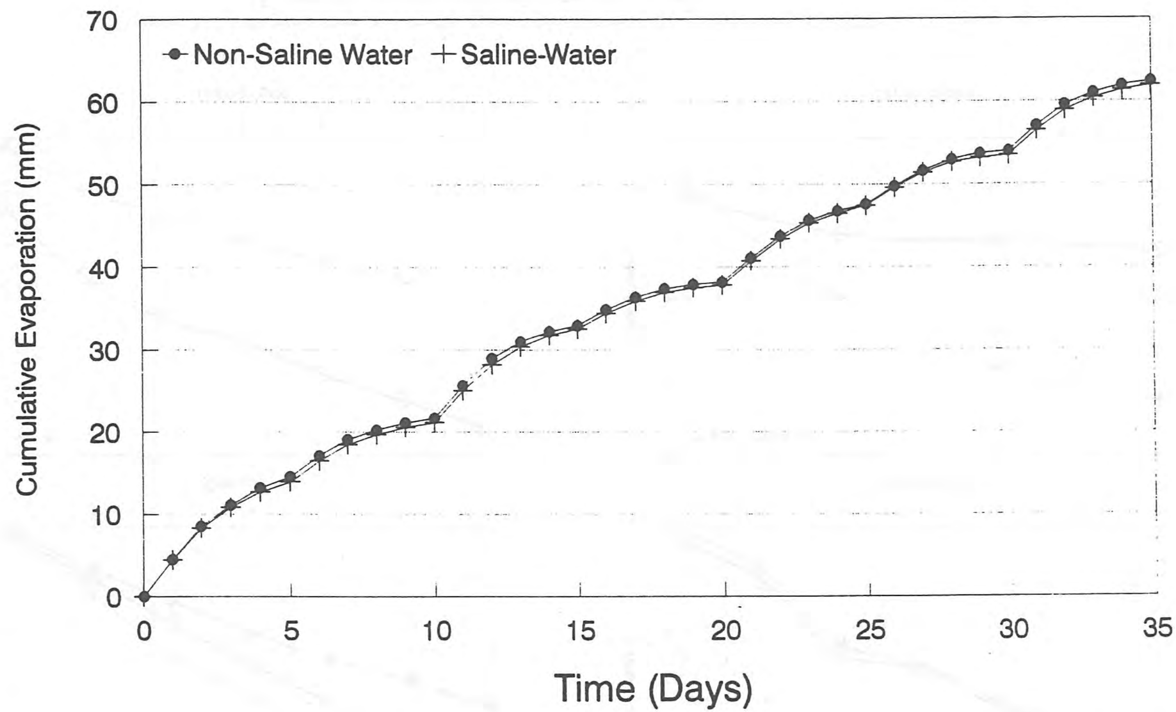

Figure 3. Cumulative evaporation versus time as affected by water quality. Each point is the mean of 24 determinations.

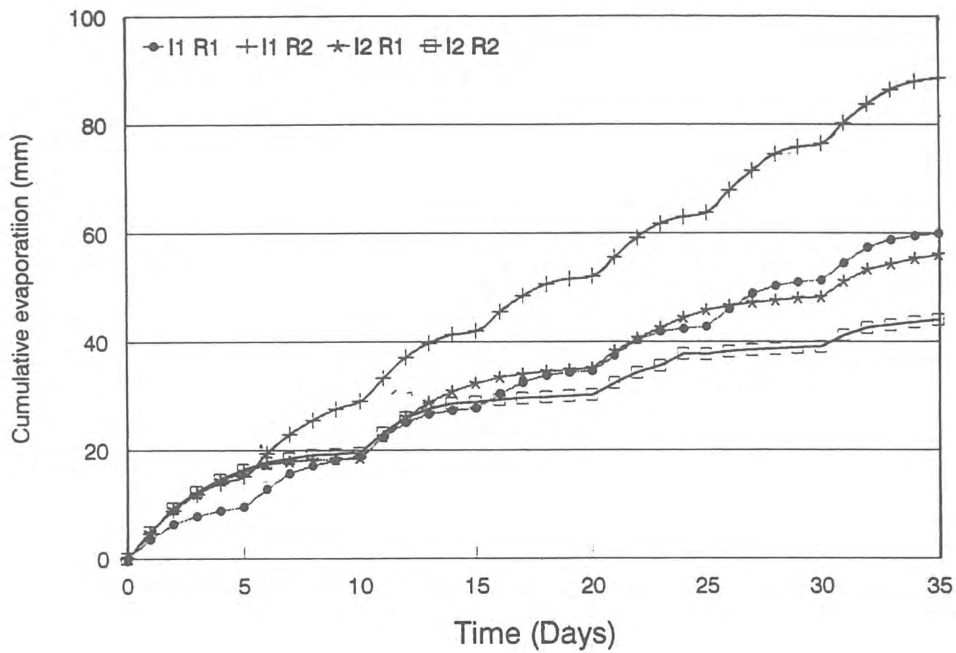

Figure 4 . Cumulative evaporation versus time as affected by the interactions of irrigation interval and rate. Each point is the mean of 12 determinations.

Irrigation Water Quality and Frequency Effects on Cowpea (Vigna Unguiculata L.) and Soybean (Glycine Max L.) Yields

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IRRIGATION WATER QUALITY AND FREQUENCY EFFECTS ON COWPEA (Vigna unguiculata L.) AND SOYBEAN (Glycine max L.) YIELDS

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ABSTRACT

Cowpea and soybean plants were planted in a loamy sand soil. A randomized split-split plot was designed with water quality as main plots, irrigation frequency as subplots and nitrogen phosphorus fertilizers as sub-sub plots. The three irrigation water qualities tested were canal water (EC=2.8-3.3 dS/m), drainage water (EC= 13.417.7 dS/m), and mixed canal and drainage water (8.0 - 10.6 dS/m) with 1:1 ratio. Two irrigation frequencies (F1=4 and F2=7 days) and three rates of nitrogen application were also tested.

Cowpea seed yield was significantly reduced by irrigation with drainage water but the reduction was less with mixed water application. Increased irrigation frequency of 4 days significantly increased seed yield and reduced the accumulation of salts at both surface and subsurface soil. The high rate of nitrogen application under both drainage and mixed waters increased number and weight of nodules besides the increase in seed yield.

Similarly, soybean yield increased significantly at F1 and nitrogen rates of 250 kg/ha and 350 kg/ha. Clearly, drainage water was not suitable for either cowpea or soybean production. However, the mixed water would be suitable for irrigation of those crops especially at 4 days frequency and high rates of nitrogen fertilizer application.

Keywords: Saline irrigation water, drainage water, cowpea growth and soybean growth.

INTRODUCTION

There is an increasing tendency to use more saline irrigation water in the arid and semi-arid regions of the world where supplemental water is needed to intensify agriculture. The low soil moisture and the high salinity affect about 28% of the world's soil (Dudal, 1976) and osmotic and matric stresses often occur simultaneously. Thus, irrigated agriculture faces the challenge of using less water, in many cases of poorer quality, to provide food for an expanding population (Oster, 1994).

The salt tolerance of the crop and the salinity of irrigation water are the two bases that determine the appropriate crops for irrigation (Ayers and Westcot, 1985; Mass, 1990; Pratt and Suarez, 1990). In irrigated agriculture it is vital to prevent salt build up in the root zone beyond salinity limits that a given crop can tolerate (Papadopoulos and Rending 1983; and Papadopoulos et al. 1985). Gungoretal. (1993) found that soybean yield and oil content decreased but mineral composition increased with increasing salinity. Protein contents were not affected by salinity.

Salinity-fertility relationships are of great economic importance and have been the subject of many greenhouse and field studies (Bernstein et al. 1974; Kafkafi, 1984; Kafkafi et al. 1982; and Papadopoulos and Rending, 1983). These studies were conducted to evaluate improved fertilization management as a means of alleviating growth inhibition due to salinity. The research work resulted in different and even contradictory conclusions. Positive, negative, and no effects of fertilization on crop salinity tolerance were found.

The objectives of this study were to evaluate the effects of the irrigation water qualities on growth and yields of cowpea and soybean. In addition, the interactive effects of irrigation salinity, irrigation frequency, and nitrogen fertilizer on crop tolerance were also investigated.

Materials and Methods

The soil chosen for this experiment is located on the Eastern region of Saudi Arabia at Al-Hassa Oasis. In this region the maximum air temperature ranges from 34-43.5°C whereas, the minimum air temperature ranges from 26.4-34.2°C and the pan evaporation ranges from 8.6-17.3 mm/day during the growing season. The soil texture is loamy sand as determined by the procedure of Gee and Bauder (1986). The two crops under investigations are cowpea (California Black eye Number 5 or CB5) and soybean (Cutler 71). For each crop the field was divided into three main plots for the three irrigation water quality treatments tested. The irrigation waters were canal irrigation water (1), mixed irrigation and drainage water (M) at 1:1 ratio, and drainage water (D) with electrical conductivities ranging from 2.8-3.3, 8.1-10.3, and 13.4-17.7 dS/m respectively. Each main plot was divided into six sub-plots for two irrigation frequencies (F1 = 4 days and F2 = 7 days) with three replicates each.

Basin flood irrigation was used with three PVC main lines. The irrigation and drainage water were pumped from a canal and drainage ditch to their mainlines, The mixed water was pumped from a tank filled to its half with canal water and completed the other half with drainage water using 7.5 HP electric pumps.

For cowpea *(Vigna unguiculata L.)* experiment each subplot was 2.5 x 4 m with four rows each. Three rates of nitrogen fertilizer N1, N2, and N3 were applied as urea at the rates of 150, 250 and 350 Kg/ha-N respectively. In addition, phosphorus was applied as superphosphate at the rate of 45 Kg/ ha-P. Four seeds per hole were sown at 10 cm within row spacing (Warrag, 1988) on March 9th. After planting, 7 cm of canal irrigation water was applied to ensure good germination and establishment. Since the availability of some good quality irrigation water, particularly before and after planting (Pasternak et al., 1986; Mass and Poss, 1989) could facilitate the use of moderately saline irrigation water. After two weeks the plants were thinned to two plants per hole then the three irrigation water qualities (I, M, and D) were imposed.

At maturity, number of pods per plant was recorded. Seeds were oven dried (80°C for 48 hrs) and the number of seeds per pod, weight of 100-seed, and total seed yield were determined. In addition, number and weight of nodules were determined.

For the soybean *(Glycine max L.)* experimental plots were inoculated with appropriate nitrogen commercial granular inoculant at 10 Kg/ha and soybean was seeded on March 5th at rate of 60 Kg/ha in four rows per plots, both N and P were applied at the same rates used with the cowpea experiment. The quantity of water required for irrigation of either crop at the experimental area was specified in the study of Ministry of Agriculture and Water, Riyadh (1986). It were 6400, 7900 and 9400 m^3 ha/month for canal, mixed and drainage water, respectively.

At maturity roots and nodules were dried (80°C for 48 hrs) and weighed. Number of pods and nodules per plant were recorded. Weight of pods and nodules were determined. Then 100-seed weight and the seed yield were determined. In addition, the total soil salinity of the saturation extract at the surface (0-25 cm) and subsurface (25-50cm) layers at the beginning and end of the experiment were measured (Figures 2 and 4) using the procedure described by Rhoades (1982). All parameters were averaged over the two year study. Analysis of variance of the data was performed and the means were compared at 5% probability level.

RESULTS AND DISCUSSION

The cowpea seed yield decreased significantly in response to the three water qualities used (Table 1). In comparison to the canal water, seed yield was reduced 13% by the mixed water and 75% by the drainage water. The seed yield reduction was attributed primarily to the reduction in the number of pods per plant. These are in agreement with the response of other bean cultivars (Csizinsky, 1986; Coons and Pratt, 1988). Increased salinity significantly decreased the number and dry weight of pods. The decrease in 100-seed weight (Table 1) was the main cause for the seed yield reduction.

The correlation between seed yield and either pods number per plant (r=0.76*) or pods weight (r=0.86**) indicated that both parameters are important regulators of cowpea seed yield. Among the other evaluated yield components the pods number per plant showed the most change in response to water quality. That was in agreement with cowpea and other grain legumes (Herbert and Litchfield, 1982; Shouse et al. 1981; and Turk et al. 1980) which showed that, the pods number per plant was the most sensitive component to environmental stress.

Table 1. Means of Cowpea yield and yield components for single effects of water quality, irrigation frequency, and rate of nitrogen fertilizer.

Treatments tons/ha	Seed yield per plant	Pods per meter	Pods wt.	100-seed wt.(g)	Nodulesperplant Numbers	Wt. (g)
Water quality						
I	2.15a	4.3a	380.2a	23.0a	35.0a	82.0a
M	1.86b	3.6b	304.2b	20.2b	28.3b	65.5b
D	0.53c	1.8c	101.8e	14.0c	7.5c	12.8c
Irrigation frequency						
F1	1.57a	3.4a	278.7a	20.0a	26.6a	60.1a
F2	1.45b	3.0b	251.6b	18.1b	20.5b	46.7b
Nitrogen fertilizer						
N1	1.16c	3.0c	219.8c	18.3b	19.6c	45.0c
N2	1.54b	3.2b	249.1b	19.0b	24.6b	53.3b
N3	1.83a	3.4a	318.6a	19.8a	27.6a	61.9a

Means within a column for each trait having the same letter are not significantly different at 5% level.

Nodule numbers and dry weight per plant were significantly higher using canal water compared to mixed and drainage waters. The 4 day irrigation frequency produced higher numbers and weight of nodules especially at 250 and 350 kg/ha-N (N2 and N3) application. The high nitrogen dose promoted the early vegetative growth of the plants and produced well developed root system hence the nodulations were increased. Furthermore, the soil is loamy sand and some of the nitrogen was losted by leaching which emphasize the importance of high nitrogen rate, to promote the growth and modulation under such conditions. Thus, increasing the nitrogen rate with cowpea under saline conditions could improve numbers and weight of nodules. That is besides the positive effect on other yield components and consequently on seed yield.

The increase in irrigation water salinity reduced the seed yield (Fig. 1). Under the three waters used the yield order was canal > mixed > drainage. The seed yield ranged from 1.66-2.63 and 1.31-2.45 tons/ha for canal and mixed waters, respectively, However, The drainage water reduced the seed yield sharply to < 0.61 tons/ha in all cases except in one case (N3F1) where the yield reached to 0. 84 tons/ha.

The increase in irrigation frequency to 4 days produced a significant increase in seed yield under all the water qualities tested. Differences between nitrogen treatments became less apparent as the irrigation salinity increased. The nitrogen rates applied increased the yield as the N rate increased at each water salinity type. The increases were high at canal and mixed waters but with lesser extent with drainage water application. However, the seed yields under mixed water were close to its comparable yields under canal water.

The two irrigation frequencies had significant effects on seed yield but with lower magnitude compared to water salinity since the difference between them was about 7%, The F2 irrigation frequency imposed negative effect on yield due to high evaporation rate at the summer under the experimental condition which induced high EC associated with F2 application in both surface and subsurface soil layers (Fig. 2). Therefore, reuse of drainage water through cycling drainage and low salinity waters is difficult due to the high salt content of drainage water. However, irrigation of cowpea (moderately sensitive) or soybean (moderately tolerant) with mixed water could be more acceptable than using drainage water alone. In that case, the use of water for irrigation might be beneficial for leaching and the management of water is usually easier when water is less scarce as stated by Wolters and Bas (1990).

Increased salinity of the irrigation water significantly decreased the number of soybean pods per plant, number of seeds per pod and 100-seed weight. Therefore, the soybean seed yield decreased markedly (Table 2). The differences in seed yield were mainly due to differences in pods number per plant (r = 0.95) rather than to the differences in seed number per pod (r=0.63) or to the 100-seed weight (r = 0.75).

Both number and weight of nodules per plant showed significant reduction with mixed and drainage waters. However, the reduction in nodules weight was comparatively greater than the reduction in nodule numbers. Nodulation of soybean was almost inhibited under drainage water conditions. That could be due to reduction of growth and multiplication of rhizobia besides, the decreased ability and susceptibility of root hairs.

Table 2. Effect of water quality, irrigation frequency, and nitrogen fertilizer on yield and yield components of Soybean.

Treatments	Seed yield Kg/ha	Pods perplant	Seeds per pod	100-seed wt.(g)	Nodules per plant Numbers	Nodules per plant Wt. (g)
Water quality						
I	304.4a	9.5a	2.9a	20.0a	30.4a	64.4a
M	248.8b	6.3b	2.1b	17.0b	17.2b	33.9b
D	87.4c	2.2c	1.2c	9.0c	3.6c	6.1c
Irrigation frequency						
F1	225.8a	6.6a	2.6a	16.5a	19.9a	44.7a
F2	199.5b	5.2b	1.6b	14.0b	14.2b	24.9b
Nitrogen fertilizer						
N1	186.7c	5.5c	1.5c	14.0c	14.5b	29.8b
N2	204.3b	5.9b	2.2b	15.1b	17.0ab	33.7b
N3	280.7a	6.2a	2.6a	16.6a	19.8a	40.9a

Means within a column for each trait having the same letter are not significantly different at 5% level.

The decrease in irrigation frequency from 4 to 7 days resulted in significant reduction in seed yield and yield components. On the other hand, nitrogen fertilizer increased yield significantly. That increase reached to 9% and 50% with N2 and N3 plants respectively (Table 2).

The seed yield followed the order of canal > mixed> drainage waters and the 4 days irrigation frequency produced higher yield than the 7 days irrigation frequency in all cases (fig. 3). The seed yields were ranged from 254.8 to 368.6 and from 196.2 to 303.5 Kg/ha tinder canal and mixed waters respectively. However, the seed yield ranged from 65.0 to 113.5 kg/ha under drainage water. Nitrogen fertilizer encouraged plant growth especially at canal and mixed waters. The reduction in yield under drainage water was significantly greater than mixed water.

The interaction of Q(water quality) x F, Q x N and Q x F x N had significant effects (5% level of significance) on seed yield, number of pods/plant, number of seeds/pod and 100-seed weight. However, there were no significant effects observed with Q x P(Phosphorus), Q x F x P and Q x F x N x P interactions at both crops.

Hoffman et al. (1980) rated soybean and cowpea plants as moderately tolerant, and moderately sensitive crops, respectively. They stated that, their threshold salinity levels (the salinity which will not affect crop yield when salinity does not exceed that level) are 6 and 3 dS/m for soybean and cowpea respectively. The initial saturated extract soil salinity of surface and subsurface layers in figures 2 and 4 are much higher than the threshold levels of both crops. Besides that, the high salt built up in the soil through the irrigation affected the yield significantly. Therefore, the yield of both crops decreased sharply under drainage water which caused detrimental effect on growth and seed yields. That was clear under 7 days irrigation frequency and with N1 or N2 nitrogen addition whereas, both crops under mixed water and high nitrogen application produced good yields.

CONCLUSIONS

Among the three water qualities used for irrigation the most suitable one is the canal water. However, under the circumstances of water shortage in the and zone soils the mixed water could be an other alternative for irrigating of cowpea and soybean. The mixed water used half of its amount from the high salinity drainage water besides that, it produced an acceptable yield under the condition of the experiment especially at 4 days irrigation frequency. On the other hand, the drainage water should be avoided since it produced very low yield due to the high moisture stress prevailed. Addition of high nitrogen rate could enhance cowpea and soybean growth and compensate the reduction in yields under saline irrigation water.

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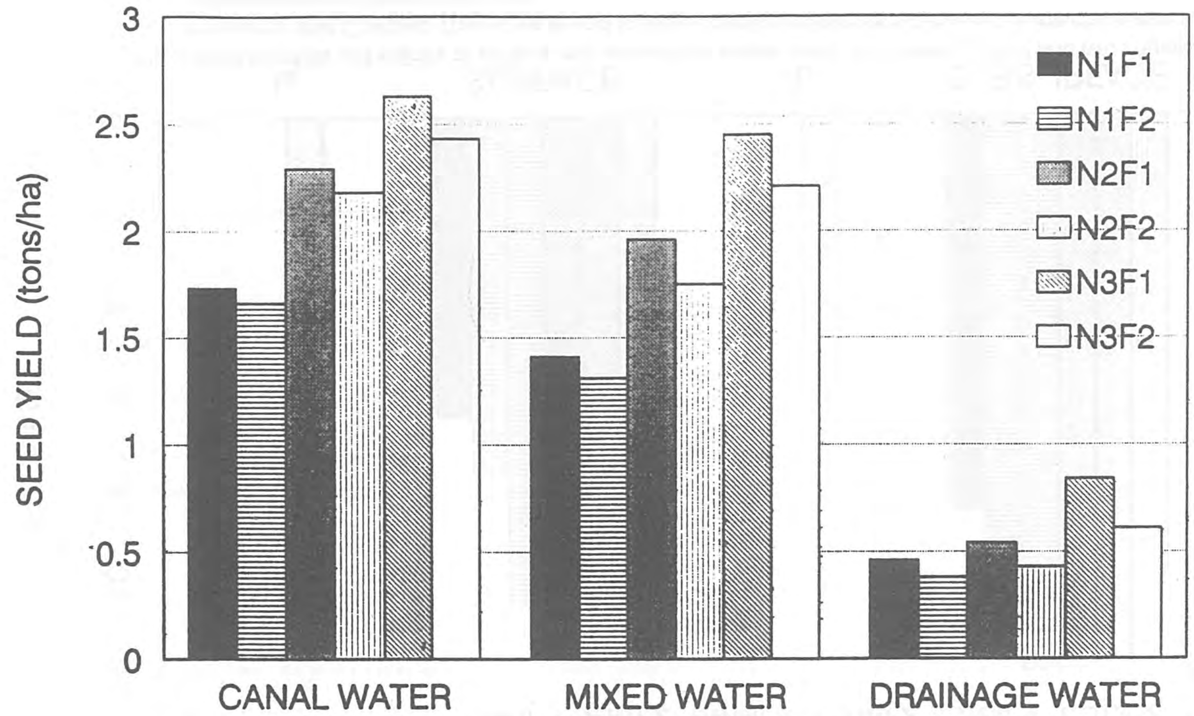

Fig.1 Cowpea seed yield under three irrigation water quality and two irrigation frequency with three rates of nitrogen fertilizers. All letters are defined in the text.

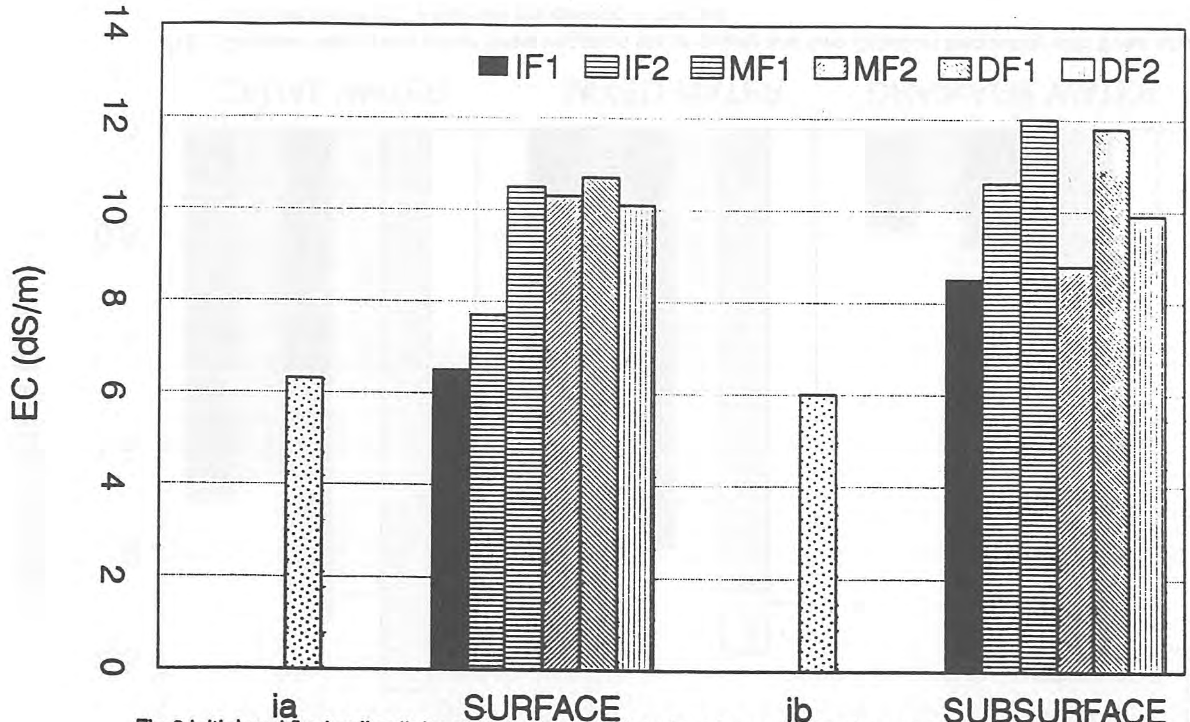

Fig.2 Initial and final soil salinity at surface and subsurface layers under three water quality and two irrigation frequency after Cowpea. The letters ia and ib refers to initial salinity for surface and subsurface layers. All other letters are defined in the text.

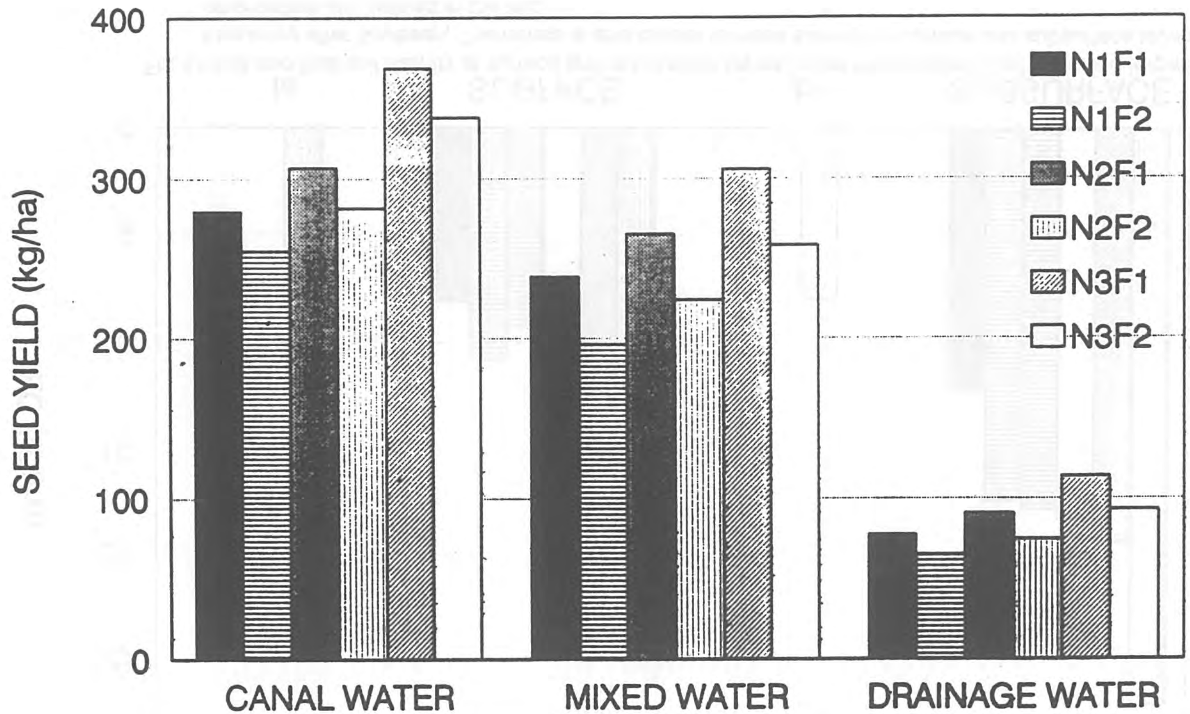

Fig.3 Soybean seed yield under three irrigation water quality and two irrigation frequency with three rates of nitrogen fertilizer. All letters are defined in the text.

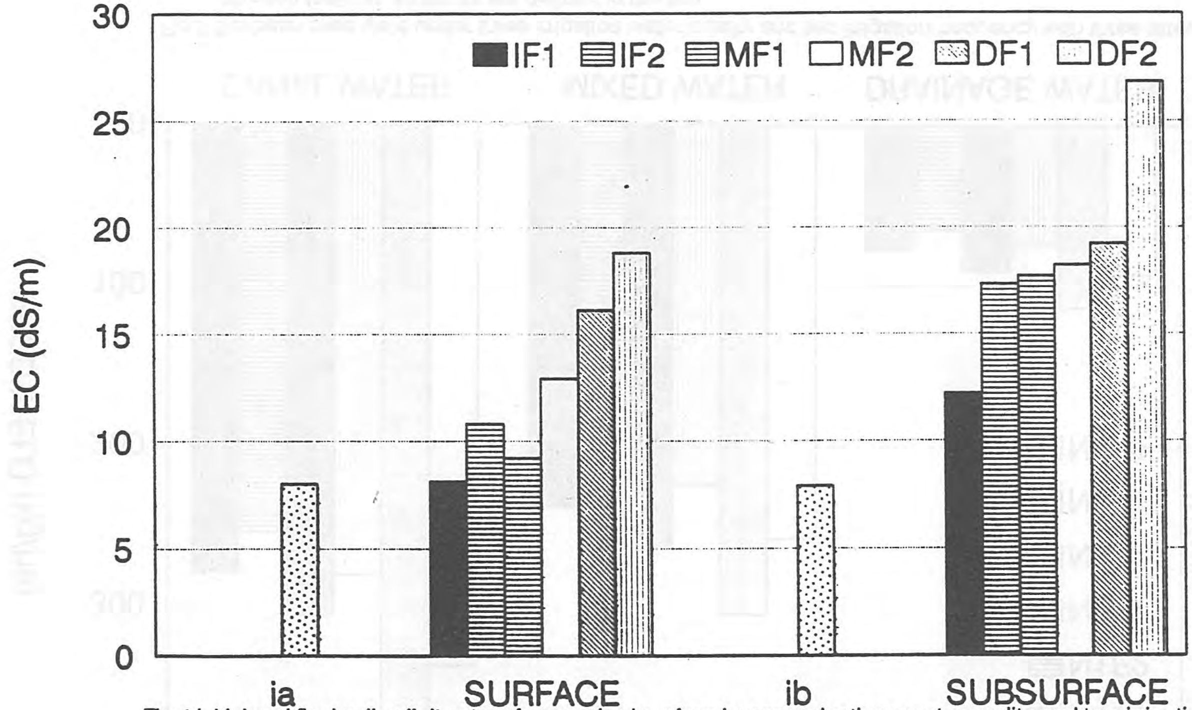

Fig.4 Initial and final soil salinity at surface and subsurface layers under three water quality and two irrigation frequency after Soybean. The letters ia and ib refer to initial salinity for surface and subsurface layers. All other letters are defined in the text.

Irrigation of Date Palms in Sultanate of Oman

Hassan Wahby and Emad Abdul Majeed

IRRIGATION FOR DATE PALMS IN THE SULTANATE OF OMAN

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ABSTRACT

Date palms are considered as the main crop and one of the most important fruit yielding trees in the Sultanate, as they provide the main food to the Omanis. The increase of population, socio-economic development and the vast expansion in irrigated agriculture, which the Sultanate achieved during the last 25 years, resulted in high demand for irrigation water. As the water resources in Oman are very limited, the increase of water use efficiency becomes really a crucial issue.

The flood irrigation practised by Omani farmers, using earth channels to convey and distribute water to farm lands, resulted in applying irrigation water with low efficiency, hence achieved only low productivity. Moreover, weeds grown within the farm lands consume water and fertilizers allocated to crops.

With advanced irrigation technology, it becomes possible to control, manage and distribute irrigation water to plants without any waste.

The bubbler irrigation system has been proved as a suitable and successful technology, since it can provide water to the trees as required, and consequently high productivity with lesser agricultural inputs can also be achieved even for trees of different ages.

This paper emphasizes the importance of modern irrigation technology and the associated practices in the application of irrigated agriculture for the best benefit of farmers.

An Integrated Agriculture System: A Self-Sufficient System of Energy and Irrigating Water

Hassan E.S. Fath

AN INTEGRATED AGRICULTURE SYSTEM: A SELF SUFFICIENT SYSTEM OF ENERGY AND IRRIGATING WATER

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ABSTRACT

This paper presents the description and the performance of an integrated greenhouse-solar distillation-solar heating/drying system for agriculture purposes. The integrated system is self sufficient of energy (ventilation, winter heating, summer cooling & humidification, and products drying) and irrigating water requirements. The system consists of: i) a naturally ventilated greenhouse with built-in solar stills, ii) additional solar distillation unit, and iii) a solar air heating unit with built-in latent heat thermal energy storage system. The developed integrated system utilizes the abundant sun (and wind) energies to: (i) induce upward ventilation air flow due to buoyancy forces and chimney thermal effect. A waste heat and mass recovery system (WHMRS) is added to enhance the ventilation process. In summer, the ventilated air is extracted into the greenhouse from outside through a wet pad (evaporative cooler), thus producing air cooling by means of evaporation. (ii) In winter, the solar air heating unit (designed to continuously operate for 24 hrs/day) will provide the greenhouse with the required heating load particularly over night, and (iii) distillate the available saline water (brackish or sea water) to provide the rather modest demand of the greenhouse for irrigating fresh water. A locally developed water pump(s), driven manually or by wind mill, is also provided for pumping saline and irrigating fresh water. A back-up mechanical power / heating system, for extremely cold and cloudy days, will also be provided. The integrated system is passive and, therefore, requires minimum maintenance operation skills, almost need no electricity, and yet present an exciting possibility for the support of the agricultural activities in hot and rural regions of the Gulf Countries.

Keywords: Agriculture, Greenhouse, Solar distillation, HVAC

INTRODUCTION

In most Gulf states, it is difficult to grow vegetation in the open field due to; (i) the harshness of the land and climates, and (ii) the unavailability of suitable water for irrigation purposes. To overcome these difficulties, the use of greenhouses can provide a proper solution for different plants growth at all seasons. The greenhouse controls its internal environment and reduces the rate of irrigating water requirements. The use of greenhouses allows also for the production of high quality plants (of high economical return) even during off season periods. On the other hand, a simple, cheap and environmentally clean technology such as solar distillation unit can provide the proper solution for the rather modest greenhouse requirement of irrigating water.

The successful operation of greenhouse depends, however, on maintaining the inside conditions of the greenhouse (temperature & humidity) within a specific desired range and the continuous supply of suitable irrigating water. During the hot months, however, the greenhouse inside temperature can reach a high value that prevent its effective utilization or, otherwise, a costly mechanical air conditioning system should be used. On the other hand, during the nights of the winter seasons, a greenhouse heating system is needed to maintain the inside temperature within tile specified range required for plant growth. Moreover, the unavailability of suitable fresh water for irrigation purposes limits the best utilization of a large areas, particularly near the coastal regions (with the availability of seawater) or near the wells of salty (brackish) water.

The present paper presents the description and the performance of an integrated greenhouse-solar distillation, solar heating/drying system for agriculture purpose. The integrated system is self sufficient of energy (ventilation, winter heating, summer cooling & humidification, and products drying) and irrigating water requirements. The system can, therefore, enhance the agricultural activities in places where only saline or brackish water is available.

SYSTEM DESCRIPTION & PERFORMANCE

The integrated system consists, see Figure (1), of. i) a naturally ventilated greenhouse with built-in solar stills, evaporative cooler(s), and waste heat & mass recovery system (WHMRS), ii) additional solar distillation unit of a group of multi effect stills, iii) a continuously operating (24 hrs/day) solar air heating/ drying unit with built-in latent heat thermal energy storage system. A back-up heating system will be used for extremely cold and cloudy days), and iv) a locally developed water pump(s), driven manually or by wind mill, for saline & fresh water circulation. Detailed description and performance of each component of this system will be presented below.

I - Greenhouse With Built-in Solar Stills & WHMRS

In hot climates the greenhouses inside temperature can reach a high value that limit its effective utilization or, otherwise, a costly mechanical air conditioning system should be used. Fath [1] proposed a system to decrease the greenhouse cooling load and to use the surplus solar energy during the day for natural ventilation of the greenhouse. The system consisted of a transparent roof with built-in solar collector and thermal energy storage system. Another way of reducing the cooling load was also proposed by Fath [2], through replacing the solar collectors with solar distillation unit(s) on the top of the greenhouse, near its transparent roof, Figure (1). Although several solar still-greenhouse combinations were presented in the literature [3-6], none, as far as the author is aware, incorporated the system for ventilation of the greenhouse. The advantages of the present greenhouse-distillation configuration arise from the facts that :

a. Solar distillation may, in most cases, be able to provide the rather modest demand of the greenhouse for fresh water (10% of the water requirement for irrigation in an open field). Thus, in areas where fresh water for irrigation is not available or costly to obtain, the solar still-greenhouse combination can support local agricultural activities. No water transport or storage costs are required, since the distillate may be fed directly into the greenhouse.

b. The diurnal and seasonal fluctuations in solar still productivity are intrinsically linked to the fluctuating water requirements of plants.

c. The part of solar radiation essential for the growth of plants will be provided by having the stills spacing and basin material, made of transparent material which permits the amount of visible solar radiation to penetrate into the greenhouse and help plant growth due to unproved photosynthetic activity.

d. The solar still, being at the top of the greenhouse, will also be utilized to enhance natural draft ventilation (with the assistance of thermal chimney) and suck out the greenhouse top air and, therefore, limits the greenhouse heatload.

e. The top outlet heat and mass could partially be recovered through the installation of an effective heat exchangers, where cold make-up brine could be stored and heated, and then fed to the stills basin.

Figure (2) shows the schematic sketch of the greenhouse, integrated with the solar still, solar induced fan (with thermal chimney effect) and WHMRS heat exchanger. A transient analysis of such greenhouse design has indicated that, Figure (3), the greenhouse stills system configuration is able to ventilate the greenhouse for the 24 hrs with an air flow rate which varies from 0.1 kg/s at midnight to 1.0 kg/s at midday. The corresponding ventilation Air Change Rate (ACR) varies from 1.2 to 12 ACR/h, respectively. The ventilation air rate increase with increasing chimney height or decreasing system flow resistance. The system daily yield of fresh water varies from 1.26 to 1.82 kg/M^2 and increases with increasing basin-water and WHMRS heat capacities and increasing WHMRS effectiveness or decreasing the system flow resistance. With such modest distilled water production, an additional solar distillation unit may be needed to supply more fresh water, for irrigation requirements and other fresh water domestic uses. An additional farm of solar stills will, therefore, be built near the greenhouse for additional water production.

II - Additional Solar Distillation Unit

Although a diversity of approaches are used for the separation of fresh water from saline water; namely multi stage flash (MSF), multiple effect (ME), reverse osmosis (RO), electrodialysis, ion exchange, phase change, and solvent extraction. These methods are expensive, however, for the production of small amount of fresh water. In addition, large size electrical power unit is necessary for the operation of these systems that limits its effectiveness for desert and remote regions. The development of solar distillation has demonstrated, however, its suitability for the desalination process when the weather conditions are suitable and the demand is not too large, i.e. less than 200 m^3/day.

The problem of low daily productivity of the solar stills triggered scientists to investigate various means of improving the stills productivity and thermal efficiency. These include various passive methods; such as lowering the depth of water in the basin, injecting black dye in the Water mass, reducing sides/ bottom heat losses - through using proper insulation, air and vapor tightness, proper orientation of the still for intercepting the maximum solar radiation... etc. In addition to these passive methods, the thermal efficiency of the unit can also be increased by the use of active methods such as coupling the still to a solar heater or a solar concentrator. On the other hand, the wasted latent heat of condensation can be recovered so as to increase the productivity of the distillate water. This can be carried out in two or more stages, generally referred to as a multiple effect solar distillation system. The re-utilization of latent heat of condensation was investigated using different methods, see Fath [7]. Fath [8], for example, presented a simple design, two effects, solar distillation unit, where the evaporated vapor from the first effect is allowed to be purged to the second effect, Figure (4). The distillation unit consists mainly of a second effect still connected to a single slopped solar still, of a movable shutter fashion type reflector back and located at its shaded side. The movable shutter reflector will maximize the reflected solar energy at different sites locations and different seasons and allow purging the vapor. The second effect cover (need not to be glass) may have a finned outer surface to maintain the cover at or near ambient temperature. The second effect still acts as an additional heat and mass sink that sucks the evaporated water vapor from the first effect still. The purged vapor condenses and its sensible and latent heat is utilized to heat the basin water of the second effect for additional evaporation. Purging the vapor (and the gases) maintains the first effect still at relatively low pressure (and free of non-condensable gases) which enhances evaporation. In addition, the evaporative and convective heat load on the first effect glass cover is reduced, and, therefore, the first effect glass cover temperature is also reduced. The stills basins water temperatures are raised through maintaining a minimum water level. By increasing the temperature difference between the basins and the covers, the evaporation rate and the overall still productivity will increase. On the basis of the numerical analysis, the results indicated that, the overall unit productivity was found to be as high as 10.7 kg/ m^2/day, Figure (5), for a typical climatic summer conditions of the city of Dhahran, Saudi Arabia.

The size and the configuration of the additional farm of solar stills (to be built near the greenhouse for additional water production) should be selected based on the amount of water needed, for irrigation and other domestic uses, and on the economical considerations). It is worth mentioning, here, that a solar water concentrator with built in latent heat thermal energy storage system (LHTESS) could enhance the water production rate for the 24 hrs/day. This active solar distillation system with built-in LHTESS is now under development, see Fath [9].

III - Solar Air Heating/Drying Unit

During the nights of the winter seasons, the greenhouse heating is needed to maintain a suitable internal environment (maintain the inside temperature within the specified range) required for plant growth. On the other hand, one of the most potential applications of solar air heaters is the supply of hot air for drying of agriculture products. Solar Air heating/drying unit(s) could utilize the abundant sun energy during day time, store the excess energy and use it during the night. The passive thermosyphon solar air heaters can, for example, induce a sufficient draft in the range that suits such applications (a typical 0.005 - 0.02 kg/s drying air flow rate, with an outlet to inlet air temperature difference of 5-10 C). Thermosyphon solar air heaters have the advantages of being simple, cheap, self-flowing, self regulating systems. In addition they are passive and do not require air pumping power, and therefore suit remote rural areas.

There are various possible configurations of solar air heaters which could offer a wide range of performance efficiencies. Air heaters show, in general two drawbacks; the relatively lower efficiency and limited storage capabilities. The heaters efficiency can be increased by increasing the heat transfer coefficient and surface area, and reducing the heat losses to the surroundings. The conventional heaters can only provide hot air during sunny (day) hours, due to the limited heat capacity. Air heaters heat capacity could be increased through introducing an effective thermal energy storage. These factors were achieved by Fath [10] and [11], by replacing the conventional absorbers by a set of tubes that act as both solar energy absorbers and turbulent creator. Filling the tube set with a Phase Change Material - PCM- such as paraffin wax (latent heat thermal energy storage system), will increase the system thermal heat capacity and also reduce the heat losses (due to lower absorber temperature) and therefore increase the heater efficiency.

The performance of a Thermosyphon solar air heater with built-in LHTESS indicated that, Fath [10], the heater filled with PCM of 51C and 43C melting temperature discharges the thermal load for a long time after sunset. The heater can discharge the thermal load of a minimum 0.01 kg/s (30 m^3/hr) air flow rate with up to 8C outlet to inlet temperature difference and for the 24 hrs of the day.

Air heaters will be used for the greenhouse during nights. Excess energy during hot days and summer could, however, be utilized for agriculture products drying, more water desalination and to enhance natural greenhouse ventilation. Depending on the heating load of the greenhouse, the surface area of the air heating unit could be selected. For extremely cold & cloudy winters, a standby source of heat should be installed for the greenhouse heating. A back-up system will, therefore, be needed.

IV - A Back-up Unit

A standby back-up unit to supply the agriculture system with the energy and irrigating water in case of the unavailability of solar energy or the malfunction of one or more of the solar unit(s). The unit will also be used to supply the mechanical and electrical power requirements. The stand by unit could be a Diesel engine with energy recovery from various waste heat of the engine exhaust and cooling systems. Generally, the utilization of waste heat technologies is basically known for many engineering applications, see Reay [12] and Fath [13]. The additional back-up heating source that simulates the waste heat recovery will be utilized for greenhouse heating in winter and saline water desalination and greenhouses ventilation in summer. Mechanical and electrical energies are used for irrigation (pumping), mechanical ventilation (fans), lighting and other domestic uses.

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NOMENCLATURE

A	= Area (M^2)	Eff	= Effective
H	= Height (m)	I	= Solar intensity (W/m^2)
LHTESS	= latent heat thermal energy storage system		
L	= Latent heat (J/kg)	M	= Mass (kg)
M	= Mass flow rate (kg/s)	Q_{ph}	= Photosynthetic Energy (W)
T	= Temperature (°C)	t	= Time (s)
WHMRS	= Waste heat & mass recovery system		

Subscripts

air	= Air	amb	= Ambient
av	= Average	b	= Basin
el (e2)	= Evaporation from First (second) Effect		
1	= Inlet to greenhouse	2	= Outlet from greenhouse

Greek letters

α	= Absorptivity	β	= Fraction for air flow area
ε	= Thermal emissivity	η	= efficiency
s	= Radiation constant	τ	= Transmissivity

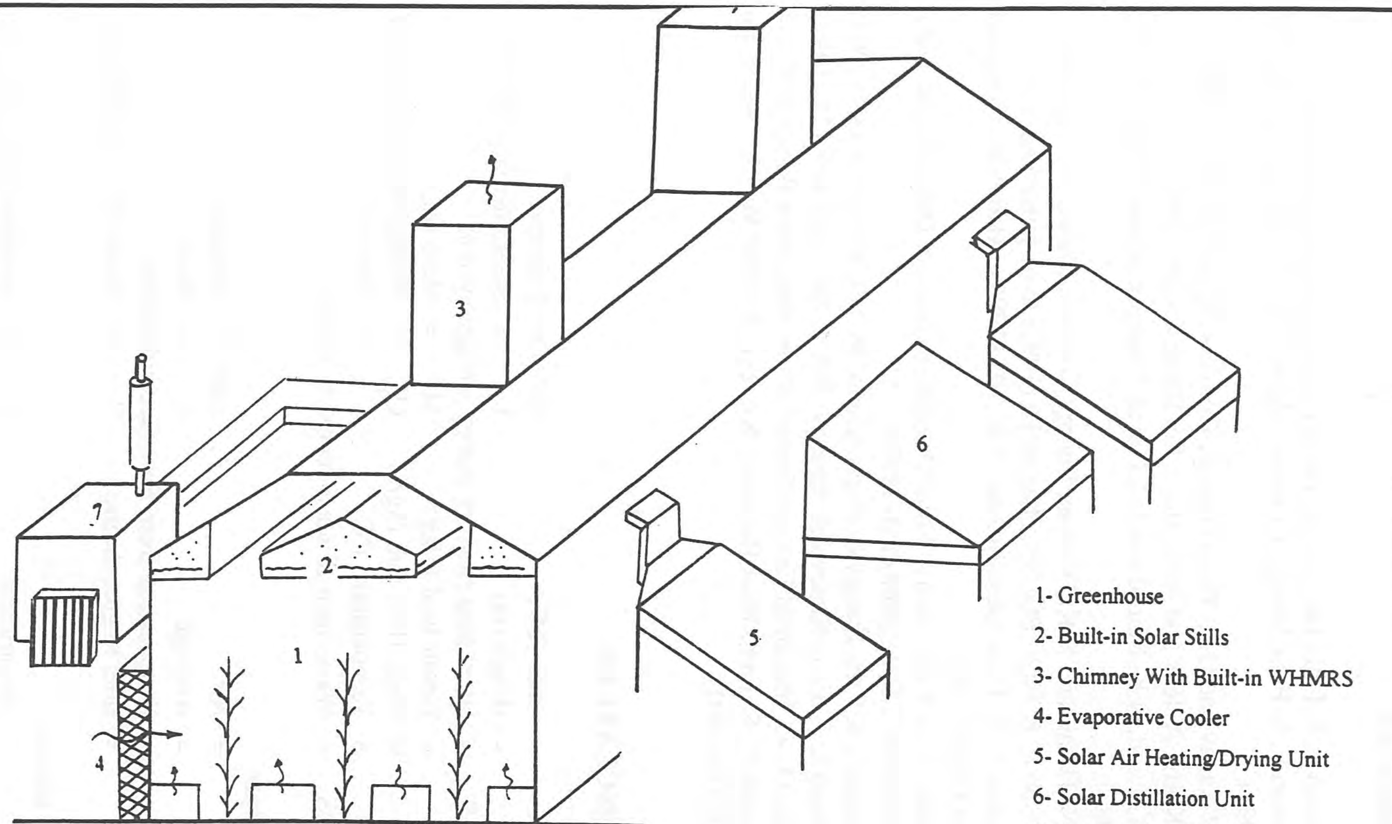

Figure (1) Schematic of The Integrated Agriculture System

(Self Sufficient of Energy & Irrigating Water)

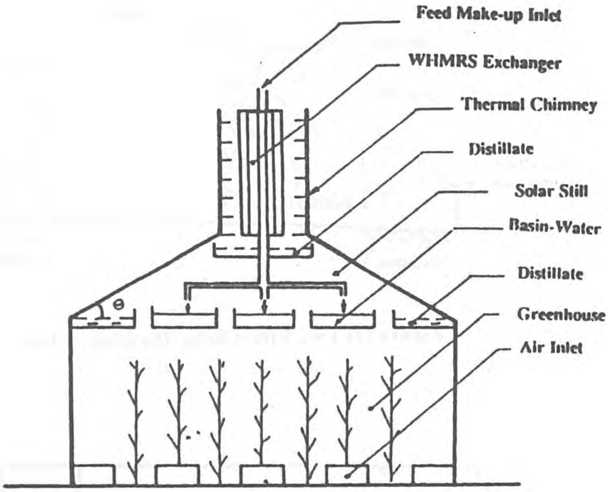

Figure (2) Naturally Ventilated Greenhouse with Built-in Solar Stills & WHMRS

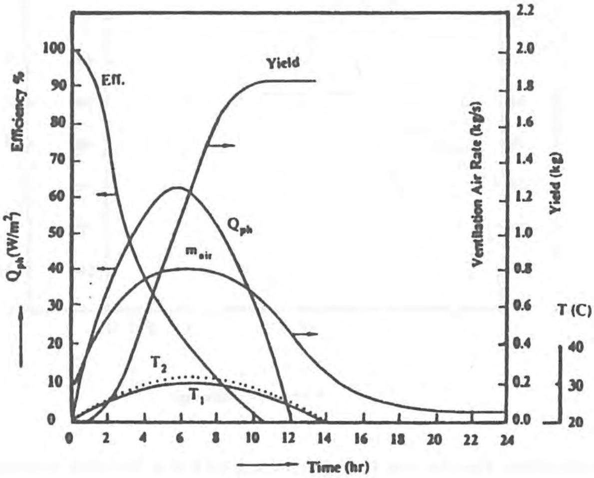

Figure (3) Greenhouse Performance For a Selected Parameters, Fath [2]

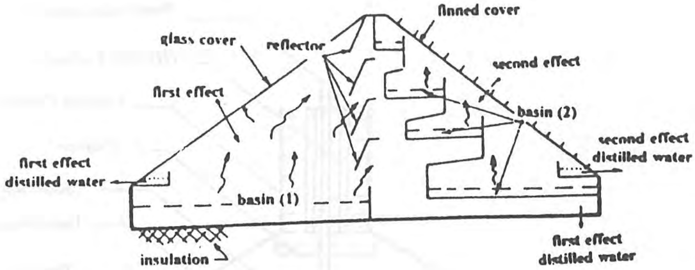

Figure (4) Two Effect Solar Distillation Unit

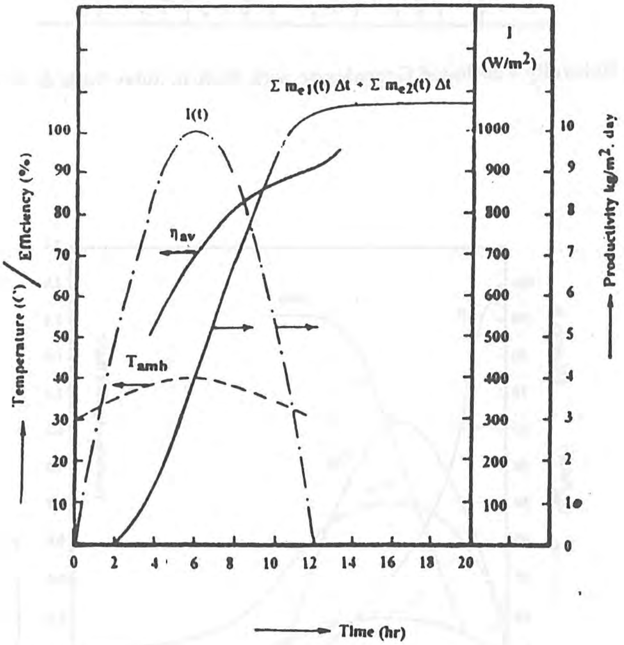

Figure (5) Solar Distillation Unit Performance For a Selected Parameters

(City of Dhahran, Saudi Arabia)

Modeling the Sensitivity of Pumped Groundwater Salinity to Irrigated Agriculture in Data Shortage Regions

Mahdi Al-Sayed and George Fleming

MODELLING THE SENSITIVITY OF PUMPED GROUNDWATER SALINITY TO IRRIGATED AGRICULTURE IN DATA SHORTAGE REGIONS

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ABSTRACT

Agriculture is the world's most important industry, and irrigation is well known to be its essential part. Within the global regions, agricultural environments vary with respect to the prevailing climates, land use, and water resources. In the and to semi-arid regions, the agricultural environment is limited and discontinuous both in scale and time. In the Al-Wafra agricultural area in Kuwait, the limited supply of good water necessitates the use of a poor (brackish) supply for irrigation. The available hydrological and hydro chemical data are reviewed and indicate that the major causes of groundwater quality deterioration are the variable irrigation system, heterogeneous soil, well design, crop plan practice, and sources of irrigation water. The existing groundwater quality models are reviewed and classified on the basis of their consistency, applicability and validity to the current problems, and a number of limitations in these models were uncovered. These models generally, consider the simulation of water quality trend both horizontally and regionally. As a tool for a better understanding of the problem, a practical lumped hydrological and salinity model has been developed, to study the irrigation impact on groundwater quality in Kuwait. The model is based on the Flow Processes - Salinity Balance (FPSB) approach, which simulates the irrigation water application, distribution, movement and crop growing as a site-specific problem causing an increase in groundwater salinity. The model has also been used to simulate the role that climatologic, hydrologic, and physical parameters play in controlling the underground hydro-salinity. The input to the model requires climatic data that is available over a number of years, such as temperature, wind, relative humidity, solar radiation outside atmosphere, global radiation, and root depth all of which play

a dominant role in influencing groundwater salinity under small irrigation basins. The significance of this work is that the model uses data from existing tables as an input for most of the parameters, since the availability of the historical data is limited for this work. The model is part of a quality control management programme, which should overcome the problems of data shortage in simulating water quality in and regions.

INTRODUCTION

The increase in world population has placed more demand for water would be a source for irrigation and food production. The increasing need for crop production has caused a rapid expansion of irrigation in private farms in Kuwait. In the absence of high rainfall, poor groundwaters with a high proportion of total dissolved solids (between 4000 - 7000 mg/1) is used for growing various salt tolerance crops (Figure. 2). Hence, with the lack of awareness and improper utilization of the groundwater resources used for irrigation has steadily deteriorated the quality of groundwater. Isotope analysis of Oxygen-18 and deuterium ranked the waters in the Al-Wafra area as an old brackish groundwater not receiving adequate recharge from rainfall (Al-Sayed and Fleming, 1996a; Figure. 3), in this case most of the recharged water derives from irrigation return flows.

The major problem in the agricultural area is the increased salinity of the pumped ground water used for irrigation, particularly in the Al-Wafra area southern Kuwait (Figure. 1). The quantitative assessment of the volume of water infiltrating the root zone and reaching the groundwater table by deep percolation has been found to be mainly dependent on water balance of the irrigation system. In deep percolation the soil loses water partly through evapotranspiration and partly through water movement in the root zone. As a result, most of the dissolved solids are left behined and increasing the salinity of infiltrating water. The transport of salts via the natural groundwater (horizontal movement) is much slower than the addition of salts from the surface irrigation (Otto J. Helweg et.al, 1981).

Protection of groundwater quality for irrigation depends on good management, as emphasized by Bouwer (1987) in his study of deep percolation as a tool to prevent groundwater pollution. The Kuwait Institute for Scientific Research (KISR) has carried out several projects to study groundwater quality in the saturated zone but only examined the groundwater- irrigation system to a limited extent. However, they did not focus on soil moisture content in the unsaturated zone (Al-Sayed et al, 1992; Al-Sulaimi et al, 1993).

Recent progress in groundwater management research has been mainly concerned with modelling the flow and quality of pumped groundwater in agricultural areas. Advances in ground water quality modelling have been successful to some extent. Recent trends in groundwater quality modelling investigated in this work are classified as follows:

1. Flow rate-head dependent concentration models (Konikow and Bredehoeft, 1978)
2. Dispersion - advection - diffusion dependent concentration models (Murty and Scott, 1977).
3. Density dependent concentration models (Voss C.I, 1984).
4. Soil-Plant-Water-Atmosphere Models (Kinsel, 1980; Abott et.al, 1986 Walid, 1992; IGSM, 1995)
5. Coupled hydrological models (Crawford and Linsley, 1966; Wardlaw, 1978; Fleming 1992; Crowe,1993).

It could be concluded that:
1. These models are only valid under conditions identical to those prevailing during the experiment.
2. These models are valid to areas with conditions identical to the empirical approach used by the model.
3. Most models includes a default data base which is often used due to the low quality of available field data.
4. Insufficient historical data available for model evaluation as it is the case in Kuwait.

Good quality input data is always an important part of modelling systems. The data requirement is not, however, exactly the same for each model, and the empirical parameters are not necessarily derived from actual data but are optimized by a trial-and-error matching procedure as in the case of the FLORA model (Al-Sulaimi et.al., 1993). Studies have shown that extrapolating point specific measurements such as groundwater discharge or the TDS obtained from well water measurement for a particular year to different year will lead to errors (Crowe, 1993).

This work investigates the suitability of the Flow Process and Salinity Balance (FPSB) model (Al-Sayed and Fleming, 1996a) in the data starved regions like Kuwait and reports the ways the lack of data can be compensated to the maximum extent possible to arrive at acceptable results.

DESCRIPTION OF THE FLOW PROCESSES AND SALINITY BALANCE MODEL (FPSB)

The purpose of the FPSB model is to study the sensitivity of pumped groundwater salinity to water movement and salts in soil-water system and their relevant irrigation scheduling. The model uses simulation techniques that independently simulate the surface runoff, infiltration, deep percolation in the unsaturated zone using the SOIL MODULE; flow from various aquifer layers, discharge rate using AQUIFER MODULE; salinity balance using SALINE MODULE; potential evapotranspiration and crop water requirement using the EVAPTR MODULE.

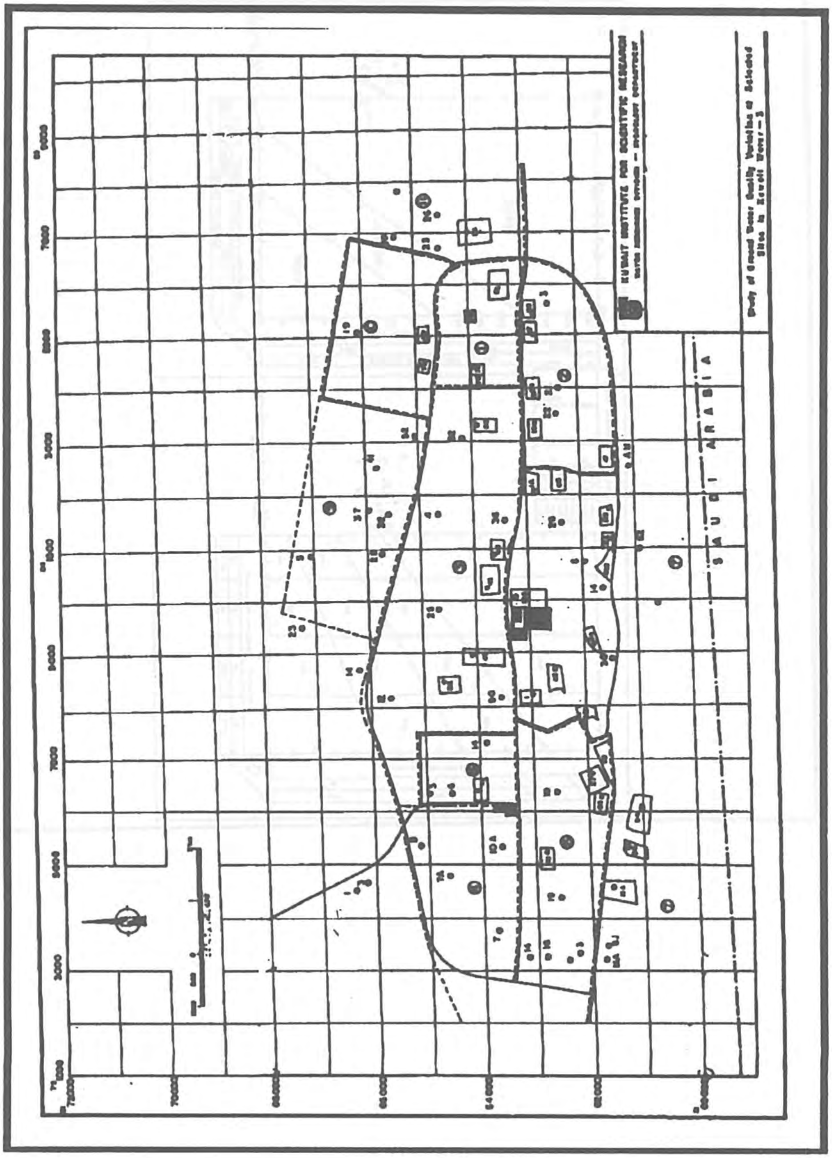
These processes within the irrigation site are lumped together sequentially starting at the surface (irrigation basin), moving downward through the various layers and ending up in the discharge well. The solution technique considers soil water content for each layer in different MODULES simulated independently each day is a single simulation period. The program consists of four sub-models IRGEVAP, SOIL, AQUIFER, and SALINE, which are responsible for generating the soil-water balance in each layer.

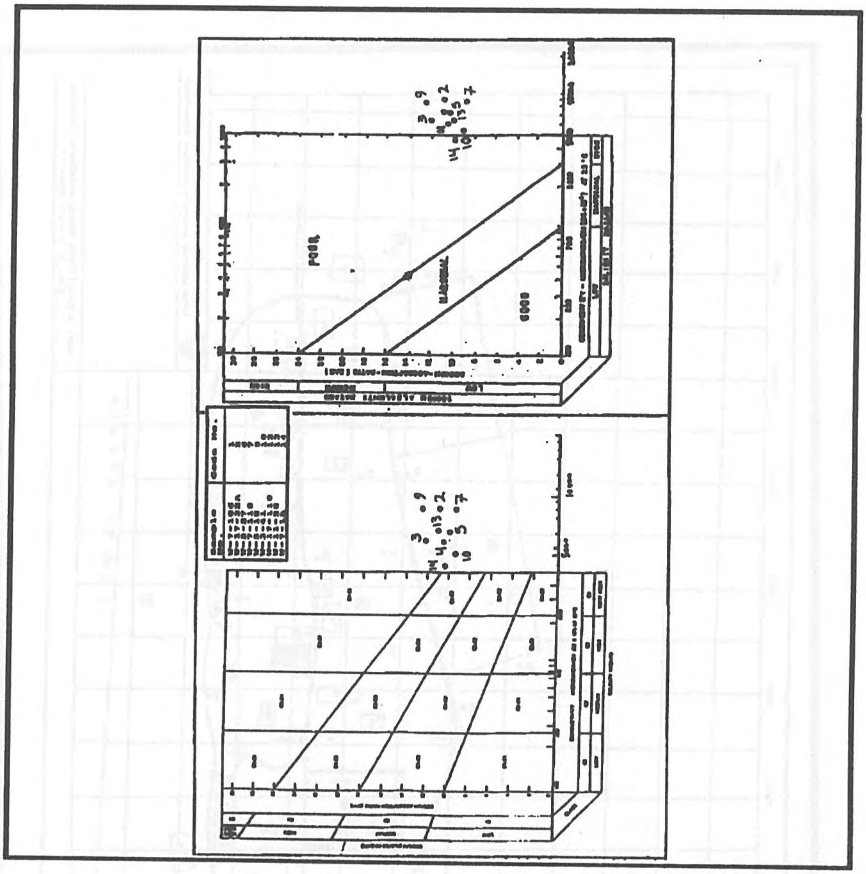
The potential evaporation from bare soil, and potential transpiration are calculated considering crop type, length, and stages of growth (crop maturity period). The effect of ploughing CIPL will be added to the initial moisture capacity in the sub-program SOIL. Ploughing has a short duration and insignificant effect on the infiltration (Makkink and Van Heemest, 1975). The depth of water required for irrigation is then calculated, and its value distributed into surface runoff, and infiltration.

Infiltration water stored in the soil cover either percolates through the next clay or sandy layers or remains on the plot as surface runoff. Runoff, is computed by the Soil Conservation Services (SCS) runoff curve number method USDA,SCS (1972) and percolation by Darcy's law for saturated flow with modification for unsaturated conditions (Buchanan,1993; Taj, 1995).

The Multi-Aquifer Production Well discharge(MAPW) is simulated with the approximation method developed by Bennett et al (1 982). The discharge rates into the production well from aquifer layers open to the well $\mathbf{Q}_{ijk}$ are calculated with the equation adapted from Bennet et al (1982). Values of the head in aquifer layers **b** at node **ij** at end of time increment in m $\mathbf{h}_{ijb}$ are generated by iterative techniques (Alternating Direct Implicit Approach ADIA) and substituted into an equation of Bennet et al (1982) to calculate the drawdown in the MAPW

hc_{ij}. Values of hc_{ij} and h_{ijb} are substituted to estimate the rate of flow Q_{ijk} (m^3/d) for each aquifer layers equation into the production well. The salinity of discharged water is calculated by the salt-balance equation.




POOR
MARGINAL
GOOD

DATA REQUIREMENTS

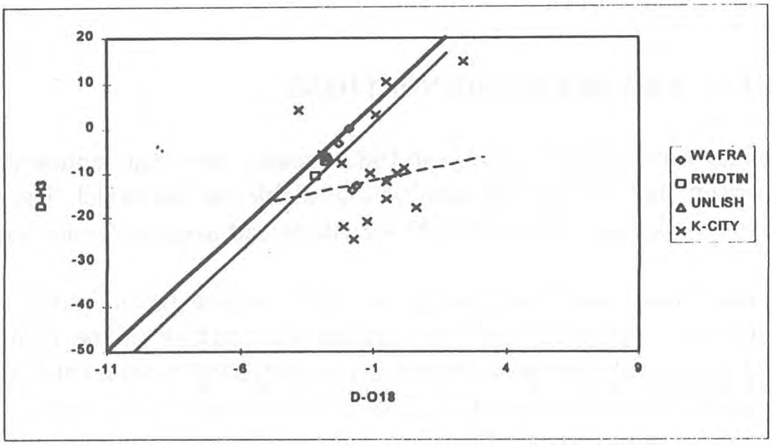
Inputs to the model are grouped into physical and real time or time dependent variables. The physical variables are site-specific measures which represent crop type, crop growth stages, soil moisture retention parameters, aquifer and salinity (TDS mg/1) data.

On the other hand, the time dependant variables consist of weather information or climatological data (Table 1).

Site - Specific Variables There are three sets of data required to define crop information, soil moisture retention parameters, well and aquifer characteristics, and the salinity condition, This information is expected to be from the tables of crops and derived soils standards, and from the daily irrigation scheduling in the farming area.

Time-Dependent Variables These real time data account for the fluctuating conditions during simulation. They represent the daily weather data, which controls irrigation scheduling and are involved in calculating the crop consumption and irrigation water requirements that controls the groundwater salinity.

The climatological information defines the strength of the model to generate and initialize the crop water requirements, infiltration, and deep percolation in each balance period. Since the weather records are the simplest available data, in this work it was planned to use this information to demonstrate the possible changes in the groundwater quality. Data from the meteorological office at Kuwait International Airport compiled for the years 1967, 1982, and 1987 were used to evaluate the model.



MODEL APPLICATIONS

This model could be applied to a single farm or a small irrigation site (Garden), with an irrigation scheme consisting of nearly 10000 m^2 flood irrigation basin with different crop types. The irrigation basin is divided into 4 small basins in the range of 2500 m^2 each of different crops and irrigation schedule are required. Groundwater salinity can be estimated at the end of the year (or season) for a particular irrigation scheduling at a particular farm area. The model was applied to estimate the 1982 groundwater salinity of the irrigation site W-5-18 under different irrigation methods (surface and sprinkler) (Al-Sayed and Fleming, 1996a).

MODEL CAPABILITIES

The model FPSB is capable of dealing with one farm at a time due to the huge amount of the daily weather data, crop, and site and farm information. The system can also perform the following:

1. Calculate crop reference evapotranspiration according to the modified Monteith Penman equation (Monteith, 1965), and the work of Rijtima (1975). The model assumes no ET_0 data available as a daily input in the region.
2. Calculate irrigation water requirement, leaching requirement, and the applied depth of irrigation water.
3. Calculate the infiltration, percolation, and surface runoff for each soil type.
4. Calculating the total pumped water and the relevant discharge from each layer in the case of the multi-aquifer option.
5. Estimate the potential groundwater salinity changes due to different irrigation scheduling.

RESULTS AND RECOMMENDATIONS

The model was applied to the year 1982 because this year represented the driest season, and site-specific data were available for the model. The model was used to calculate ETO, ETCROP for alfalfa and irrigation water required.

The model has shown that during the 1982 season the irrigated alfalfa crop, and the geological and the surface soil settings of the farm have resulted in a good agreement between the simulated groundwater salinity (5.53 mg/1) to that measured TDS of the well water (5.12 mg/1).

The model also showed a good agreement between the simulated and the actual irrigation scheduling with 20% leaching requirements and 50% irrigation efficiency, Figure 4. illustrates the daily water operation efficiency between the simulated and applied irrigation water in the Al-Wafra farm W-5-18.

The annual statistics of the water budget of the irrigation - groundwater system in the farm area are given in Figure (5), which shows the distribution of the potential infiltration and the deep percolation with respect to the amount of water applied for irrigation.

The sensitivity of the pumped irrigation water was tested on two stages. First the effect of changes in irrigation basin parameters on the annual salinity output was evaluated, and was found that the saturated hydraulic conductivity of the clay layer in the unsaturated zone will probably increase the (potential) groundwater salinity. Secondly the overall effect of various hydrological processes on the annual salinity output was evaluated. The irrigation water salinity of 10000 mg/l and the upper saturated zone water salinity will greatly affect the underground water quality. Generally speaking, it is unusual to experience a severe changes in water quality within a short period of time, but the limit and potential pollution should be allowed for when aiming at a sustainable irrigation water resource. The sensitivity test was applied to hypothetical conditions in the site and the results are given in Tables (2) and (3).

As groundwater resources are limited to slightly brackish water, any detrimental usage will have major consequences on the quality of irrigation water and crops as well. Over pumping or irrigation will have a detererious effect on groundwater quality. The model was tested for its sensitivity against several elements such as crop maturity, irrigation efficiency, soil cover parameters, aquifer layering, rate of abstraction, and hydraulic conductivity. It is recommended that the model to be tested under more complex irrigation conditions.

ACKNOWLEDGEMENT

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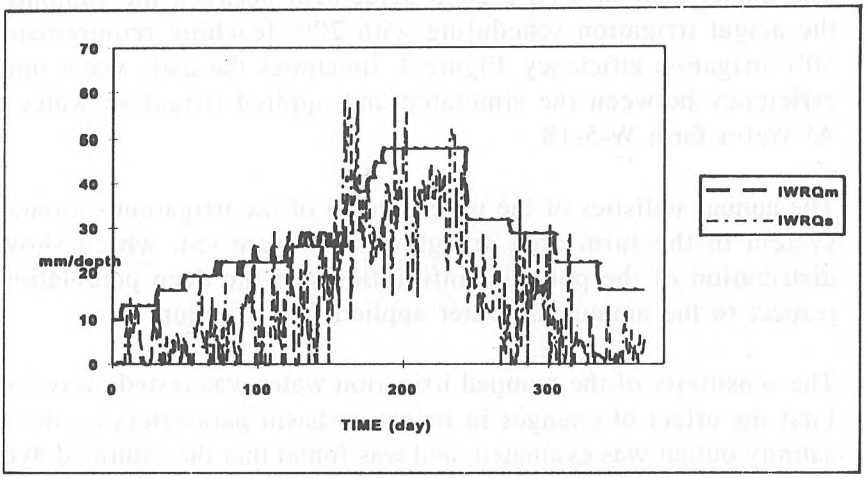
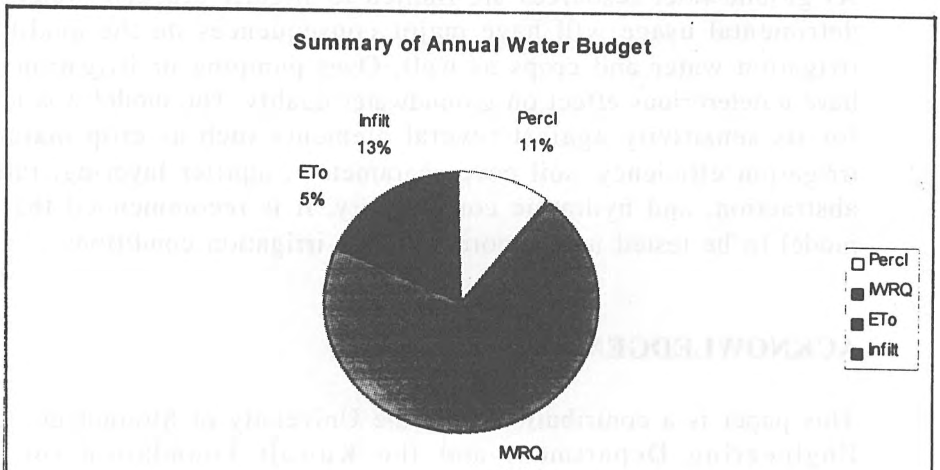


70
60
50
40
30
20
10
0
mm/depth
0
100
200
300
TIME (day)
IWRQm
IWRQs



Summary of Annual Water Budget
Infilt
13%
Percl
11%
ETo
5%
IWRQ
71%
Percl
IWRQ
ETo
Infilt

Table 1.
Input data for FPSB Model (After : Al-Sayed and Fleming, 1996a)

Parameters	Range	Base Value	Units
<u>1. Irrigation and ETR Input Values</u>			
Duration of effect of ploughing		90.0	Day
Max capacity increase by ploughing		20.0	Day
Concerning day		1	Day
Day of ploughing		-32	Day
Day of dying of crop 1		209	Day
Day of dying of crop 2		365	Day
Day of Appearance of crop 2		231	Day
Number of days to run		364	Day
Total plots area		10000	m.sq
Irrigation Efficiency	.20-.75	.50	%
Leaching requirement	.20-.75	.20	%
<u>2. Meteorological Data (Daily input)</u>			
Average daily Temperature per 24/h	0-50	daily	C
Dew point temperature	0-50	daily	C
Relative Humidity		daily	%
Wind speed at 2m height above surface	0-9	daily	m/s
Crop height	0-100	daily	cm
Roughness length of evaporation body	.1-5	daily	cm
Radiation outside atmosphere	0-900	daily	cal/day/cm.sq
Global radiation	0-700	daily	cal/day/cm.sq
Depth of transpiration zone	0-2	daily	cm
<u>3. Soil Cover Data</u>			
Total soil thickness TDEPTH	.75<SD>1.5	400.0	cm
Root zone thickness RDEPTH	0.1<RD>2.0	120.0	cm
Type of soil filling	Table-A	CoS	
Soil type category	Table-B	A	
<u>4. Soil Moisture Retention Parameters</u>			
SCS curve number	0<CN>100	62	
Saturated Hyd.Cond	Table-C	3.7E-4	cm.sec
Thit S	Table-C	.397	vol/vol
Thit F	Table-C	.032	vol/vol
Thit W	Table-C	.013	vol/vol
Thit I	Table-C	.032	vol/vol
Soi12 Saturated Hyd.Cond (Cshc)	E(-6)<Kc>E(-8)	5.8E-3	cm.sec

soil thickness		9.2	m
Saturated Hyd.Cond	Table-C	.480	cm.sec
Cpf		zero	cm.sec

5. Salinity Data

Initial pumped water salinity	5000-11000	5000	mg/1
Irrigation water salinity	5000-11000	5120	mg/1
Upper saturated zone		5480	mg/1
Lower saturated zone		6000	mg/l
Total irrigated area		10000	m.sq

6. Aquifer and Production Well

Number of stress period	1-50	1	days
Time	1-21	1.0	days
Aquifer Layers	1-2	3	

Aquifer Layer Number 1:

horizontal hydraulic conductivity	1-10000	0.1992	gpd sq.ft
vertical hydraulic conductivity	1/10-1/100	.00200	gpd sq.ft
aquifer artesian storetivity	1E-6, 1E-3	.006	
aquifer specific yield	.005 to .4	0.1	
aquifer thickness		42.75	ft
aquifer top		0.0	ft
aquifer base		42.75	ft
elevation of initial head in the aquifer		50.06	ft

Aquifer Layer Number 2:

Kh		129.95	gpd sq.ft
Kv		12.98	gpd sq.ft
S		.001	
Sy		0.1	
THICK		141.086	ft
TOP		42.75	ft
BASE		183.73	ft
elevation of initial head in the aquifer		50.06	ft
number of layers in which p.w. is open	1-4	2	
default grid spacing	10-10000	41.01	ft
number of grid nodes	1-20	8x8	
p.w. coordinates		4x4	
upper layer open to p.w.		1	
Lower layer open to p.w.		2	
p.w. radius		1.00	ft
p.w. discharge rate from ma-p.w.		33.5	gpm

Darwdown in the p.w. at present time period	78.73	ft
drawdown at beginning of present time period	65.61	ft
discharge pipe radius	.246	ft
time at end of present simulation time period	.45	minutes
Depth of percolation zone(ITDEPTH)	13	ft

Table 2.
Step-l: Effect of irrigation basin parameters changes on annual output.

Elements	Parameters	Range	Irrigation site Hydrological Processes and salinity					
			IWRQ mm	ETA cm	Infilt cm	Percl cm	Qto *TDS	Diff%
	Base value	0	1964.7	21.77	166.32	95.14	5.53	5.53
Maturity	***HC Jan***	0	23.13	7.71	10.27	5.94	5.89	0.25
	July	120 cm	107.69	0.0	15.97	8.21	4.84	0.49
Irrigation Efficiency	***LR***	+50%	2245.3	22.29	166.32	95.14	4.01	0.76
		-50%	1746.3	22.70	166.32	95.14	5.10	0.21
	IE	50%	785.89	22.159	165.94	95.17	4.94	0.41
		70%	561.33	21.995	164.98	95.12	4.87	0.46
Soil- Cover	***Sat Hyd Cond Ks***	10	1964.7	21.73	167.84	95.07	5.53	0.0
Clay -Soil								
		.1 times	1964.7	167.92	167.84	6.60	5.69	0.08
	θs	+ 10%	1964.7	30.89	136.46	95.50	5.10	0.21
		- 10%	1964.7	22.17	165.46	94.88	5.10	0.26
	θi	+ 50%	1964.7	22.17	165.46	97.66	4.95	0.26
		- 50%	1964.7	21.50	167.45	93.22	5.51	0.01
	θw	+ 50%	1964.7	21.25	162.95	93.88	5.05	0.24
		- 50%	1964.7	23.52	168.18	95.48	5.17	0.18
	θf	+ 50%	1964.7	119.93	95.30	8.74	5.41	0.06
		- 50%	11964.7	204.20	210.43	21.98	5.72	0.09
	RD	+ 50%	1964.7	107.93	240.15	81.54	5.13	0.20
		- 50%	1964.7	109.76	94.94	14.42	5.33	0.09
	CN	+ 50%	1964.7	12.66	32.94	94.18	4.92	0.30
		- 50%	1964.7	22.17	7.51	95.26	5.05	0.24
	Ck	10	1964.7	21.38	166.32	103.27	5.10	0.21
		.1 times	1964.7	168.11	166.23	42.60	7.27	0.87

*TDS mg/1 X 1000

Table 3.
Step-2: The overall effect of various hydrological processes on the annual changes of quality of groundwater.

Parameters	Range	Ground water Salinity TDS (mg/1)	Diff %
Base values	**0**	**5.53**	**5.53**
Percolation (cm)	103.27	**5.10**	**0.21**
	6.60	**5.69**	**0.08**
Infiltration (cm)	240.15	**5.13**	**0.20**
	7.51	**5.05**	**0.24**
Rate of Groundwater Abstraction	33.5 gpm	**5.53**	**0.0**
	60.5 gpm	**4.79**	**0.52**
	100.0 gpm	**4.87**	**0.46**
Irrigation Water Salinity	4000 mg/1	**5.41**	**0.08**
	10000 mg/1	**5.59**	**0.04**
Upper Saturated Zone Salinity	3000 mg/1	**4.44**	**0.55**
	6000 mg/1	**5.81**	**0.19**
Lower Saturated Zone Salinity	3000mg/1	**4.16**	**0.96**
	5000mg/1	**5.07**	**0.32**
Layer-1 Kh - Kv	10	**5.05**	**0.33**
	.1 times	**5.53**	**0.0**
Layer-2 Kh- Kv	10	**5.53**	**0.0**
	.1 times	**5.53**	**0.0**

* Only tow layers assumed
* No difference in head between the tow layers

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A Remote Sensing Approach for Monitoring Salt-Affected Soils: A Case Study in Saudi Arabia

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A REMOTE SENSING APPROACH FOR MONITORING SALT-AFFECTED SOILS: A CASE STUDY IN SAUDI ARABIA

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ABSTRACT

Various image analysis techniques have been applied to multitemporal Landsat Thematic Mapper (TM) data collected over a two-year period for an arid region north of Saudi Arabia. Results of the analysis were used to: 1) show the spectral classes and the corresponding areas of the different land uses covering the region, 2) delineate and map those areas that are salt-affected, and 3) monitor the temporal changes in salinity in terms of its severity and a real extent for the period under investigation. The study has indicated that a serious salinity problem exists and it is getting worse. Moreover, it calls for an urgent salinity management program for controlling the spread of salinity and reclaiming the damaged areas to be used for economic agriculture.

INTRODUCTION

Soil salinity in irrigated areas is becoming a serious problem for agriculture, especially in and semi-arid climates. Saline soil conditions have resulted in reduction of the value and productivity of considerable areas of land throughout the world. Salinity commonly occurs in irrigated soil because of the accumulations of soluble salts introduced from the continuous use of irrigation waters containing high or medium quantity of dissolved salts.

Management of the salt balance to mitigate its adverse effects on agriculture output is required. Management includes application of excessive irrigation water for leaching excess salts, providing soil drainage, and using proper agronomic practices such as growing salt-tolerant crops. Unfortunately, most of these requirements are rarely provided leading the world to increasing salinity problems.

The ability to determine and monitor the effects of salts on soil and plants are of great importance to agriculture. Conventional ground survey procedures are time consuming and costly. Thus the application of satellite imagery to agriculture fields detection and delineation of problematic soil is considered an attractive alternative. Remote sensing techniques can make breakthrough in terms of their efficiency and extent of coverage.

Nowadays commercially available earth-observing optical satellite systems loaded with sensors that record broad bands in the visible and infrared spectral regions like Landsat MSS, TM and SPOT, economically provide a wide range of images of increasing spatial resolution (1000 - 10 m). In addition, processing these satellite data which are primarily based on statistical pattern recognition and related topics such as classification, clustering, discriminate analysis, and principal component analysis, have become popular and quite widely accepted.

Several researchers have attempted to detect the distribution and severity of soil salinity with either visual or computer remote sensing techniques, or using combination of both methods. Abdel-Hamid et al. [1] presented a study in which Landsat Thematic Mapper (TM) data have been used to identify and map saline areas of Nile delta in Egypt with reasonable accuracy. Moreover, these affected areas were monitored with support of ground information using Geographic Information System (GIS).

Using Remote Sensing for mapping and monitoring salt affected soil has also been studied by Verma et. al [7]. Their study concluded that the degree of soil salinity influences the land cover and land-use pattern as a result of which these units exhibit different tone, texture and pattern on the TM image. An attempt has been made by the authors to correlate these variations with the degree of salinity. They also used the image interpretation to assign the amount of gypsum used to overcome the salinity problem. Thompson et al. [5] used different techniques in the delineation and classification of soil salinity. Their study has confirmed that saline affected soil can be reasonably detected using Landsat data.

Successful and partially successful techniques are varied and require adaptation according to data quality, size of mine areas to be detected, degree of salinity, environmental conditions, and biophysical setting. On the whole, detection and mapping of salinity related problems using remote sensing have been studied by many other researchers such as Venkataratnam [6], Manchanda [3], Millington et al. [4] and Csillag et al. [2], just to name a few.

The objective of this study is to use Landsat TM data for the delineation, mapping, classification and temporal change detection of salt-affected soils in the agriculture area of Skaka, north of Saudi Arabia. Remote sensing using Landsat TM data, coupled with image processing techniques are expected to provide elective and efficient means for inventory and monitoring the extent of this problem.

Site Characteristics

For the last decade, Saudi Arabia has shown an extraordinary agricultural development. This rapid growth combined with improper agricultural practices have resulted in many soil problems in different areas over the country. Skaka city, north of Saudi Arabia, is an example of those affected areas that are merging from a serious salinity crisis. Skaka city is located in Al-Jouf region north of Saudi Arabia. It is centered between 40°N and 30°E with an area of 612.5 km^2 (24.5 x 25 km). The area has a typical desert climate which is very hot in summer and very cold in winter.

The topography of the area consists of sand dunes covering the northeast part of the city and medium to small mountains scattered in the northern west. The rest of study area, in general, is relatively flat mainly used for agriculture purposes.

METHODOLOGY

As an attempt to map and monitor the salt affected soil in the region under investigation using an efficient technique, remote sensing approach was utilized as opposed to the conventional ground surveying methods. Nowadays, remote sensing is with no doubts one of the most efficient technologies used in gathering information, particularly after the tremendous developments which affected cameras, photographic techniques, films, aviation and satellites.

The procedure employed in the salinity evaluation process of the irrigated lands in Skaka are in the followings: 1) Requesting and obtaining at least two images representing the area spatially and temporally. The source of the images depends highly on cost and resolution required. In this project Landsat TM images covering the area under investigation were collected for two time periods - 1987 and 1993. During the time of conducting the study, the 1993 image was the most recent one conveniently available; 2) Performing an explorative unsupervised classification for the 1993 image to be used as a guideline for field data collection. Minimum amount of field data should be collected to provide training sets for the more accurate "Supervised classification" phase. Data collected include soil types, crop types, and water quality; 3) Using the analyzed field data to create a supervised classification map for the study area for the year 1993. The resultant map is employed to trace salt affected soil; 4) Producing a 1987 map using the unsupervised classification technique for the purpose of detecting general landuse changes and salinity spread as compared to the 1993 conditions.

Field Studies and Laboratory Analysis

With the Guidance of the 1993 unsupervisedly processed image, the site was carefully surveyed to observe and collect necessary information needed for the analysis. Detailed data such as farm establishment data, well digging date, evapotranspiration, water quality deterioration, bare soil types, and cultivated crop types were obtained for almost all the farms in the Skaka area. The data acquired was used first for the salinity mapping, which is the scope of this paper, and will be used later for the development of a salinity management program.

The soil chemical and physical properties and the water characteristics (pH and electric conductivity, EC) for all the samples collected were analyzed. Examples of the results are presented in Table 1.

Table 1 Soil Properties in Chosen Areas

Land	Soil Analysis (grain size distribution)					Soil Testing	
	% Gravel	% Sand	% Silt	% Clay	% Fine	Electric Conductivity (mmhos)(EC)	% Organic Matter
Farm 1	5.1	62.1	10.8	22	32.84	3.94	2.91
Farm 2	1.26	71.32	19	8.42	27.42	26	1.24
Farm 3	7.45	76.45	7.7	8.38	16.09	7.5	1.84
Farm 4	0.3	39.26	23.95	36.49	60.44	4.0	4.11
Farm 5	3.1	69.6	9.3	18.0	27.3	16.3	2.01
Farm 6	2.96	64.8	0.31	32.55	32.24	5.5	2.66
A	-	2.8	50.05	47.15	97.2	9	5.17
B	17.53	31.57	30.5	20.4	50.9	6.5	2.86
C	12.2	33.48	38.87	15.45	54.32	0.4	4.25
D	4.18	66.54	13.5	15.78	29.28	0.6	2.68
E	0.64	25.28	50.74	23.34	74.08	14	1.86
F	7.64	77.68	8.5	6.18	14.68	3.4	0.70

Image Interpretation

The Classification process involved the use of two techniques: supervised and unsupervised classifications. Both classification schemes were conducted using the well known image processing package "ERDAS". The interpretation process involved the following:

a. Loading and displaying the contents of the tapes, that storing the digital maps of the area for the years 1987 and 1993, on a high speed workstation. The produced images were used for visually determining the extent of the area to be analyzed and then extracting that portion out of the file.

b. Image Enhancing: Histogram Equalization, which is a nonlinear sketch, was applied on both images to enhance the distinction among its feature.

c. Color composing: Colors were composed using three bands - Red, Green, and Blue. The red, green and blue fights were added together to produce a wide variety of colors needed for features geographic recognition. Different color combinations were used to specify different classes for each land use. The signature divergence process was used to choose image colors.

d. Performing supervised classification using the selected band combination for the (1993) image, Figure 1. In addition the same band combination was also used for performing unsupervised classifications for the (1987) image, Figure 2 as well as the (1993) image which was used in the field survey stage as mentioned earlier.

e. Using Maximum Likelihood process: This process is used to get color combination and classes classifications. The maximum likelihood decision rule is based on the probability that a pixel belongs to a particular class. The basic equation assumes that these probabilities are equal for all classes, and that the input bands have normal distributions.

RESULTS AND DISCUSSION

In this study, two Landsat TM images for the years 1987 and 1993 for Skaka city were used to monitor landuse changes and salinity affected soil.

SPATIAL AND TEMPORAL LANDUSE DETECTION

Results of the unsupervised classification for 1987 and 1993 are presented in Table 2. Comparison of the results show noticeable change in landuse during the six years period. Results also show that some of the landuses have expanded such as urban setting while some others like bare soils have decreased.

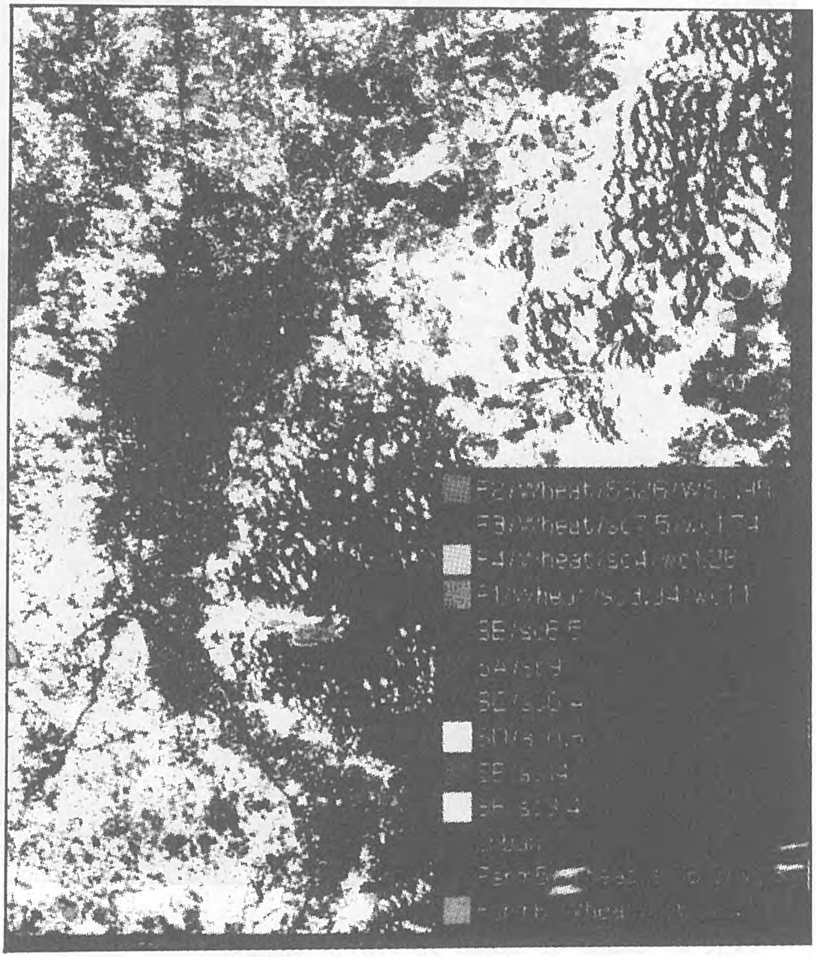

Fig. 1 Image of Skaka in 1993: Supervised Class

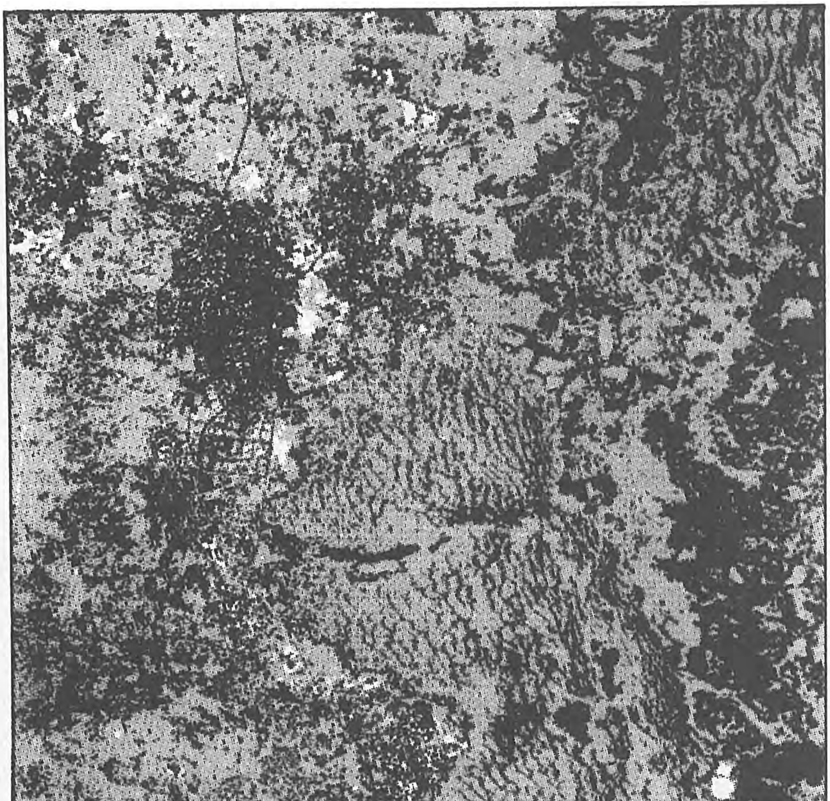

Fig. 2 Image of Skaka in 1987: Unsupervised Class

Table 2 Unsupervised Classification for Study Area

Class #	Image 1987		Image 1993		Land 1987	Land 1993
	% Cover/Full	Class Area (Km^2)	% Cover/Full	Class Area (Km^2)		
1	40.904	256.64	40.522	256.72	SF	SF
2	7.372	46.25	4.287	27.16	Urban	Urban
3	20.497	128.60	24.661	156.23	Sand	Sand
4	1.708	10.72	1.989	12.60	Urban	Urban
5	0.416	2.61	2.351	14.89	F3	F4
6	0.389	2.44	0.885	5.61	Urban	Urban
7	0.184	1.15	0.005	0.03	SA	SA
8	0.215	1.35	0.278	1.76	Urban	Urban
9	0.026	0.16	0.038	0.24	F4	F4
10	1.424	8.93	3.656	23.16	F5	FI+F2+F 5
11	0.089	0.56	0.167	1.06	SB	F6
12	1.13	7.09	0.031	0.19	SD	F3
13	6.306	39.56	6.447	40.84	Sand	Sand
14	0.775	4.86	0.855	5.42	SD	SE
15	18.564	116.47	12.384	78.46	SE+SF	SE
Total	100	627.39	100	624.37		

Results of the supervised classification of the 1993 image, on the other hand, are presented in Table 3. In this procedure, signatures of predefined areas using field data were determined on the image. Accordingly each pixel (i.e. either farm or bare soil) on that same image was then classified. Percentage of each class along with its size and class type are displayed.

Results in Tables 2 and 3 were used to classify the area according to the land use. The classification is based on soil type. Therefore, three categories were defined: Cultivated, bare soil, and urban. Table 4 shows the size and percentage of cover to the total area of each category for the unsupervised and supervised classification, respectively. It is clear that a growth in the cultivated areas was noticed. The area has grown from 11.7 to 39.54 km^2. On the other hand, bare soil areas decreased from 88% to about 72%. Also, Urban setting has increased during the six years period to about double. Generally the results of landuse changes are as expected in any developing town.

Table 3 Supervised Classification for Study Area				
Class #	Image 1993	Image 1993	Land 1993	Class Color
	Cover/Full	Class area (Km^2)		
1	0.506	3.21	F2	Green
2	0.348	2.21	F3	Red
3	0.127	0.81	F4	Sand
4	3.076	19.48	FI	Ochre
5	11.17	70.77	SB	Magenta
6	15.81	100.17	SA	Cream
7	0.622	3.94	SC	Blue
8	2.65	16.81	SD	White
9	0.321	2.03	SE	Blue-Green
10	39.146	247.99	SF	Yellow
11	24.803	157.13	Urban+Sand Shadow	Black
12	1.351	8.56	F5	Brown
13	0.044	0.28	F6	Orange
Total	100	633.39		

Table 4 Land Use Categories

Land	Image 1987 (unsupervised)		Image 1993 (unsupervised)		Image1993 (supervised)	
	Class area (KM^2)	% Cover/ Full	Class area (KM^2)	% Cover/ Full	Area (KM^2)	% Cover
Cultivated	11.70	1.87	39.54	6.24	34.53	5.45
Bare Soil	554.93	88.45	459.24	72.49	441.71	69.72
Urban + Sand -Shadow	60.76	9.68	125.59	19.49	157.13	24.81
Total	627.39	100	624.37	100	633.39	100

Salinity Analysis

Analysis of the supervised and unsupervised images with support of field data were performed in order to first assist the existing salinity conditions and then calculate the rate of increase of salinity during the period of study. The salinity and alkalinity conditions for each category (either farm or bare soil) were determined based on field data and using a standard classification system. The results are in Table 5.

Table 5 Salinity and Alkalinity Conditions for Sample Areas

Land	EC (mmhos)	Salinity Condition	Water pH	Alkalinity condition
Farm 1	3.94	Low	8.0	LOW
Farm 2	26	Severe	8.0	LOW
Farm 3	7.5	Medium	7.9	LOW
Farm 4	4.0	Medium	7.8	LOW
Farm 5	16.3	V High	8.0	Low
Farm 6	5.5	Medium	7.7	Low
Soil A	9	High	-	
Soil B	6.5	Medium		
Soil C	0.4	V Low		
Soil D	0.6	V Low		
Soil E	14	High		
Soil F	3.4	Low		

From Table 5 it is noticed that alkalinity is low for all farms. On the other hand, salinity ranges from very low (Soil C and D which are sand dunes) and low (Farm 1) to very high (Farm 5) and severe (Farm 2).

These salinity indicators for each category were then used to reclassify the two 1987 and 1993 images. Later the size of the affected soil associated with each salinity level was determined as shown in Table 6 which reveals that salinity has increased during the study period in cultivated areas. This increase can be visualized clearly by noticing that only 14.4% of the land have very high salinity in 1987, while in 1993 a 45.2% of the land (using unsupervised classification) got affected with very high salinity. These results prove that the cultivated areas in the study area (Skaka) are affected by salinity and need an urgent management program to determine the factors causing this damage and the correct methods for mitigation.

Table 6 Salinity Conditions in Cultivated Areas

Salinity Conditions	1		2	
	1987 Unsupervised		1993 Unsupervised	
	Area (Km^2)	% of cultivated areas (1987 +1993)	Area (Km^2)	% of cultivated areas (1987 +1993)
Medium	2.77	5.4	16.38	31.9
V. High	8.93	17.4	23.16	45.2
Severe	0	0	3.2	6.2

CONCLUSIONS

Several conclusions can be drawn from this study:

a. Landsat Thematic Mapper (TM) data could be used for delineating and monitoring soil salinity. Accuracy could be significantly improved by using computer enhancement techniques. Lots of effort, time, and money have been saved by using remote sensing techniques. Yet very reasonable descriptive results were achieved.

b. It has been proved that the majority of the cultivated lands in the study area are affected by salinity at different levels.

c. Temporal analysis revealed that a rapid increase in salinity level and extent have been detected during the six year study period which is presumed short.

d. In terms of providing guidance to ground based money, use of remote sensing data may make significant improvement in monitoring the spread of the saline solid.

RECOMMENDATIONS

Based on the results the following are recommended:

a. More samples data should be collected to improve the accuracy of results.

b. When studying soil related problems, it is better to use images that were taken when there is no heavy vegetation cover such as right after crop cultivation.

c. An enhanced supervised classification can be achieved when samples (field data) are collected within the time the satellite image was taken for the study area.

d. It is advisable to regularly monitor lands that are potentially affected by salt to get good periodical estimates of the extent and severity of salinity.

e. Related authorities should initiate the necessary soil amendments and the suitable reclamation program to control salinity damage of cultivated areas.

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Comparison Study Between Native and Soil Irrigated by Brackish Groundwater, Southern Kuwait

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COMPARISON STUDY BETWEEN NATIVE SOIL AND SOIL IRRIGATED BY BRACKISH GROUND WATER, SOUTHERN KUWAIT

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ABSTRACT

This study was conducted to evaluate the impact of irrigation by ground water on soils in Wafra farms, southern Kuwait. The study also compare between the native (reference) soil and irrigated soil till a depth 1.0 to 1.2 m; the rooting zone. Comparison include EC, pH, TDS, and major cations and anions. By using the Sodium Adsorption Ratio (SAR) and Exchangeable Sodium Percentage (ESP) equations types of soils were determined; whether it is saline, non-saline or sodic. In order to evaluate the seasonal effects samples were collected in dry and wet seasons.

It was found that the majority of irrigated soils in Wafra farms are saline due to irrigation by brackish ground water. This phenomenon was found to be concentrated in the central part of farm area, where older farms exist. Virgin non-cultivated soils found to be normal non-saline even within the farm borders, indicating that the sole reason of saline soils within the study area is the brackish ground water used for irrigation.

In order to stop the deterioration of both ground water and soil qualities and from the results of the study, it is recommended that fresh desalinated water planned to be supplied to all Wafra farms, should be considered for irrigation under a cost code that reflect the valuableness of this water and under the supervision of PAAF (Public Authority for Agriculture and Fisheries) to ensure the application of new irrigation techniques that conserve the amount of irrigation water and minimize the wastage of such expensive water. Further studies should be conducted on obtaining the optimum amount of water needed for irrigation and leaching of salts soluble on soils without reaching the ground water levels.

INTRODUCTION

As part of the and regions, Kuwait suffers from a scarcity of natural water resources of acceptable quality to satisfy domestic as well as agricultural demands. In addition, ground water in Kuwait is mostly brackish to saline. The location of the agricultural areas (see Fig. 1), cost of fresh desalinated water and the primitive irrigation methods used like furrow and basin irrigation by the farmers, all these factors led to the over exploitation of the ground water in order to satisfy the irrigation needs. Since the early 1960's all irrigation needs were met from the ground water which has been depleted and its quality has been deteriorated (Al Sulaimi et al, 1994).

This deterioration of ground water was reflected on the soil, where soluble salts increased in the top soil zone and the soil was changed from normal non-saline to saline. In order not to affect the crop quality, these soluble salts are being leached during irrigation periods. This procedure of soluble salts leaching requires extra amounts of ground water.

The deterioration of soil quality in agricultural areas due to salinization and/or sodicification is an international problem recognized by the World Resources Institute (1986), which indicated that around 1-1.5 million ha of irrigated land all over the world is affected yearly by salinization. There are two main reasons for the soil deterioration in agricultural areas, one is natural which is the ground water salinity, the other is a man-made reason which is the outdated low efficiency irrigation practices that consume huge amounts of water. The consequences of these practices are clear from the estimation of FAO and UNESCO of about one-half of all existing irrigation systems around the world (totalling about 250 million hectares) are seriously affected by salinity and water logging problems and 10 million hectares of irrigated land are abandoned annually due to these problems (Rhoades et al., 1990; and Szabolcs, 1985).

Wafra farms occupy an area of about 30 km^2 at the extreme south of Kuwait (Fig. 1), with around 1000 wells producing ground water from the Kuwait Group; the shallowest aquifer in Kuwait. During the last 30 years, farmers in the Wafra area have been mining the brackish ground water. Hence, both ground water and soil quality were affected during this long period of extraction, irrigation and leaching. This deterioration of ground water quality led many farmers to shift towards protected environment production, using expensive desalinated water.

Wafra's importance as a major national agricultural asset in Kuwait should be supported by both the government and farmers through their joint efforts to improve quality and quantity of production on a long-term basis. Any improvement of soil properties will be reflected on the crops produced.

The main objective of the study is to determine the effects of irrigation by brackish ground water on the soil of Wafra area, by comparing the virgin non-cultivated soil with the soil irrigated by the brackish ground water.

MATERIALS AND METHODS

To achieve the objective of the study, the following tasks were conducted:

1. Sampling Plan Design

The design of the sampling plan based on the available data and the data collected in the reconnaissance stage of different parameters expected to affect the salinity and/or sodicity of the soil, such as ground water quality and depth, age of farm, and method and duration of irrigation.

2. Field Work and Testing of Samples

From the selected farms, soil samples were collected by manual drilling to a depth of around 1.2 m. From each farm, four holes were drilled; two inside an irrigated area and another two in a non-irrigated area to collect reference samples representing the native soil of the farm. Soil samples were collected for each 20 cm depth intervals. Samples for detailed analysis from each hole were selected on the peak salinity basis. Soil samples were collected and placed in PVC bottles, labelled with block, farm and site (irrigation or reference) numbers, sample depth and date of collection. The total number of these samples was 560. These samples were tested for salinity and pH values after being extracted in the laboratory. From the peak salinity test (soil sample of maximum salinity among samples collected from different depths within the rooting zone), one representative sample was collected and chemically analyzed. Within the same farm and from the nearest bare uncultivated soil, another sample was collected and analyzed as a reference sample.

From the 27 farms, selected according to the bases mentioned in the sampling plan design, 216 samples were selected for full analysis for both dry and wet seasons. The purpose of having both seasons is to assess the consequences of seasonal climatic changes; temperature, evaporation, rainfall and influence of irrigation variation.

A ground water inventory was conducted during the field work were production rate for every operational well within the selected farms was recorded along with the pumping duration and water salinity. Ground water levels were also recorded for operational and non-operational wells. All these measurements were recorded for dry and wet seasons for around 75 wells.

RESULTS AND DISCUSSION

All the collected soil samples were analyzed after being extracted in the laboratory. The leaching method used was vacuum extraction with an extraction ratio of 1:2 (500g soil and 1000ml of deionized water). The extraction ratio was taken into consideration during the analyses of the extracted water. An example of these analyses results is shown in Table 2.

Saline top soils, often recognized by the presence of white salt encrustations on the surface due to the presence of chloride and/or sulfates of Na, Ca and Mg, were recognized within the study area. From the chemical analyses of the soil samples collected between the top soil and the depth of around 1.2 m, it was indicated that the bottom soil (rooting zone) is of better quality than the top soil, which characterized by these encrustations due to the high evapotranspiration rates and high salinity of the irrigation water.

From the chemical results of the soil samples and on the basis of the Sodium Adsorption Ratio (SAR), which is between 13 and 15, and the Exchangeable Sodium Percentage (ESP) of greater that 15 as the definition of a sodic soil, none of the collected samples are sodic (USDA, 1973). Considering the Electrical Conductivity (EC.) of the saturation extract of soil samples as a measure of soil salinity, where soils of EC_e more dm 4,000 μs are considered as saline soils, it can be concluded that six farms of the 27 selected farms are considered of saline soils. These farms are W-3-50, W-4-10B, W-10-40, W-E-4, W-3-61 and W-6-10. The rest of the selected farms have soils of non-saline normal alkaline type (Fig. 2). Saline soils concentrated in the central part of Wafra, where older farms are located, with ground water is relatively deeper and with higher salinity. Reference soil samples representing virgin soil were not affected by salinity, where average salinity was around 500-1000 μs (EC), while irrigated soil, in general, is more saline than the reference soil even in farms not yet affected by soil salinity, where the average salinity for irrigated soil samples was between 2,500 and 3,000 μs (EC), see Fig. 3.

The results of the irrigation water inventory show that the soil salinity decreases with the increase of duration of irrigation periods during the day because of the effect of leaching of salts soluble in the soil from the rooting zone.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. 22% of the selected farms were affected by soil salinity and the rest of the farms are of non-saline normal alkaline soils.

2. Saline soils are concentrated in the central part of the study area, where older farms exist underline by relatively deep and poor quality ground water.

3. Reference soil samples representing native soil were not affected by salinity, where average salinity was around 500-1000 µs (EC_e)

4. Irrigated soil, in general, is more saline than the reference soil even in farms not yet affected by soil salinity, where the average salinity for irrigated soil samples was between 2,500 and 3,000 µs (EC_e).

5. By comparing the salinity of native soil with that of the irrigated soil it can be concluded that soil salinity within the study area was originated by the using of brackish ground water for irrigation for the last thirty years.

6. Irrigation methods used in Wafra is almost the same (basin irrigation). However, soil salinity found to be always decrease with the increase of the duration of irrigation due to the flushing and leaching of soil salts from the rooting zone.

Recommendations

From the results of the study it is recommended that fresh desalinated water planned to be supplied to all Wafra farms, should be considered for irrigation only under a cost code that reflect the valuableness of this water and under the supervision of the Ministry of Electricity and Water (MEW) and Public Authority for Agriculture and Fisheries (PAFF) to ensure the application of new irrigation techniques that conserve the amount of irrigation water and minimize the wastage of such expensive water. The other choice is to continue using the brackish ground water with proper management of irrigation and leaching practices that ensure the optimum use of ground water for these two purposes by the implementation of proper techniques that help in determining the optimum amount of water needed within the rooting zone for irrigation and leaching of soluble salts and the drainage of these soluble salts before it reach the water table. Further studies should be conducted on obtaining the optimum amount of water needed for irrigation and leaching of soluble salts within the rooting zone without reaching the ground water levels.

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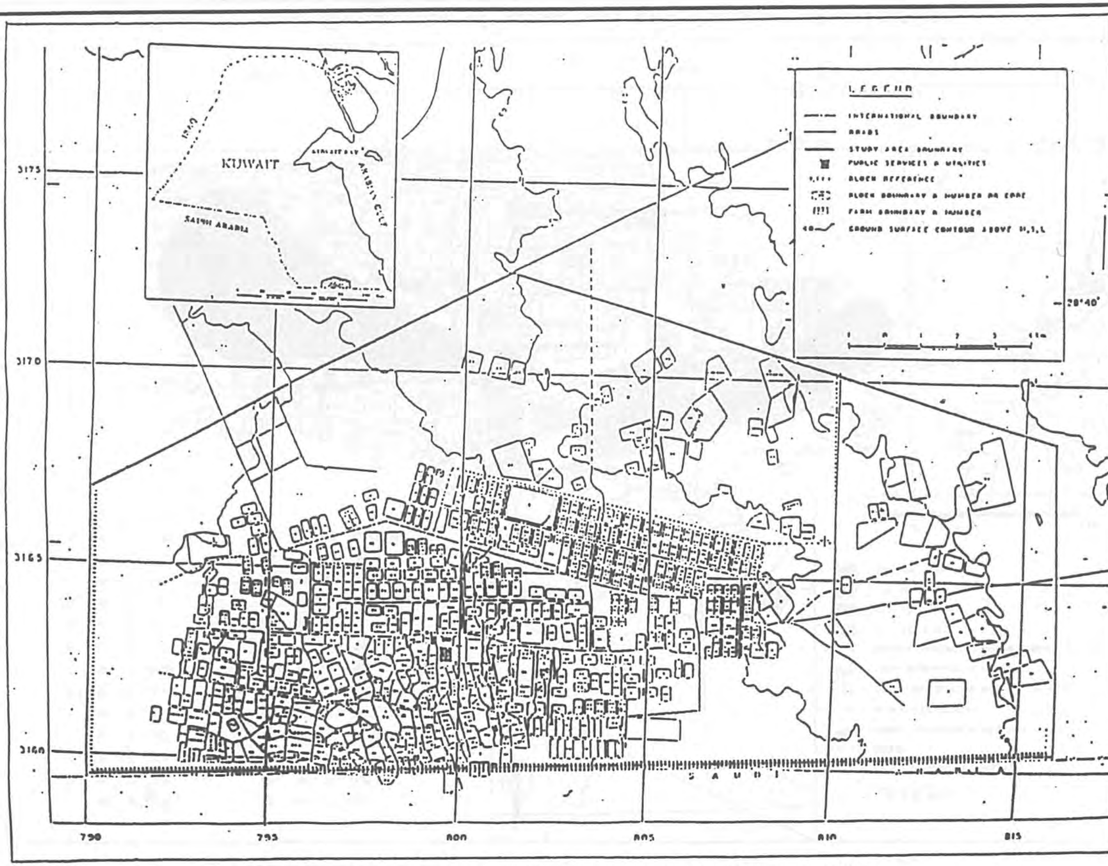

Fig. 1 Location map of the study area (after Al-Sulaimi et al, 1994)

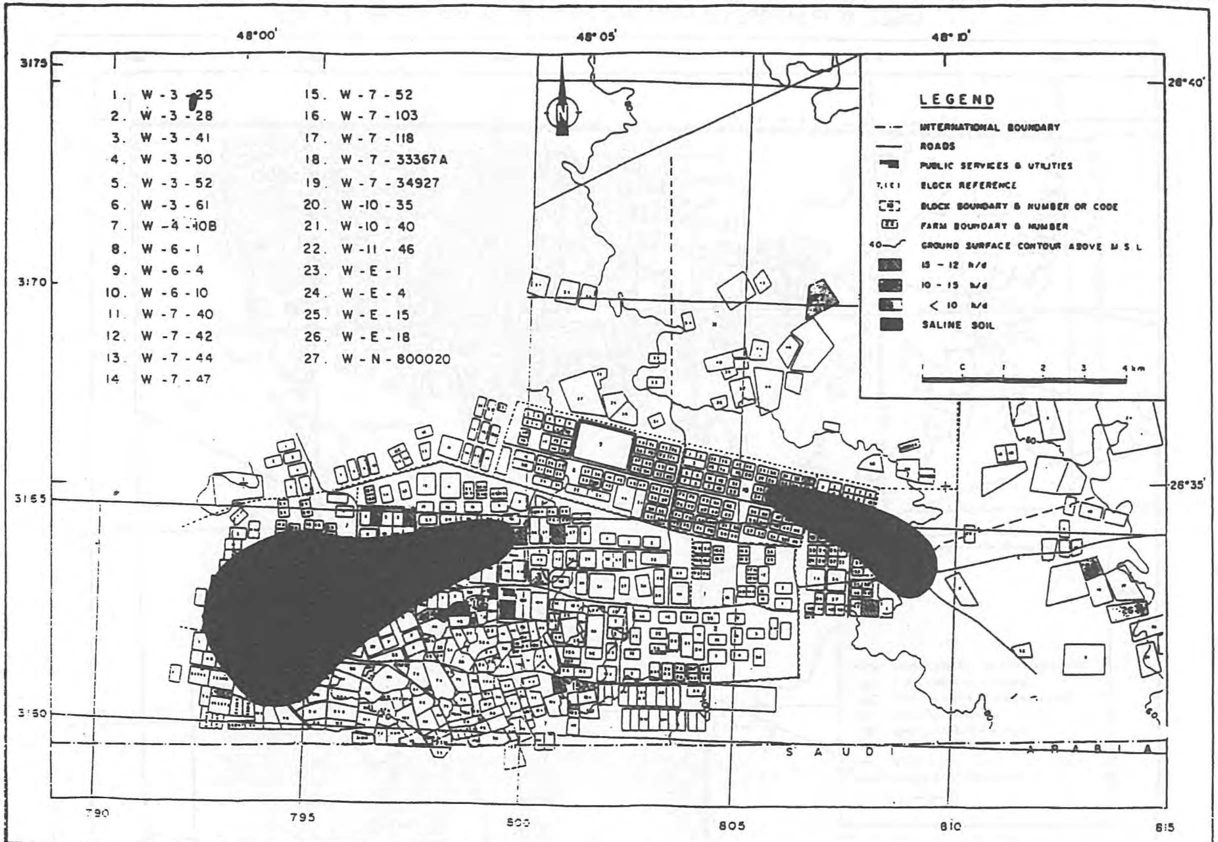

Fig. 2. Distribution map of saline soil and duration of irrigation.

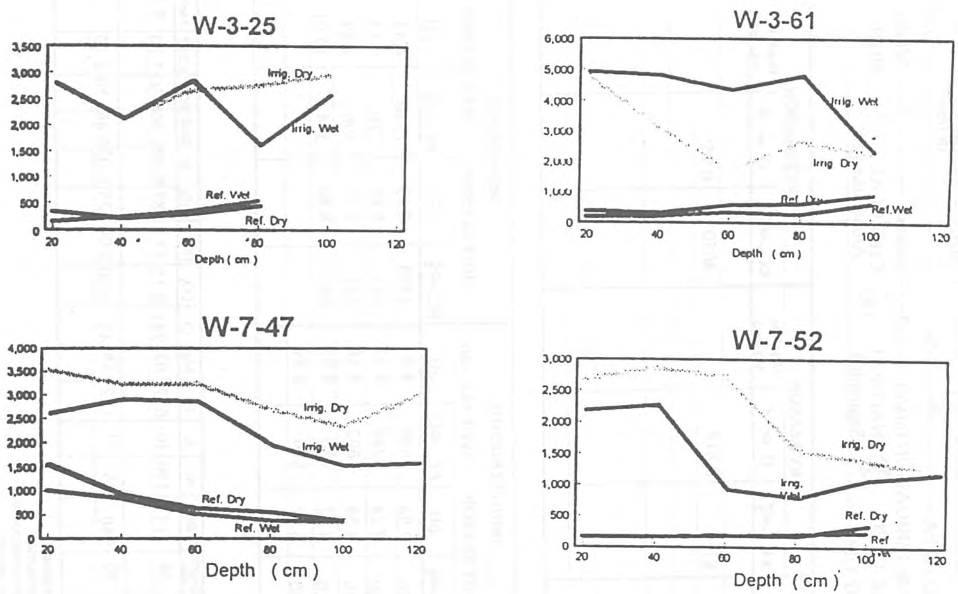

Fig. 3. Change in soil salinity (EC us) with depth for nature and irrigated soils in dry and wet seasons for selected farms within the study area.

Table 1. Data collected for soils for Farm No. W-7-42.

LOCATION ------------W-7-42------------------ CODE-----------12------------

CULTIVATED AREA ------------90-------% ----------------38 000---------------m^2

DURATION OF IRRIGATION (hrs/d) --------4----- Summer ------------4----- Winter

FERTILIZERS USED (x) NATURAL (x) CHEMICAL ( ) NON

FERTILIZING TIME-----------September-------------Around the year-----------------

WELL NO	DRY SEASON			WET SEASON		
	EC μ/s	Q m^3/d	Depth to WL (m)	EC μ/s	Q m^3/d	Depth to WL (m)
1						
2	8115	0.818		8650	0.955	
3						
4						
5						
6						
7						
8						

DEPTH cm	IRRIGATED SOIL				REFERENCE			
	DRY SEASON		WET SEASON		DRY SEASON		WET SEASON	
	EC μ/s	pH	EC μ/s	pH	EC μ/s	pH	EC μ/s	pH
20	2930	7.94	3480	8.03	1408	8.15	1520	8.43
40	2100	8.24	2282	8.32	675	8.88	720	9.13
60	2130	8.34	1602	8.58	611	9.37	596	9.29
80	2610	8.12	920	8.92	946	8.80	304	10.01
100	2180	8.27	876	8.89				
120								

Sample type	Season	Depth cm	TDS	Na	K	Ca	Mg	Cl	CO_3	HCO_3	SO_4	B	SAR*	ESP*	CEC*	Moisture %
IRRIGATED	DRY	20	3155	196	16	677	65	241	0.15	39	187	0.05	1.90	.50	5.20	8.7
	WET															
REFERENCE	DRY	20	940	25	17	192	28	43	0.00	0.00	525	0.05	0.46	.50	5.30	
	WET															

* TDS - TOTAL DISSOLVED SOLIDS
* SAR - SODIUM ADSORPTION RATIO
* ESP - EXCHANGABLE SODIUM PERCENTAGE
* CEC - CATION EXCHANGE CAPACITY

Field Estimation of Unsaturated Hydraulic Parameters Using Point Source and Disc Tension Infiltrometer

Salem A. Al-jabri and A.W. Warrick

FIELD ESTIMATION OF UNSATURATED HYDRAULIC PARAMETERS USING POINT SOURCE AND DISC TENSION INFILTROMETER

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ABSTRACT

Two experimental methods, point source and disc tension infiltrometer, were used to estimate the saturated hydraulic conductivity (K_s) and the macroscopic capillary length (λ_c) at three sites. The textural classification of these sites were sandy loam (Site 1), loamy sand (Site 2), and clay loam (Site 3). In the point source method, three different flow rates (2,3,4 $l$hr^{-1}) were applied to measure the steady-state ponded area. In the disc tension infiltrometer method, three different tensions (-15, -10, and -6 cm of water) were applied to measure the steady-state flow rate per unit area, From these measurements, the saturated hydraulic conductivity and the macroscopic capillary length were determined. Both methods produced good and reliable estimates of the hydraulic parameters. There was good agreement between the two methods in estimating K_s and λ_c for the first site. However, the point source gave estimates of K_s about twice as large as the estimates from the disc tension infiltrometer for sites 2 and 3.

Keywords: unsaturated hydraulic conductivity, macroscopic capillary length, point source, disc tension infiltrometer.

INTRODUCTION

The hydraulic parameters (hydraulic conductivity and water retention) of unsaturated soils are very important to many disciplines, e.g., agriculture, hydrology, environment, forestry, and engineering. They determine how much water will infiltrate into the soil and how much will flow on the soil surface, which may cause erosion problems. Thus, estimating the hydraulic properties of field soils can aid in predicting the time that water and pollutants travel to ground water. Consequently, this helps in developing the best soil management practices in order to minimize the potential contamination of the ground water from land-applied chemicals. This also helps in designing irrigation systems and improving the efficiency of irrigation practices.

Recent advances in technology and basic sciences have provided new understanding of soil hydraulic properties of unsaturated soils. Much work has been conducted on the determination of these properties. Yet to date, there is not a consensus on which method may be suitable for all soils and circumstances (Dirksen, 1991). Thus, investigations are needed to evaluate different methods of determining soil hydraulic properties. Field methods for estimating the hydraulic parameters are potentially more accurate than laboratory methods, because they are more sensitive to soil structure. However, they are also more time consuming.

In recent years, new devices and techniques have been utilized to estimate in-situ hydraulic parameters, e.g., point source method (Yitayew and Watson, 1986; Shani et al., 1987; Yitaew and Khan, 1995; and Ward et al., 1995) and disc tension infiltrometer (White and Sully, 1988; Perroux and White, 1988; Smettem and Clothier, 1989; Lein, 1989; Reynolds and Ehick, 1991; and Hussen and Warrick, 1993).

The objective of this study is to use the point source and disc tension infiltrometer methods to estimate the unsaturated hydraulic properties (K_s and λ_c) compare the results.

THEORY

Water flow in a homogenous, isotropic, unsaturated soil is generally described by Richard's equation:

$$\nabla - (K \nabla H) = \frac{\partial \theta}{\partial t} \qquad (1)$$

where K is the unsaturated hydraulic conductivity (LT^{-1}), H is the total hydraulic head (L), 0 is the volumetric water content (L^3L^{-3}), t is the time (T) and Δ is the vector gradient operator (L^{-1}). Water flow from a disc or point source is three-dimensional. This is because of gravity forces acting downward and capillary forces acting in all directions (Hussen and Warrick, 1995).

For stead-state flow in a uniform soil, Eq. (1) can be rearranged to yield (Philip, 1969):

$$\nabla . (D \nabla\theta) = \frac{\partial K}{\partial z} \tag{2}$$

where D = K (dh/θ) is the soil water diffusivity (L^2T^{-1}) and z is the soil depth (L). Both K and D in Eq. (2) depend strongly on θ and the matric potential h (L), which is a component of H. The above equation (Eq. 2) can be linearized by defining the matrix flux potential, θ, (Raats, 1971) as:

(3)

where θ_n and h_n correspond to the background (driest) conditions considered and the unsaturated hydraulic conductivity function, K(h), is assumed to follow an exponential form as proposed by Gardner (1958):

$$K(h) = K_s \, e^{\alpha h} \tag{4}$$

in which K_s is the saturated hydraulic conductivity (LT^{-1}) and a is the soil texture/structure parameter (L^{-1}). The reciprocal of α is called the macroscopic capillary length, λ_c, which is an important parameter because it quantities the importance of capillarity relative to gravity in a soil (Philip, 1983). Commonly, it is large in fine textured soils and small in coarse textured soils (Ward et al., 1995).

Using the above relation, a linearized form of Richard's equation can be developed as:

$$\nabla^2 \phi - \alpha \phi = . \, 0 \tag{5}$$

Wooding (1968) solved the above linearized flow equation (Eq. 5) for a shallow circular pond of radius (r) on the soil surface. He presented a solution for the steady-state flow per unit area, q as:

$$q = \frac{Q}{\pi r^2} K_s \left(1 + \frac{4}{\pi r \alpha}\right) \tag{6}$$

where Q is the volumetric flow rate (L^3T^{-1}). He assumed that the soil is uniform homogenous and non-swelling. Substituting (4) into (6), Wooding's relationship can be written as:

$$q = K_s e^{\alpha h} \left(1 + \frac{4}{\pi r \alpha}\right) \tag{7}$$

For Wooding's solution, α is considered constant (Philip, 1969). However, Parlange (1972) and Parlange and Hogarth (1985) suggested that for real soils, α should be a function of θ. The appropriateness of constant α, as opposed to α (θ), is still being debated (Ward et al., 1995).

FIELD PROCEDURES

The study was conducted on three sites at the Campus Agricultural Center, The University of Arizona, Tucson, Arizona, USA. The first site was a Gila soil, which is classified as Typic Torrifluvents, coarse loamy, mixed, thermic. Site 2 was a Brazito soil which is classified as Typic Torrifluvents, sandy, mixed, thermic. Site 3 was a Pima soil, which is classified as Typic Torrifluvents, fine-silty, mixed, thermic. The particle size distributions of soil samples from the three sites are shown in Table 1. The soil texture of each site was assumed uniform.

A completely-randomized design was used. Three square plots measuring 4m x 4m were established for each site. Each plot was then divided into subplots of 2m x 2m area. With this procedure, 12 subplots were produced. Nine of these subplots were selected randomly to run the point source experiments, while the other subplots were used for running the disc tension infiltrometer experiments.

Table 1 Particle size distribution of the three sites

Site	% Rock fragment*	% Sand	% Silt	% Clay	Texture
1	1-2	52	38	10	Fine sandy loam
2	10-15	118	17	5	Loamy sand
3	<1	23	49	28	Clay loam

*% by volume

Point Source

A constant head point source was designed and used for applying the water. A clear Plexiglas cylinder was used as a water reservoir. The constant head was established by means of a tube open to the atmosphere and inserted from the top into the reservoir. The height of the tube above the outlet valve controls the flow rate. Other than the tube, the whole system was considered to be air-tight. By maintaining a constant positive pressure head, a constant flow rate was obtained.

Three different flow rates (2, 3, 4 lhr-1) were applied in this study. Each flow rate was applied on a separate plot. During the experimental work, the flow rate was checked every hour. The steady state radius of the ponded area was then measured. Before applying the water, the soil was levelled to achieve a symmetric and uniform wetting pattern.

Disc Tension Infiltrometer

The disc tension infiltrometer is designed to measure the infiltration rate at a controlled water pressure within a circular area at the soil surface (Warrick, 1992). The water pressure can be slightly positive, but usually is at a small tension, i.e., subatmospheric pressure (Warrick and Ojeda, 1993). The greater the tension applied, the smaller will be the diameter of the pores that can participate in water flow (Perroux and White, 1988).

A disc tension infiltrometer, which has a radius of 10 cm was used to measure the steady-state flow at three different tensions (-15, -10, -6 cm of water). The highest tension (-15 cm) was applied first, followed by the lower tensions. The time taken to achieve steady-state flow at each tension was recorded, using a stop watch.

RESULTS AND DISCUSSION

Data collected from point source and disc tension infiltrometer measurements were used to determine the saturated hydraulic conductivity, K_s, and the macroscopic capillary length, λ_c. With the point source method, the above unsaturated hydraulic parameters were calculated from Eq. (6) using a fitting procedure, where q is controlled in the experimental procedure and r is measured. With the disc tension infiltrometer, K_s and λ_c, were computed by a non-linear fitting procedure using Eq. (7), where h and r are controlled in the experimental procedure and q is measured,

Table 2 fits the average K_s and λ_c for each site as determined from the replicate measurements of the point source method and the disc tension infiltrometer. The point source method yielded larger estimates of K_s and smaller estimates of λ than the disc tension infiltrometer for all of the three sites. For Site 1, there was good agreement between the two methods in estimating K_s and for Site 2, the point source method yielded an estimate of appropriately twice as large as that from the disc tension infiltrometer. However, both techniques yielded relatively similar estimates of λ_c. For Site 3, the same results were found as with Site 2. The point source method gave a larger estimate of K_s (i.e., 150% higher) than the disc tension infiltrometer, but both techniques yielded relatively similar estimates of λ_c.

It is shown in Table 2 that the point source produced almost equal estimates for K_s for Sites 1 and 3, even though the latter is finer in texture. This is probably because the measurement was taken before the steady-state condition was achieved (at Site 3), which would result in a higher saturated hydraulic conductivity than otherwise. Ward et al. (1995) noted that variability due to instrumentation and soil are associated with field experiments of the point source method. Variable in the discharge rate and in the shape of the ponded area are problems associated with point source experiments in the field. Furthermore, changes in climatic conditions during the experiments can alert experimental results. Figure 1 shows a plot useful for determining the saturated hydraulic conductivity and the macroscopic capillary length from the point source method using Wooding's relationship. Note that a wide range of discharge rates is desirable to obtain good results.

The disc tension infiltrometer produced reasonable and consistent estimates for the hydraulic parameters for all three sites as indicated in Table 2. With this method, the hydraulic parameters were computed from unsaturated infiltration measurements made at three tensions on the same infiltration surface. This contributed to minimizing variability in the measurements. For determining hydraulic parameters with the disc tension infiltrometer, the last five infiltration measurements were used to find the steady-state flow rate (Fig. 2). The hydraulic parameters were then computed by using a best-fitting procedure (Fig. 3).

Table 2. Average hydraulic parameters obtained from the two methods for the 3 sites.

Method	K_s (cm/hr)	λ_c (cm)
Site 1		
Point Source	1.52	7.01
Disc Tension Infiltrometer	1.46	7.86
Site 2		
Point Source	10.43	5.47
Disc Tension Infiltrometer	5.10	6.40
Site 3		
Point Source	1.15	9.95
Disc Tension Infiltrometer	0.43	11.26

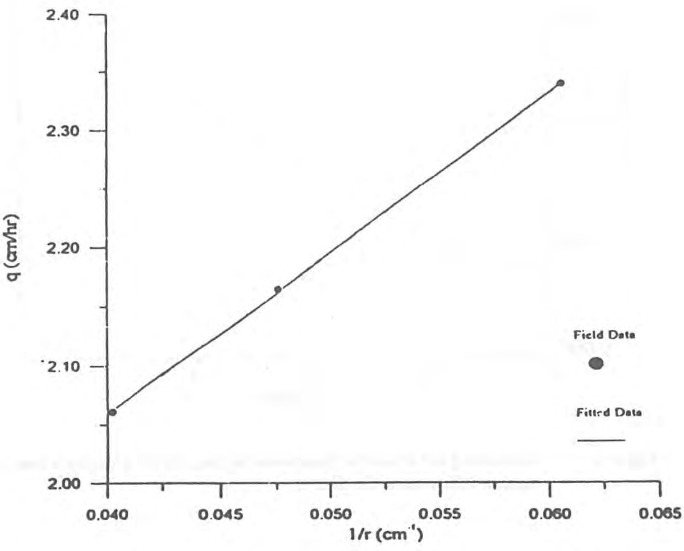

Figure 1. Example of determining K_s and λ_c using point source data (Site 1).

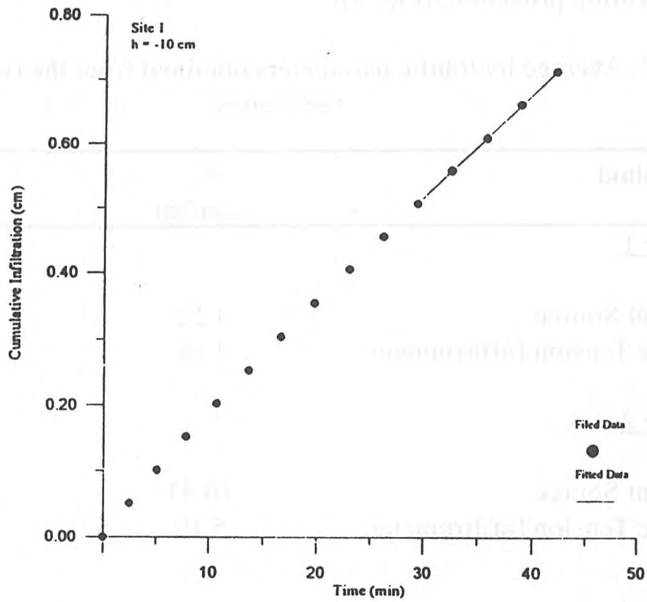

Figure 2. Cumulative Infiltration vs. Time (disc tension infiltrometer).

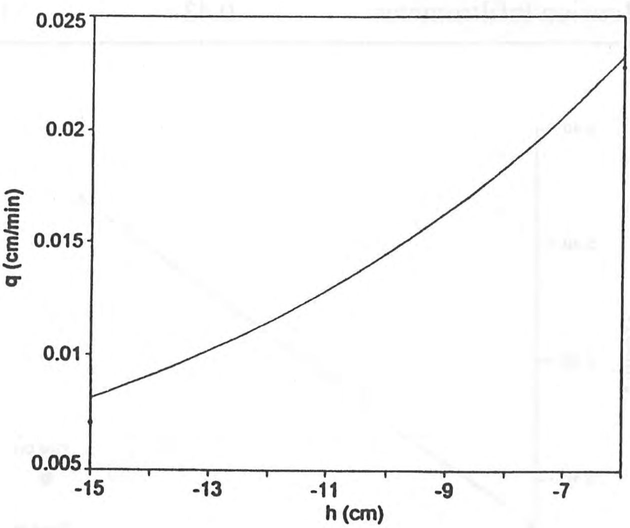

Figure 3. Calculating the hydraulic parameters by best-fitting procedure from disc tension infiltrometer for Site 1.

CONCLUSION

This study was conducted to estimate the average hydraulic parameters for three different soil types in the field. The two methods gave close estimates of the hydraulic parameters for the first site. The estimates using point source method for K_s were about twice as large as those produced by the disc tension Infiltrometer for Sites 2 and 3. Climatic conditions (e.g. wind) and variability in discharge rates and the shape of the ponded area can have a significant effect on the point source technique. Moreover, each discharge rate was applied on a separate plot, which increases the effect of soil variability on the measurements. On the other hand, all the tensions imposed by the disc tension infiltrometer were applied on the same area. This minimizes the effect of spatial variability, which results in more consistent and stable measurements.

Generally, both methods are applicable and reliable in determining in situ hydraulic transport properties. They are simple to use, repeatable and applicable to a wide range of soils. However, some difficulties and experimental errors may arise when measurements are made in heavy textured soils; e.g. underestimating the time to reach the steady-state conditions.

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Wastewater Treatment and Reuse in the Sultanate of Oman

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WASTEWATER TREATMENT AND REUSE IN THE SULTANATE OF OMAN

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ABSTRACT

Increasing urban densities of expanding, longer living, populations are generating an ever increasing demand for water, which in turn is generating equally increasing quantities of waste water by way of domestic, industrial and institutional discharges. By way of example, water consumption in Muscat increased from 63 million gallons per day in 1971 to over 9,089 million gallons per day in 1990, obviously this figure will be even greater today.

Wastewater generation is directly related to population numbers and location. The total population in Oman as given by the 1993 Census is 2,071,591 of which 1,480,531 are Omanis and 537,060 are expatriates. The greatest population densities occur along the north-east coastal plain and in the area comprising Muscat, the capital city.

Traditionally population distribution has been dependant upon water availability. This still holds true but the need to live near naturally available sources has been relaxed by the introduction of desalination plants, pipelines, boreholes, roads and road transport.

Whilst recognising that the generation of large volumes of polluted wastewater is an item of concern, the concept of water conservation in a dry and country such as Oman is of equal, if not arguably greater concern.

In the light of enhanced knowledge, understanding and technology, the ever increasing amounts of wastewater are recognised as a valuable resource in and areas like Oman and they must be utilised as such, whilst at the same time protecting against any pollution and affording the greatest degree of protection for the environment and the health and welfare of the people against water borne diseases.

Generally however, the philosophy of treated wastewater reuse has advanced further than the development of practical experience. Thus the prime concern

in Oman still remains, despite great pressure created by the demand to provide water for irrigation, as the protection of the health of the community and the prevention of pollution.

Domestic wastewater (sewage) is classified amongst the most dangerous pollution sources to the environment due to its sheer volume and because of its human waste component and inherent ability to transmit water borne diseases as the sewage will contain whatever viruses, bacteria, pathogens and other organisms that are endemic in the community. Combined with a hot climate and a high dependence on groundwater supplies (wells) for drinking, these dangers are greatly multiplied.

The degree and extent of the wastewater treatment process provided is directly related to the extent of removal or destruction of such organisms. It must be noted however that the presence of an infectious agent in wastewater or treated wastewater is not adequate to declare an emergency situation. Any substance poses no risk if people are not exposed to it.

With the rise of industrial development, the sewage of a community has also come to contain a second group of components which must be safeguarded against as they also can give rise to different types of pollution and risk to human health.

Apart from the more familiar industrial chemicals contained in discharges such as lead, copper, zinc, ammonium compounds etc. which can have significant effects on health and the environment if present in large quantities, today's industry is generating an ever increasing number of complex organic compounds. Many of these are carcinogenic or can cause a wide variety of detrimental impacts on human health either by contact or consumption which can even come from the food chain rather than direct consumption.

In the Sultanate of Oman the type of industry of potential to generate such impact on wastewater is controlled by environmental protection legislation which requires that a full environmental impact assessment (EIA) is carried out, and that an environmental permit must be formulated and issued in respect of all developments regardless of their nature.

Thus any such potential is evaluated and controlled at source. Also the Ministry of Regional Municipalities and Environment carries out ongoing monitoring, inspection, sampling, analysis and evaluation of all discharges to the environment in accordance with the requirement that they are also subject to the conditions of permits to discharge.

The nature of the topography of Oman in areas of population (in rocky wadi beds or their coastal confluences, mountainous areas and remote desert areas), and the scattered locations and nature of many towns and villages impose real restrictions on total development of centralised sewerage systems. At present such public sewerage facilities cover limited areas of the Capital city, Muscat, and sections of only one or two townships. In part this is also due to the unprecedented explosion of growth in the recent years following Oman's Renaissance from an isolated rural footing.

This issue, essential to the health of the nation and the prevention of pollution, is a key element of national development and numerous government projects are under construction whilst major designs have been completed for many regional townships.

There are currently approximately some 250 wastewater treatment plants operating in Oman. Other than a few limited centralised facilities, the majority of the treatment plants are of a localised nature and are site specific to individual more modern housing developments or urban pockets associated with the major hospitals, colleges, government premises, hotels, industrial estates, security force bases and private housing compounds.

There is a high percentage of septic tanks and holding tanks in urban housing areas from which sewage is tankered to local, purpose built reception facilities and treatment plants.

Septic tanks play a major role both in some urban areas, and almost exclusively all rural areas.

The effluent from these is discharged into soakpits and the septage sludge goes to dumping sites.

The referred treatment plants currently in use range in capacity from small 8 m^3/day "package type" plants, up to civil engineered units of 15,000 m^3/day. In total these generate some 28.6 million cubic metres per year of reclaimed waste water.

From this total, 21.5 million m^3/yr is reused for irrigation; 7.2 million m^3/yr is used for aquifer recharge via soakaways; 0.1 million m^3/yr goes to industrial reuse and the balance is discharged to the sea. As a brief example, the maximum allowable limits shown below represent some of the contamination control parameters applied to reclaimed wastewater reuse and discharge in Oman. These limits are more stringent if the case demands it - for example the figures in italics represent the limit if the treated wastewater is reused in public areas.

		Max	*Public Area*
Biochemical Oxygen Demand	(BOD)	20 mg/l	*(15)*
Suspended Solids	(SS)	30 mg/l	*(15)*
Nitrogen as Ammonia	(NH3)	10 mg/l	*(5)*
Faecal Coliform Bacteria	(count)	1000 per 100 ml	*(200)*

The practice of reuse is actively pursued as a matter of policy. However there are Regulatory conditions as to the methodology, sludge reuse is also encouraged subject to similar controls, and paramount importance is given to inspection and control to ensure compliance with the Regulations in order to sustain the best levels of protection whilst at the same time benefiting from the reuse of this precious resource.

Most of the treated wastewater in Oman arises from sewage treated by the *activated sludge extended aeration process* or variations thereof. The water is usually then filtered and sterilised. In the interest of economy there is a growing interest in less energy demanding processes such as *waste stabilisation ponds* and *constructed wetlands or reed bed treatment.*

Much research has been conducted over recent years into these methods of treatment. 'There is genuine potential for their use in certain areas and although only two or three such installations exist in Oman. Several government designed *waste stabilisation ponds with reed bed tertiary treatment* are now being installed in order to speed up the provision of treatment facilities in some rural areas.

WASTEWATER TREATMENT

Topics

Methods of Treatment: - Alternatives to Conventional Sewage Disposal; Nightsoil collection: Pit latrines: aqua privies: Septic tanks and holding tanks: Septic Tank Design: Groundwater protection in Oman; Present Regulations for: - Septic Soakaway pits, Holding tanks

TABLES: Sewage Flows to Soakaway: Septage Characteristics

Methods of Treatment / Disposal

An objective of the Government of Oman is for all families to have elective sanitation. The methods recognised within current legislation are: a) water closet connected to sewerage & treatment facility, b) holding tank or septic tank.

Septic tanks are allowed at installations where population equivalents are less than 150, equivalent to discharges of 30 m^3/d, and where the installation of aerobic treatment works is impractical or unavailable. At all other points holding tanks with tankering to places approved by the Ministry or connection to sewage treatment plant is required.

The theoretical impact of the former methods on groundwater quality is negligible other than through irrigation as the final disposal route. Waste water can however infiltrate to groundwater via soakaway pits attached to septic tanks or directly through cess pits and tanks in areas which are not yet in compliance with Ministry regulations.

The Regulations as set out are presently under examination by a subcommittee appointed by Ministry of Regional Municipalities and Environment.

A list of various alternatives for sewage disposal as encountered in Oman are:

(a) Initial Collection
septic tank
holding tank / cess pit
nightsoil collection / sullage soakaway
aquaprivy
pit latrine

(b) Treatment
primary treatment - screening / settlement
secondary treatment - aerobic biological treatment and further settling.

tertiary treatment - filtration/micro straining/chemical/biological

(c) Final Disposal
marine disposal
soakaway into ground
irrigation
recycling to industry

Nightsoil Collection
Since nightsoil collection is not common in Oman it is not dealt with any further.

Pit Latrines/Aqua Privies
In low income rural areas excreta disposal used to be direct to pits dug below privy buildings. Sullage was disposed of to open ditches where evaporation was the final method of disposal. Aqua privies required a more efficient means of soaking away liquid waste but sullage is still disposed of separately in some remote locations. There is however now little use of pit latrines or aqua privies in Oman. Further it is the norm that the majority of dwellings now have conventional plumbing connected to septic tanks or holding tanks, therefore no further consideration is given to these methods.

Numbers of Septic Tanks and Holding Tanks

Muscat
There are about 16,000 dwellings connected to the sewerage system. The remainder are connected to septic tanks or holding tanks. There may be other connections to crude soakaways which come under neither category. There is a tanker collection system for septic tank desludging and for holding tank emptying. It is not possible to differentiate between septage and holding tank effluent from the tanker records. The difference between tanker volume plus recorded influent at the treatment plants and the total water supplied (operated on by a suitable reduction factor) is the volume reaching the ground through soakaways, although this figure is normally reduced to about 60% to account for losses of various types.

Total sewage = total water supplied x 0.60	70 000 m^3/d**
Less	
Sewered sewage	16 900 m^3/d
Tankered septage	26 100 m^3/d
Total Sewage to Soakaway	27 000 m^3/d

Thus the total infiltration to groundwater via soakaways in the Capital Area is equivalent to 312 1/s or approximately ten million m^3 per year. To this figure can be added the return flows infiltrating from irrigation with treated sewage effluent.

Other Urban Areas

As Muscat is the only town with significant sewerage, (with very minor exception) other towns use septic tanks and holding tanks of one form or another There are plans under preparation to sewer the following towns: Ibra, Ibri, Saham, Sumail, Khasab, Nizwa, Sur, Rustaq and Salalah.

Sohar is also in the process of developing a sewerage system. It is possible to estimate current water supply to each of these towns and hence to estimate the approximate volumes going to soakage each day.

The total infiltration to groundwater via soakaways, cess pits and waste water disposal areas in the Sultanate is probably in excess of 810l/s or approximately 25 million m^3 per year**. To this figure can be added the return flows infiltrating from irrigation with treated sewage effluent.

The figures in the following Table suggest that there are significant amounts of untreated waste water infiltrating to groundwater in the Sultanate. Within the Capital Area, the infiltration of treated sewage effluent below irrigated areas, leakage from sewers and leakage from water supply pipelines are substantially in excess of groundwater pumped and would be expected to lead to rising groundwater levels as has occurred below other cities in the Gulf for example Doha, Kuwait and Dubai.

No long-term regular water level records are available for wells within the Capital Area and it is therefore difficult to provide evidence of any groundwater level rise. In the Sohar area, a water level rise in recent years has been attributed to leakage from water pipelines, septic tanks and treated sewage effluent.

***Source:- National Water Resources Master Plan, Mott MacDonald International Ltd 1991*

Table Of
Sewage Flows to Soakaway

(Source: Mott MacDonald International Ltd, Masterplan For Groundwater Pollution Protection 1996)

Town	Estimated Sewage Flow, m³/d	Sewage Flow Treatment Plant, m³/d	Sewage Flow to Soakaway m³/d
Ibri	2 950		2 950
Ibra	1 360		1 360
Sur	5 300		5 300
Khasab	1 300	260	1 040
Saham	1 600		1 600
Sumail	2 000		2 000
Rustaq	2 700		2 700
Capital Area[1]	70 000	43 000	27 000
Buraimi	5 300		5 300
Nizwa	4 400	100	4 300
Sohar	10 000	1 500	8 500
Salalah[2]	12 500	4 500	8 000
Totals	119 410	49 360	70 050

Effects of Domestic Waste Water Disposal on Groundwater

The natural soil profile has long been recognised as an effective system for the disposal and purification of human sewage by the removal of faecal microorganisms and the breakdown of many chemical compounds due to bacteriological action and filtration. However many factors play a role in the extent to which the removal mechanisms are effective. When effluent enters the unsaturated zone, pore clogging eventually develops at the infiltration surface and forms a crust. This clogging allows effective filtration and purification mechanisms to proceed. The thicker the unsaturated zone the more elective will be the removal of contaminants.

Where the underlying geological formation is consolidated, fractured and unweathered, many open fractures provide access directly from the septic tank into groundwater without any natural treatment through the unsaturated zone. Groundwater will frequently show high bacteriological contamination for example by high faecal coliform bacteria values.

Additional points of contamination will lie below areas of extreme loading, for example waste disposal areas, schools or other public places. In such circumstances, the nitrate content can be regarded as of minor importance compared to the danger of faecal bacteria and viruses in the water supply.

Septic Tanks and Potential Waterborne Disease

Yates (1985) estimated that the consumption of untreated or inadequately treated groundwater was responsible for more than 50 percent of all waterborne outbreaks and 45 percent of all cases of waterborne disease in the United States from 1971 to 1979. Overflow or seepage of sewage from septic tanks or cesspools was found to be responsible for the illness in 43 percent of those cases where a direct cause of the illness could be determined. Thus septic tanks represent a significant threat not only to preserving the potability of groundwater but also to human health.

No similar data have yet been compiled for Oman but it is estimated that at 1east broadly similar incidence rates are experienced.

Septic tank Design

Domestic sewage which is a mixture of solid organic waste and washwater is allowed into a settling compartment where the majority of the solids are retained and the liquid passes through into a second compartment. The sludge solids in the first compartment undergo anaerobic digestion and reduce in volume considerably.

From the second compartment the liquid effluent flows either to a soakaway or to piped sewerage. The liquid effluent reaching the soakaway still has the characteristics of a very strong sewage. Typical values experienced in Oman for the main determinants are given below:

Septage Characteristics in Oman (mg/l)

(Source: Water Pollution Section Records)

Parameter	Range	Typical value
5 - day BOD mg/1	2,000 - 15,000	8,000
Suspended Solids mg/1	7,000 - 20,000	15,000
Volatile Suspended Solids as		
%age of Suspended Solids	45 - 80	65
COD mg/1	5,000 - 30,000	15,000

Septic tanks m Oman are designed so that they have sufficient capacity to hold the digested sludge volume produced over a period of six months to two years.

Design

The three main criteria for the engineering design of septic tanks in Oman are as follows:

Retention - 24 hours for single family units; less for large contributing populations

Sludge Storage - desludging at intervals of 1 to 3 years
Soakaway - sufficient to disperse the effluent without choking or clogging the local soil microstructure.

To assist with the application of the above principles semi-empirical design charts are available to arrive at the dimensions of tanks and soakaways for various sizes of contributing population. The Omani Regulations also provide such a design guideline.

If septic tanks and other forms of subsurface domestic waste disposal are not well-designed or are installed at unsuitable locations where there is insufficient aerobic zone between the tank and groundwater, entrance of bacteria/viruses is allowed into groundwater. The increase in nitrate and other mineral contents in groundwater below unsewered areas is an unavoidable consequence of the denitrification process.

The present regulations on disposal of waste water are based on a requirement for holding tanks as the preferred means of domestic waste water disposal in unsewered areas.

Details of the present applications are summarised as follows:

Septic Tanks
Field surveys carried out in Oman show septic tanks are not being desludged at regular intervals and they are left in service until "sewage overflow" takes place. The "sewage overflow" is thus detected only after it has clogged and polluted the soakaways and the surrounding ground. Some instances of water jetting the soakaways to "clean" soakaways are also reported.

Soakaway Pits
A deficiency in the current Regulation is that it does not specify the maximum depth of the pit, i.e. no consideration is given to the shallow water table in areas such as Batinah. Where deep soakaways are provided in poorly buffered soils (relatively thin layer of unsaturated soils) the waste water reaches the water table without undergoing adequate reduction in organic matters.

Holding Tanks
The current Regulation specifies the minimum capacity of a holding tank as 2000 l/person which is just sufficient for a connected population of five. Dwellings with five people are rare in towns of Oman.

The design guidelines given in the Regulations are now considered difficult to implement and in some cases impracticable for remote sites. For example the floor slope of one in four, and the liquid depth of 1.5 m minimum and 2 m maximum cannot be maintained except in small size tanks. Since the Regulation permits a single holding tank up to a population of 100 (design capacity of tank being 40 m^3) the design guidelines are in need of amendment to include several sumps and access points.

Present Situation

For several years sewage tankers in the Muscat Area dumped sewage into the waste ponds at Al Ansab. Following the commissioning of the new sewage treatment plant, the dumping of sewage into the waste pond was discontinued. The Muscat Municipality have recently introduced a tariff of 1 baiza per gallon of sewage dumped into the new sewage plant. The cost of dumping 5000 gallons of sewage (discharge of a standard tanker truck) is therefore RO 5.

The tanker operators now charge between RO 15 and 20 for collecting 5,000 gallons of sewage depending upon the district. This includes the cost of haulage of approximately 20 km to the discharge point and the tariff of RO 5 for discharge into the treatment plant. The introduction of a high tariff appears to have had a severe negative effect on the sewage tankering business in Muscat. There are indications that tanker operators are trying to find alternative dumping sites to avoid paying this high tariff.

Another factor affecting the sewage tankering activity in Muscat is the reduction in the quantity of sewage to be tankered. The main cause of this could be the increasing number of properties connected to the sewer network in some areas. However there is a possibility that people are finding ways of reducing the quantity of sewage retained in the holding/septic tanks by deliberately constructing them with porous materials such as hollow blocks or making seepage holes in the tanks. It is apparent that although the benefits of paying for a clean water supply are well established, the costs of sewage treatment have not yet been accepted by users.

Future Actions

The future scenario for disposal of domestic waste water in the Sultanate is likely to involve: - increased conventional sewage schemes both within the Capital Area and selected major towns, this is in actual implementation for nine selected towns in Oman, these are:-

Buraimi; Nizwa; Rustaq; Khasab; Ibra; Ibri; Sur; Samail; and Saham. Specific Masterplans have been developed and actual work has started in Khasab and Nizwa. Major development is also in progress in Salalah.

Other aspects are: - increased usage of treated waste water for urban beautification schemes including areas outside Muscat; continued seepage to groundwater of waste water from soakaways, septic tanks and leaking holding tanks particularly outside those areas which are likely to be sewered within the present Five Year Plan (1996-2000).

It is proposed that future actions should include:

* a programme of inspection of septic tanks and holding tanks following construction should be rigorously followed;

* continuation of the programme of regular monitoring of sewage treatment plant effluents;

* examination of the effects of the Municipality sewage tariff on sewage tankering;

* use of improved septic tank designs including three compartment design;

* introduction of a land classification related to septic tank suitability; tank densities could be related to these zones; a broad classification could include:

* field surveys to measure actual density of septic and holding tanks together with estimates of waste water flows to groundwater and measurements of groundwater quality;

* continued research on relationships between septic tank and bacteria travel distances.

* in order to test the effectiveness of the present regulations, data should be collected on the amounts of sewage bowsered from selected towns and also on the numbers of septic tanks, holding tanks and cess pits;

* ensure that suitable monitoring wells are installed both upstream and downstream of the towns in which sewage collection and treatment works are constructed to allow evaluation of the beneficial effects of sewage collection to be evaluated;

* examination of chemical analyses of groundwater to interpret any trends in nitrate content or other chemical constituents which could be attributed to contamination of groundwater due to waste water disposal;

* following examination of existing data, sampling programmes could be instigated in order to define areas of high nitrate particularly downstream of towns. The programme of construction of sewerage systems would be defined

by these areas of high priority;

* evaluation of liquid waste disposal sites should include a hydrogeological survey; each site should include monitoring boreholes, if necessary specially installed, one to be located and two to be located downstream of the site.

TREATED SEWAGE EFFLUENT REUSE

Topics

Potentially Available Treated Sewage Effluent; Potable Water Demand Projections TSE Production; Existing Production (General, Capital Area, Countrywide); Future Production TSE Uses (Irrigation, General); Irrigation Methods; Soakaways; TSE Quality, Wastewater Standards; Irrigation Water Quality; Municipal Irrigation in the Capital Area; Other Irrigation; Soakaway Water Quality; General TSE Quality; General Groundwater Quality; Effect on Groundwater (Irrigation & Soakaways);

Figures & Tables:-
Sewage Treatment Plants in the Sultanate of Oman; Estimated Water Demands; Existing Production of TSE; Estimated Potential Future TSE Production; Municipal TSE Production: Capital Area; Sewage Treatment Plants Discharging to Soakaways; TSE Quality: Discharging to Soakaways TSE Quality General; Municipal Irrigation in the Capital Area; Location of STPs Discharging to Soakaways; Potentially Available Treated Sewage Effluent

Potentially available TSE

Potable Water Demand Projections:
Various water demand forecasts for the Sultanate of Oman have been prepared during the last 5 years, all of which have a relevance to the development of estimates of available and potentially available Treated Sewage Effluent (TSE).

TSE is produced as a by product from the treatment of sewage, the volume of which is closely related to the volume of potable water delivered to domestic and industrial users. Estimation of potable water demand is thus a proxy for estimating the potential availability of TSE.

The following table shows present and future estimated domestic and industrial water demands for the country for 1990, 2000 and 2010.

Water Demands In Oman (total net usage m^3/d)

(Source: Mott MacDonald / Watson Hawksley, Wastewater Masterplans For Nine towns, 1993)

Area	1990	2000	2010
Capital area	127397	198082	328493
Batinah	25425	75890	148658
Dhahirah	7753	17699	32767
Dhakliya	5288	21068	40384
Sharqiya	11726	40904	80301
Dhofar	28493	54795	98630
Musandam	1096	6301	11781
Total	207178	414739	741014

It is pertinent to note that in 1993 the population of the Capital Area was 543,512 (Census, 1993), assuming a per capita consumption of 250 l/c/d results in a demand of 135,878 m^3/d. Interpolating for 1993 gives a demand of 148,603 m^3/d which confirms the order of the figures in the table.

Existing TSE Production

General

Sewage Treatment Plants (STP) are operated by a variety of agencies and private developers. These include the Municipalities, the Royal Oman Police (ROP), the Ministry of Defence (MOD), the Ministry of Health, private developers and private individuals. These are indicated in the list of plants presented in later tables.

Capital Area

On the basis that that 60 percent of domestic and industrial water is potentially available as TSE after treatment, then in the Capital Area in 1990 some 76,438 m^3/d was potentially available. Projecting up to 1995 based on previous figures suggests a total potential TSE production of 97,643 m^3/d.

A further check may be made by considering the population, an average wastewater production at the STP of 150 l/c/d and a conversion factor to TSE of 0.8. The population of the Capital Area in 1993 (Census, 1993) was 543 512 giving a potential TSE production of 65221 m^3/d in 1993.

All these sources are comparable and support the assumption that a total potential TSE production of the order of as much as 100,000 m^3/d is presently available.

In practice only a relatively small percentage of the Capital Area is connected to an STP, it is recorded that at present there are 45,568 m^3/d of wastewater actually treated (Ministry of Regional Municipalities and Environment, MRME) and reused or 45 percent of the wastewater.

Countrywide

Once again using the figures in the table, assuming that 60 percent of domestic and industrial water is available as TSE after treatment, indicates that in 1990 some 124,307 m^3/d was potentially available. Interpolating for 1995 gives a total potential TSE production of 186,575.

Countrywide it is estimated that the total theoretical flow passing through STPs is 81,507 m^3/d of which some 59,098 m^3/d is reused and 22,409 m^3/d discharged to soakaways or marine outfalls. In fact the theoretical figure includes STPs under development and non operational for various reasons. The actual present situation as recorded by MRME is that 58,988 m^3/d are being utilised for reuse and that 11,383 m^3/d is being discharged to soakaways excluding marine discharges, with a total treated effluent of 71,733 m^3/d or 38 percent of the potential.

TSE production

Full details of the existing STPs are presented in Annex I and are summarised in tile following table:

Existing Production of TSE in Oman (m^3/d)
(Source: Water Pollution Section Records)

Area	TSE production (re-used)	TSE production (soakaway)
Capital Area	45,568	3,324
Sharqiya	2,561	90
Musandam	425	42
Wusta	595	80
Dhahirah	2,035	448
Dhakliya	2,187	20
Batinah	4,013	3,799
Dhofar	1,605	3,581
Total	58,988	11,383

Future Production
The future production of TSE will be determined by the amount of domestic and industrial water demand and the degree to which the water users are connected to STPs through sewerage networks.

At present there are over 250 STPs in the country producing TSE for reuse of 58,988 m³/d. The total future potential TSE production in the year 2010, assuming no discharge to sea or soakaways, a 60 percent reuse factor and the water demand figures presented in the above table, is 445,000 m³/d.

Estimated future TSE production calculated from the potable water demand figures given in the following table:

Estimated Potential Future TSE Production in Oman (m³/d)
(Source: National Water Resources Master Plan, Mott MacDonald International Ltd, 1991)

Area	2000	2010
Capital Area	118,849	197,096
Batinah	45,534	89,195
Dhahirah	10,619	19,660
Dhakliya	12,641	24,230
Sharqiya	24,542	48,181
Southern Region	32,877	59,178
Musandam	3,781	7,069
Total	248,843	444,609

The figures shown in the above table are clearly maximums assuming that all wastewater is treated in STPS.

TSE Uses :- Irrigation

General:- Capital Area
TSE is used for irrigation by both the municipality and other STP operators. As shown previously the total present amount of TSE used for irrigation is 45,568 m³/d of which approximately 28,000 m³/d is from the municipality and utilised in the municipality irrigation system (MRME Water Pollution Section records). A summary of the Municipal TSE production is presented in the following table:

Municipal TSE Production in Oman: Capital Area
(MRME Water Pollution Section records)

STP	TSE (m^3/d)
Shati al Qurm	1,350
Mabilah	1,920
Darsait	10,800
MAM Garrison	5,307
Al Khoud	300
Al Aniirat	600
Al Ansab	9,100

The municipal irrigation system extends from Bait Al Barka in the west to Wadi Kabir in the east. In the first figure, the approximate average volumes of water applied per day from this system are shown. The total volume indicated on the figure is 24,000 m^3/d. This can vary by plus or minus 20 percent throughout the year giving a minimum of around 19,000 and a maximum of 29,000 (approximately equal to the total of available TSE).

During the summer months the demand fully utilises the supply from the connected STPs. During winter there is a surplus supply which is largely compensated for by discharging excess TSE to the lagoons at Al Ansab STP or occasional discharge to the sea at Darsait.

In addition to the municipal irrigation, private sector irrigation is carried out adjacent to those individual STPs shown in Annex 1 as operating reuse practice. In the Capital Area the volume of private sector reuse is of the order of 18,000 m^3/d.

Other Areas

Compared to the Capital Area the rest of the Sultanate reuses proportionately only a small amount of wastewater for irrigation: 23 percent of the total reuse for irrigation in the Sultanate is outside the Capital Area (see Annex 1). Irrigation is generally carried out adjacent to the STPs or in small volumes transported by water bowser.

Irrigation Methods

In the previous section the volume and location of irrigation were outlined. The quality of the effluent is generally within the standard defined for wastewater in Oman. There are however some deviations in individual STP cases belonging to institutions or where Regional Municipalities facilities are limited or overloaded, or inadequately designed. All STPs are monitored on a regular basis by the MRME and samples are analysed for compliance evaluation.

Irrigation in Oman using TSE is predominantly carried out by overhead and localised methods. Overhead methods comprise sprinklers and spray systems, whilst the localised methods include drip feed and other variants. Overhead irrigation is generally associated with lower application efficiency owing to non uniformity of aerial coverage and run off where application rates can exceed infiltration creating areas of concentration in depressions.

Conversely localised methods have an intrinsically high application efficiency. In simple terms the lower the application efficiency the greater the likelihood of water being lost to deep percolation.

In addition to application efficiency the amount of water applied is a function of the method of operation. Failure to operate a valve at the correct time or fear of under watering leading to over irrigation both lead to excess irrigation and a resulting drainable surplus.

The only other reason to apply irrigation water greater than the consumptive needs of the plant is for leaching of salts.

To meet the wastewater quality standard the electrical conductivity must be below 2,000 μS/cm, as such the irrigation is unlikely to require a leaching faction and so any planned drainable surplus will be minimal.

The drainable surplus is likely to be attributed to application and management losses. For the type of overhead and localised systems being utilised this is probably in the order of no more dm 10 to 20 percent. Initial qualitative studies suggest that irrigation carried out is generally more than adequate for the plants consumptive needs with a subsequently strong possibility that a degree of drainable surplus is being created.

Soakaways

At present some 47 STPs discharge treated effluent to soakaways in the Sultanate. These are listed in the following table together with discharge data recorded by MRME. Their location is shown in the following figure:

STPs Discharging to Soakaways in Oman
(MRME Water Pollution Section records)

Region	Name of STP	Discharge (m^3/d)
Capital Area	Rusayl Industrial Estate	300
	ROP Qurm	145
	Social Housing, Al Khoud	900
	Social Housing, Al Amirat	600
	Strabag, Al Ghubra	60
	Ibn Sina Hospital	75
	Quriyat Hospital	50
	ROP Hospital Qurm	33
	Al Ansab	900
	Social Housing Al Aynt	70
	Private Villa Seeb	10
Sharqiya	Samad a Shan Hospital	20
	Sur Hospital	50
	Wadi Bani Khalid Hospital	20
Musandam	Khasab Municipality	42
Wusta	Haima Hospital	80
Dhahirah	ROP Jizzi	41
	Buraimi Chemical Co	80
	PDO Fahud	272
	PDO Yibal	55
Dhakliya	Tanuf Factory	20
Batinah	Oman Sun Farms	275
	Al Wajajah	26
	Wadi Bani Ghafir Hospital	40
	Saham Hospital	40
	Al Muweylah, Sohar	1150
	Rustaq Hospital	188
Dhofar	ROP Prison, Salalah	206
	ROP Thumrait	14
	RAFO Salalah	400
	MOD Azarat Cainp	30
	MOD Um Al Ghawaraf	220
	MOD Pink Cliffs	200
	MOD Joint Housing	10
	MOD Sahalnawt, Salalah	80
	RAFO Thumrait	270
	MOD Landforce Salalah	70
	MOD Frontier Force Raysut	100
	Sultan's Special Force, Zeek	60
	Teachers College, Salalah	6
	VTI Salalah	100
	Civil Airport, Salalah	30
	PDO Marmul	85
	Municipal Oxidation Ponds	1500
	PDO Marmul Camp	200

Full details of all the STPs are presented in Annex 1.

Treated Wastewater Standards

Wastewater standards for TSE are defined by the MRME via Ministerial Decision 145/93 dated 13 June 1993 - Regulations for Wastewater Re-Use and Discharge. The maximum quality limits are reproduced m the table below:

Wastewater Maximum Quality Standards For Reuse & Discharge
(mg/l except where otherwise stated)

Parameter		A	B
BOD_5		1.5	20
COD		150	200
Suspended Solids (SS)		1.5	30
Total Dissolved Solids		1500	2000
EC (µs/cm)		2000	2700
SAR**		10	10
pH		6-9	6-9
Aluminum (Al)		5	5
Arsenic (As)		0.1	0.1
Barium (as Ba)		1	2
Berylium (as Be)		0.1	0.3
Boron (as B)		0,5	1
Cadmium (as Cd)		0.01	0.01
Chloride (as Cl)		650	650
Chromium (total as Cr)		0.05	0.05
Cobalt (as Co)		0.05	0.05
Copper (as Cu)		0.5	1
Cyanide (total as CN)		0.05	0.1
Fluoride (as F)		1	2
Iron (total as Fe)		1	5
Lead (as Pb)		0.1	0.2
Lithium (as Li)		0.07	0.07
Magnesium (as Mg)		150	150
Manganese (as Mn)		0.1	0.5
Mercury (as Hg)		0.001	0.001
Molybdenum (as Mo)		0.01	0.05
Nickel (as Ni)		0.1	0.1
Nitrogen	Ammonia (as N)	5	10
	Nitrate (as NO_3)	50	50
	Organic (as N)	5	10
Oil and Grease - Total		0.5	0.5
Phenols (total)		0.001	0.002
Phosphorus (total as P)		30	30

Selenium (as Se)	0.02	0.02
Silver (as Ag)	0.01	0.01
Sodium (as Na)	200	300
Sulphate (as SO_4)	400	400
Sulphide (total as S)	0.1	0.1
Vanadium (as V)	0.1	0.1
Zinc (as Zn)	5	5
Faecal Coliform / 100ml	200	1000
Viable Nematode Ova / 1	<1	<1

SAR: Sodium Absorption Ratio = a measure of the effect on soil
Source: Ministerial Decision 145/93 dated 13 June 1993
Notes: A and B in Table refer to application type. A is for vegetables, fruit etc and for public parks, lawns and areas with public access. B is for vegetables, fodder, cereal etc and for areas with no public access.

In terms of microbiological quality the wastewater standards in the table follow closely the recommendations made by the WHO (WHO, 1989). In terms of the non-biological indicators the water quality for application type A is close to WHO supply water quality with adjustments to suit its agricultural use.

IRRIGATION WATER QUALITY

Municipal Irrigation in the Capital Area

Review of sample test results from TSE used for irrigation indicated that the TSE generally complies with the wastewater standards although there are exceptions (these are identified in Annex 1). Chemical analysis covering all of the indicators covered in the wastewater standard was not available at the time of writing, however samples covering BOD, pH, suspended solids, NH_3, faecal coliform, Ni, Zn, Cu, Cr, Pb and Cd were compared to the standard and found to be generally well within the standard other than Cd and Cr which in some samples (Al Ansab) appeared high. Any water percolating to groundwater is thus likely to be at or better than the wastewater standard.

Other Irrigation

Test results shown or evaluated for TSE from private operations are restricted to BOD, pH, suspended solids, faecal coliform and ammoniacal nitrogen. The quality varies from plant to plant and they do not always comply with the wastewater standards.

Soakaway Water Quality

The STPs discharging to soakaways are listed above. Quality data of the treated effluent has recently been installed on the MRME database. An initial indication of quality has been assessed by randomly selecting one test for each soakaway. No data is shown for Dhofar. the results are summarised in the following table.

TSE Quality: Discharging to Soakaway
(MRME Water Pollution Section records)

Test	**Result Range (mg/l)**
NH_3	0.1 - 23.37
Suspended Solids	5 - 2280
pH	5.2 - 7.8
COD	22 - 14309
Total Dissolved Solids	918 - 21770
Conductivity	1720 - 3600
Faecal Coliform Bacteria	I - 600000
Total coliform	1.2 - 1575
BOD_5	

Clearly the results should be interpreted with caution, however, it is clear from this analysis that the effluent discharging to soakaways is very variable and at least sometimes below the specified standard. Further analysis is required to evaluate exactly what the quality of the discharged effluent is at present and what it is likely to be in the future.

General TSE Quality

A simple analysis has been carried out of the test results held in the MRME database for all STPs in the Sultanate (with the exception of Dhofar Region). The results are presented in the following table.

TSE Quality in Oman (mg/1 except pH)

Test	Average	Maximum	Minirnum
NH_3	5.1	2219	0 .
FRC	1.01	17.5	0
BOD5	14.67	1575	0
Faecal Coli	2541	600000	0
SS	25.3	2280	0
pH	7.21		

The results suggest that there is a possible problem with Faecal Coliform and Suspended solids. Review of the full data set indicates that in a large number of samples the Faecal Coliform count is over 100 000 with similarly high values of suspended solids.

Irrigation
In the previous sections the volume and location of irrigation are outlined. The quality of the effluent is generally within the standard defined for wastewater in Oman.

The effect on groundwater is therefore predominantly a question of how much of the applied irrigation water is lost to deep percolation as drainable surplus and subsequently is added to the groundwater resource.

The drainable surplus is basically likely to be attributed to application and management losses resulting in irrigation in excess of the consumptive needs of the plant. For the type of overhead and localised systems being utilised this is probably in the order of no more dm 10 to 20 percent. Overhead irrigation is likely to contribute a greater amount than localised irrigation for the reasons described earlier in the report. These are very much qualitative statements at this stage, further studies will be carried out to evaluate the detailed mechanisms of drainage and to quantify the amounts of irrigation water lost to deep percolation.

Nevertheless it may be assumed that of the order of 10 to 20 percent of the applied irrigation water is entering the groundwater resource where irrigation with TSE is being used.

It is pertinent to note that effects on groundwater quality may be beneficial as well as detrimental and indeed both should be considered in the final analysis (Farid, S. 1993).

This will possibly be the case for EC, where the quality of the TSE should generally be better dm 2000 μS/cm whereas the average quality of the wells in the Capital Area is over 4000 μS/cm.

Soakaways
In the previous sections the quality and quantity of TSE discharging to soakaways has been presented.

TSE entering groundwater through soakaways from STPs is predominantly discharged by four mechanisms: discharge into infiltration galleries, discharge into soakaways, discharge into infiltration/evaporation ponds and uncontrolled discharge. The different mechanisms will have different relative infiltration/ evaporation characteristics which are site specific.

Generally all the TSE will enter the groundwater other than that lost by evaporation in the ponds and also possibly in any overflow from soakaways.

It is once again pertinent to note that effects on groundwater quality may be beneficial as well as detrimental and indeed both should be considered in the final analysis.

STPs in the Sultanate of Oman

Basic Data							Analysis of maximum flows		
Name of STP	Flow m3/d	Reuse %	Problem	Reuse m3/d	Soakaway m3/d	Details	Total flow m3/d	Total reuse	Total non reuse
CAPITAL AREA									
Shatti Al Qurm STP	1,350	100		1,350	0		1,350	1350	0
Ghubrah Desal Plant Phase 2	150	100		150	0		150	150	0
Sultan Qaboos Sports Complex	108	100		108	0		108	108	0
Social Housing Bausher	415	100		415	0		415	415	0
Social Housing Mabella	1,920	100		1,920	0		1,920	1920	0
H H Sayyid Fahar Villas	112	100	y	112	0		112	112	0
PDO Ras Al Hamra Housing	300	100		300	0		300	300	0
PDO Mina Al Fahal	377	100		377	0		377	377	0
Ghoos Development	70	100		70	0		70	70	0
Madinat Al Ilam Development	22	100	y	22	0		22	22	0
Social Housing Al Ayjat	70	0	y	0	70		70	0	70
ROP Mataroma Prison	1,200	100		1,200	0		1,200	1200	0
Rusayl Industrial Estate	1,250	60	y	750	500		1,250	750	500
Gulf Hotel	220	100		220	0		220	220	0
Royal Hospital	850	100		850	0		850	850	0
Ghubrah Guest House & Staff Qtrs	33	100		33	0		33	33	0
RGO Muscat Dev. (Phase 1)	(100)	0		0	0		100	0	100
Fort Mirani	80	0		0	0	marine discharge	80	0	80
Darsait STP	10,800	100		10,800	0		10,800	10800	0
H E Mohammed Al Zubair Villa	25	100		25	0		25	25	0
H E Said Al Shanfari Villa	(20)	0		0	0		20	0	20
Madinat Qaboos East	600	100		600	0		600	600	0
Sultan Qaboos University	2,100	100		2,100	0		2,100	2100	0
Inst. of Public Administration	30	100		30	0		30	30	0
Arooj Estate - Al Khuwair	30	100	y	30	0		30	30	0
Sultan Special Force, Amilah	(200)	0		0	0		200	0	200
Al Bustan, Qurm	80	100		80	0		80	80	0
MOD Al Ansab	120	100		120	0		120	120	0
MOD MAM Garrison	5,307	100		5,307	0		5,307	5307	0
ROP D.G. of Traffic	120	100	y	120	0		120	120	0
ROP Head Quarters, Qurm	68	100		68	0		68	68	0
ROP Immigration Bldg, Qurm	16	100		16	0		16	16	0
ROP Al Amirat	69	100		69	0		69	69	0
ROP Muscat City Wall	150	0		0	0	marine discharge	150	0	150
ROP Junior Officers Flats, Qurm	108	100		108	0		108	108	0
ROP Senior Officers Housing,Qurm	207	30	y	62	145		207	62.1	144.9
ROP 24 Flats, Qurm	(69)	0		0	0		69	0	69
ROP Stables, Wattayah	(240)	0		0	0		240	0	240
ROP Maidan Al Fatah Barracks	(90)	0		0	0		90	0	90
ROP Stadia, Wattayah	400	100		400	0		400	400	0
ROP Hospital, Qurm	33	0	y	0	33		33	0	33
ROP Hospital Extn, Qurm	26	100		26	0		26	26	0
ROP Nurses Quarters, Qurm	32	100	y	32	0		32	32	0
ROP Airport Division & Housing	180	100		180	0		180	180	0
ROP Airwing Hangar	39	100		39	0		39	39	0
ROP Airwing Housing Complex	108	100		108	0		108	108	0
Zawawi Trading, Qurm	60	100		60	0		60	60	0
Royal Stables, Seeb	388	100		388	0		388	388	0
Royal Polo Ground	50	100		50	0		50	50	0
Seeb Central	1,344	100		1,344	0		1,344	1344	0
H E Dr Khaduri Villa	16	100		16	0		16	16	0
Sultan's School, Seeb	(120)	0		0	0		120	0	120
International Electric Co	33	100		33	0		33	33	0
Tayyan Complex, Muscat	88	100		88	0		88	88	0
Al Dhiyafah, Qurm	29	100		29	0		29	29	0
ROP O.I.D. Mina al Fahal	398	100		398	0		398	398	0
Bait Al Barakah Royal Zoo	6	0	y	0	6		6	0	6
Bait Al Barakah Villa	20	100		20	0		20	20	0
Social Housing, Al Khoud	1,200	25	y	300	900		1,200	300	900
Social Housing, Al Amirat	600	0	y	0	600		600	0	600
Transmitter Housing, Seeb	40	100		40	0		40	40	0
Ghubrah Desal Plant Security	89	100		89	0		89	89	0
Ministry of Development	23	100		23	0		23	23	0
Strabag Camp, Al Ghubra	120	50	y	60	60		120	60	60
Jimeeh Camp, Amiba	30	100		30	0		30	30	0
I.S.S. Qurm	188	100		188	0		188	188	0
Seeb Novotel	240	100		240	0		240	240	0
Al Inshirah Restaurant	27	100	y	27	0		27	27	0
H E Yousuf Bin Alawi Villa	9	100	y	9	0		9	9	0
Oman Cement Co (Factory)	70	100		70	0		70	70	0
Seeb Airport	195	100		195	0		195	195	0
D.G.C.A. Housing, Seeb	62	100	y	62	0		62	62	0
Al Ansab S.T.P.	9,000	90		8,100	900		9,000	8100	900
Muscat Private School	56	100	y	56	0		56	56	0
Yahya Costain, Bausher	520	100		520	0		520	520	0
Oman Tech & Indust. College	150	100	y	150	0		150	150	0
MOD Transport Regiment, Seeb	75	100		75	0		75	75	0
Min.Justice, Awqaf & Islamic Aff.	34	100	y	34	0		34	34	0

STPs in the Sultanate of Oman

Basic Data							Analysis of maximum flows		
Name of STP	Flow m3/d	Reuse %	Problem	Reuse m3/d	Soakaway m3/d	Details	Total flow m3/d	Total reuse	Total non reuse
DG of Spec & Measurement	6	100		6	0		6	6	0
Oman Oilfield Supply Co	(36)	0		0	0		36	0	36
Rusayl Ind. Estate Housing	375	100		375	0		375	375	0
Muscat Palace	90	0		0	0	marine discharge	90	0	90
RGO Halban Camp	562	100		562	0		562	562	0
Juma Bin Rajab Bin Ashour Villa	5	100	y	5	0		5	5	0
H E Sulaiman Al Harthy Villa	6	100	y	6	0		6	6	0
Oman Cement Co. Housing	230	100		230	0		230	230	0
Port Service Corporation	110	100		110	0		110	110	0
J&P Labour Camp, Amiba	360	100		360	0		360	360	0
Oman Oil Refinery	(127)	0		0	0		127	0	127
Al Bustan Palace Hotel	780	100		780	0		780	780	0
RGO Officers Mess, Seeb	165	100		165	0		165	165	0
Mawa Al Mahala, Muscat	271	0		0	0	marine discharge	271	0	271
Bait Al Baraka Nursery & Orchard	240	100		240	0		240	240	0
Amiantit Oman, Rusayl	64	100		64	0		64	64	0
VTI, Seeb	100	100		100	0		100	100	0
Al Harthy Complex	90	100	y	90	0		90	90	0
Ministry of Interior	0	0		0	0		0	0	0
Ministry of Social Affairs	0	0		0	0		0	0	0
Cabinet of Ministers	18	100	y	18	0		18	18	0
Wimpey Alawi Camp	(108)	0		0	0		108	0	108
Commercial Sec.School, Boys, Seeb	40	100		40	0		40	40	0
Al Rafa Housing, Qurm	29	100		29	0		29	29	0
Palace Office New Building, Qurm	40	100		40	0		40	40	0
Palace Office Annex, Qurm	43	100		43	0		43	43	0
Palace Office Workshop, Qurm	21	100		21	0		21	21	0
Khoula Hospital	567	100	y	567	0		567	567	0
Qurm Village Development	0	0		0	0		0	0	0
Fort Jalali	10	0		0	0	marine discharge	10	0	10
Abdulhafid Salim Rajab Villa	(7)	0		0	0		7	0	7
IBN Sina Hospital	50	0	y	0	50		50	0	50
Quriyat Hospital	50	0	y	0	50		50	0	50
Oman Refinery Housing	(23)	0		0	0		23	0	23
W J Towell, Wadi Kabir	50	100	y	50	0		50	50	0
H H Sayyid Shihab Villa, Seeb	10	0	y	0	10		10	0	10
7 Villas, S Salim Al Wahaibi(M-Ilam)	18	100		18	0		18	18	0
Bousher Slaughter House	(80)	0		0	0		80	0	80
Khaboo Guest House	8	0		0	0	marine discharge	8	0	8
H E Salim Al Baruni Villa, Qurm	8	100	y	8	0		8	8	0
S Salim Al Wahaibi Villa, Qurm	30	100	y	30	0		30	30	0
Desert Line Housing, Al Khoud	25	100		25	0		25	25	0
S Salim Al Wahaibi Villa, M.Q.	30	100		30	0		30	30	0
Manouma Village STP	140	100		140	0		140	140	0
Special Force Halban Camp	250	100		250	0		250	250	0
Royal Stables, Rumais	90	100		90	0		90	90	0
Granada Gardens, Seeb	115	100		115	0		115	115	0
Rusayl Ind. Estate Expansion	(1,200)	0	y	0	0		1,200	0	1200
Residential Complex, Al Hail	70	100		70	0		70	70	0
Gulfar Camp, Amiba	(150)	0	y	0	0		150	0	150
			total	45,568	3,324		52,071	45,568	6,503
SHARQIYA									
Boys Secondary School, Ibra	220	100		220	0		220	220	0
Teachers Training Institute, Sur	85	100		85	0		85	85	0
Oman Sea Farms, Sur	0	0		0	0		0	0	0
ROP Al Mudhaibi	23	100	y	23	0		23	23	0
ROP, Sur	40	100	y	40	0		40	40	0
R.A.F.O. Masirah	650	0		0	0	marine discharge	650	0	650
Masirah Municipality Ponds	500	100	y	500	0		500	500	0
V.T.I. Seeb	120	100		120	0		120	120	0
British Eastern Relay Stn, Masirah	108	100		108	0		108	108	0
Desert Regiment, Ibra	1,000	100		1,000	0		1,000	1000	0
Samad Al Shan Hospital	40	50	y	20	20		40	20	20
Sur Hospital	100	50	y	50	50		100	50	50
V.T.I. Sur	120	100		120	0		120	120	0
Al Qabil Guest House	(8)	0		0	0		8	0	8
Wadi Bani Khalid Hospital	20	0	y	0	20		20	0	20
Wadi Al Tayyin Hospital	35	100		35	0		35	35	0
Sinaw Hospital	120	100		120	0		120	120	0
MOD, Sur Bilad	120	100		120	0		120	120	0
			total	2,561	90		3,309	2,561	748
MUSANDAM									
R.A.F.O. Khasab	107	100		107	0		107	107	0
MOD Lima	20	0	y	0	0	marine discharge	20	0	20
MOD Goat Island	75	50	y	38	0	marine discharge	75	37.5	37.5

STPs in the Sultanate of Oman

Basic Data							Analysis of maximum flows		
Name of STP	Flow m3/d	Reuse %	Problem	Reuse m3/d	Soakaway m3/d	Details	Total flow m3/d	Total reuse	Total non reuse
ROP Khasab	32	100	y	32	0		32	32	0
Diba Ghallah	150	100		150	0		150	150	0
Khasab Municipality	140	70	y	98	42		140	98	42
MOD Dibba Fort	(45)	0	y	0	0		45	0	45
			total	425	42		569	425	145
WUSTA									
Hayma Hospital	160	50	y	80	80		160	80	80
ROP Hayma	69	100	y	69	0		69	69	0
ROP Hayma No 2	(100)	0	y	0	0		100	0	100
ROP Hayma Tribal Centre	69	100	y	69	0		69	69	0
PDO Nimr	55	100	y	55	0		55	55	0
PDO Rima	38	100		38	0		38	38	0
PDO Qarn Alam	94	100		94	0		94	94	0
PDO Bahja	110	100		110	0		110	110	0
PDO Contractors, Qarn Alam	80	100		80	0		80	80	0
PDO Contractors, Nimr	(400)	0	y	0	0		400	0	400
PDO Marmul Industrial Estate	(40)	0	y	0	0		40	0	40
			total	595	80		1,215	595	620
DHAHIRA									
ROP Border Post Hafeet	50	100	y	50	0		50	50	0
ROP Border Post Wadi Jizi	41	0	y	0	41		41	0	41
ROP Dhank	23	100		23	0		23	23	0
PDO Fahud	250	100		250	0		250	250	0
PDO Yibal	110	50	y	55	55		110	55	55
V.T.I. Ibri	100	100		100	0		100	100	0
MOD North Front Force, Ibri	408	100		408	0		408	408	0
Al Buraimi Fort	100	100		100	0		100	100	0
MOD Bait Aqeel, Al Buraimi	20	100	y	20	0		20	20	0
Tanam Hospital	(80)	0		0	0		80	0	80
Oman Chemicals & Pharma, Buraimi	80	0	y	0	80		80	0	80
PDO, Lekhwair	80	100		80	0		80	80	0
PDO Contractors Camp, Fahud	320	15	y	48	272		320	48	272
New General Hospital, Ibri	300	100	y	300	0		300	300	0
New General Hospital, Al Buraimi	204	100	y	204	0		204	204	0
MOD, Al Qabil	110	100		110	0		110	110	0
Occidental, Suneinah Field STP	100	100		100	0		100	100	0
PDO Contractors Camp, Yibal	187	100		187	0		187	187	0
PDO Contractors Camp, Lekhwair	(220)	0	y	0	0		220	0	220
			total	2,035	448		2,783	2,035	748
DHAKLIYA									
ROP, Bahla	25	100		25	0		25	25	0
Qaboos School, Birkat Al Mouz	92	100	y	92	0		92	92	0
MOD, Saiq	300	100		300	0		300	300	0
ROP, Bid Bid	25	100		25	0		25	25	0
ROP Academy, Nizwa	455	100	y	455	0		455	455	0
V.T.I. Nizwa	120	100		120	0		120	120	0
Fallaje Daris Hotel, Nizwa	120	100		120	0		120	120	0
MOD Saar Camp, Izki	400	100		400	0		400	400	0
MOD, Bid Bid	100	100		100	0		100	100	0
MOD Married Quarter, Izki	40	100		40	0		40	40	0
MOD Artillery Regiment, Izki	120	100		120	0		120	120	0
Izki Hospital	40	100	y	40	0		40	40	0
Nizwa Hospital	100	100	y	100	0		100	100	0
Adam Hospital	80	100	y	80	0		80	80	0
Tanuf Hospital	40	50	y	20	20		40	20	20
Nizwa Souq	150	100		150	0		150	150	0
Jebel Akhdar Hospital	(35)	0	y	0	0		35	0	35
			total	2,187	20		2,242	2,187	55
BATINAH									
ROP Suwaiq	138	100		138	0		138	138	0
Al Wadi Hotel	180	100		180	0		180	180	0
Oman Sun Farms	275	0	y	0	275		275	0	275
Youth Centre, Sohar	70	100		70	0		70	70	0
ROP, Rustaq	104	100		104	0		104	104	0
ROP, Al Wajajah	26	0	y	0	26		26	0	26
ROP, Khatmat Milaha	41	100		41	0		41	41	0
ROP, Khabourah	23	100		23	0		23	23	0
ROP, Saham	46	100		46	0		46	46	0
ROP, Sohar	(110)	100		0	0		110	110	0
Magan Town	360	100		360	0		360	360	0
Al Muwaylah, Sohar	4,500	30	y	1,350	3,150		4,500	1350	3150

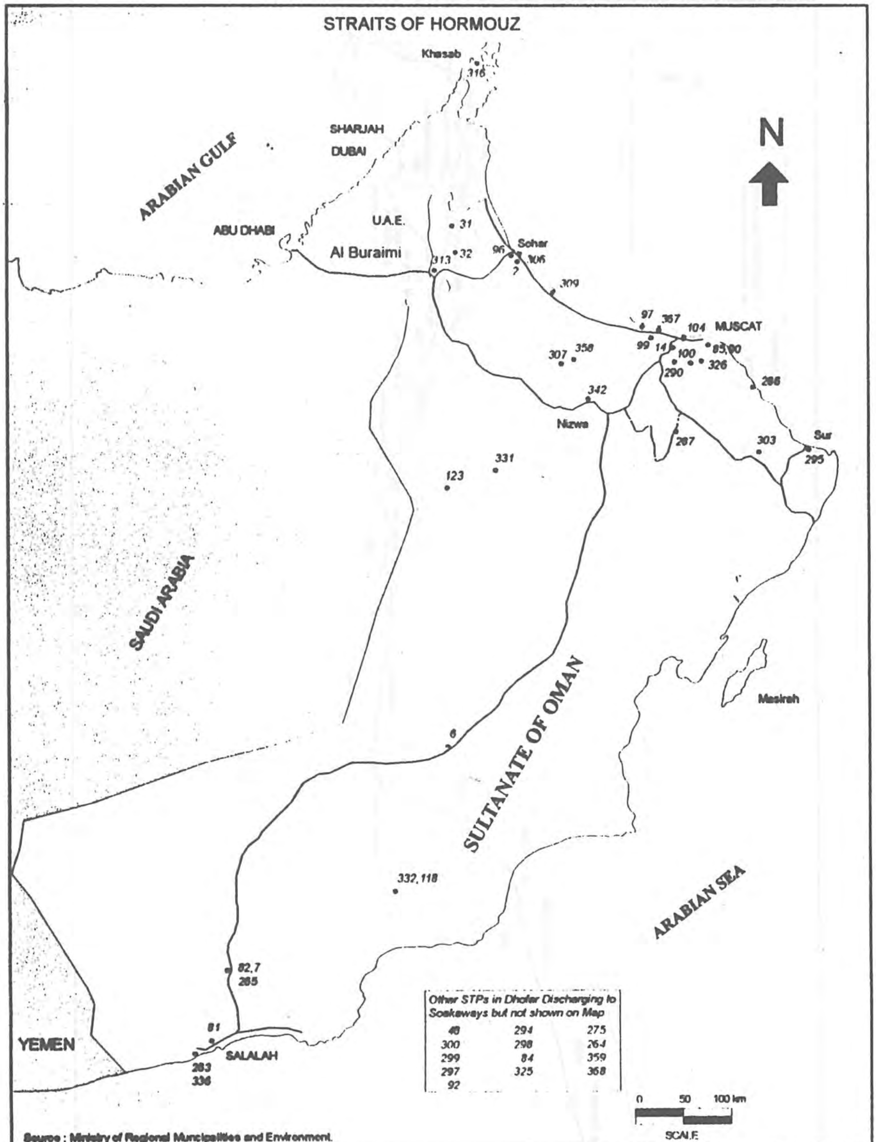
STPs in the Sultanate of Oman

Basic Data							Analysis of maximum flows		
Name of STP	Flow m3/d	Reuse %	Problem	Reuse m3/d	Soakaway m3/d	Details	Total flow m3/d	Total reuse	Total non reuse
Girls Secondary School, Saham	180	100		180	0		180	180	0
V.T.I. Al Musana	120	100		120	0		120	120	0
Tech Secondary School, Sohar	100	100	y	100	0		100	100	0
Wudam Naval Base	700	100		700	0		700	700	0
V.T.I. Saham	120	100		120	0		120	120	0
Sohar Hospital	80	0	y	0	80		80	0	80
Wadi Bani Ghafir Hospital	40	0	y	0	40		40	0	40
Parachute Regiment, Rustaq	288	100		288	0		288	288	0
Saham Hospital	40	0	y	0	40		40	0	40
Madrasat Tadreeb Al Dhahat	80	100		80	0		80	80	0
Sohar Resort Hotel	50	100		50	0		50	50	0
Sohar Industrial Estate	(775)	0	y	0	0		775	0	775
General Hospital, Rustaq	250	25	y	63	188		250	62.5	187.5
Wadi Helbi Hospital	(45)	0	y	0	0		45	0	45
Sawadi Tourist Resort	(100)	0	y	0	0		100	0	100
			total	4,013	3,799		8,841	4,123	4,719
DHOFAR									
ROP Prison, Salalah	36	100		36	0		36	36	0
ROP Auqad, Salalah	206	0	y	0	206		206	0	206
ROP Shalim	23	100	y	23	0		23	23	0
ROP Raysut	11	100		11	0		11	11	0
ROP Thumrait	69	80	y	55	14		69	55.2	13.8
R.A.F.O. Salalah	400	0	y	0	400		400	0	400
MOD Um Al Ghawarif	220	0	y	0	220		220	0	220
MOD Arzat Camp	150	80	y	120	30		150	120	30
MOD Pink Cliff, Salalah	200	0	y	0	200		200	0	200
MOD Joint Housing, Salalah	10	0	y	0	10		10	0	10
MOD(SOA) Sahalnowt, Salalah	80	0	y	0	80		80	0	80
R.A.F.O. Thumrait	600	55	y	330	270		600	330	270
MOD(SOA) Landforce, Thumrait	70	0	y	0	70		70	0	70
MOD Frontier Force, Raysut	100	0	y	0	100		100	0	100
Sultan's Special Force, Zeek	200	70	y	140	60		200	140	60
H.M. Rest House, Salalah	736	100		736	0		736	736	0
Teachers College, Salalah	25	75	y	19	6		25	18.75	6.25
VTI, Salalah	100	0	y	0	100		100	0	100
Civil Airport, Salalah	30	0	y	0	30		30	0	30
PDO, Marmul	170	50	y	85	85		170	85	85
I.S.S. Salalah	(45)	0		0	0		45	0	45
Transmitter Housing, Thumrait	(30)	0		0	0		30	0	30
Municipality Oxidation Ponds, Salalah	1,500	0	y	0	1,500		1,500	0	1500
PDO Marmul Contractors Camp	250	20	y	50	200		250	50	200
Raysut Industrial Estate	0	0	y	0	0		0	0	0
Salalah New Wastewater Plant	(5,216)	0	y	0	0		5,216	0	5216
			total	1,605	3,581		10,477	1,605	8,872
			GRAND TOTAL	58,908	11,383		81,507	59,098	22,409

Notes:

	y	problem identified as discharge to soakaway or unsatisfactoryperformance
	( )	indicates plant under development or non functional
	Source:	MRME

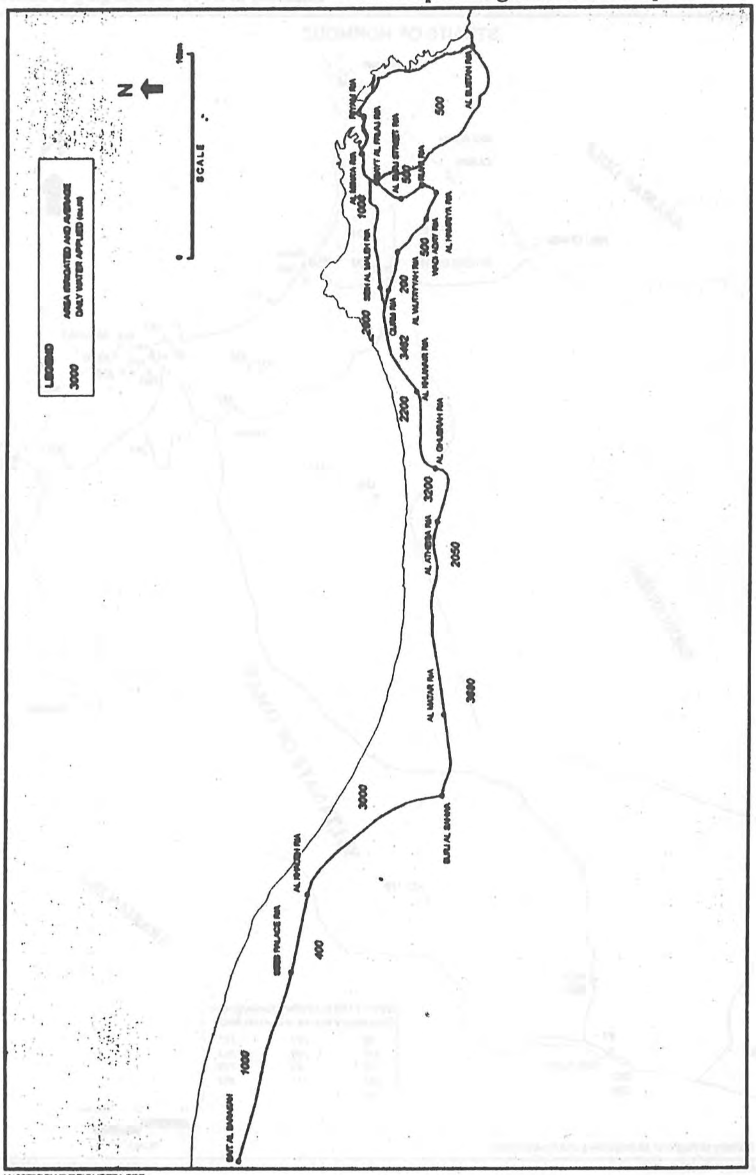
Location of STPs Discharging to Soakaways



H:\33799\DWGS\FIGUREF2.PRE

Notes : For Details of STP See Text

Municipal Irrigation in the Capital Area



Performance of Wastewater Treatment Plants in Riyadh

Abdullah El-Rahaili and Mohammed Misbahuddin

PERFORMANCE OF WASTEWATER TREATMENT PLANTS IN RIYADH

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ABSTRACT

Riyadh has experienced a spectacular growth in the last few decades. With the rapid expansion of the city, wastewater treatment projects were also established with a minimum of secondary biological treatment. Various biological processes such as trickling filter, activated sludge, and rotating biological contractors were adopted for different plants. The primary and tertiary treatment schemes also vary from plant to plant. The effluents from these plants are also reused for agricultural and landscape irrigation and industrial purposes. Hence this study was conducted to investigate the performance, and to evaluate the quality of the wastewater effluents for disposal and reuse at five major wastewater treatment plants in Riyadh. These plants are Riyadh Wastewater Treatment Plant (RP), Ministry of Foreign Affairs Staff Housing Wastewater Treatment Plant (MFP), King Saud University Wastewater Treatment Plant (KSP), Al-Imam University Wastewater Treatment Plant (AIP), and National Guard Wastewater Treatment Plant at Khashm Al-Aan (NGP). Results of this study has indicated that all the treatment plants, except MFP, produced effluents with BOD and TSS concentrations less than their respective design qualities. The average BOD and TSS for MFP during the study period were 21 mg/L and 23 mg/L, respectively, whereas, the design criteria is 10 mg/L and 15 mg/L for BOD and TSS, respectively. However, the effluent BOD and TSS levels in all the plants were far below the suggested standard for disposal. Effluents from all the treatment plants have BOD and TSS concentrations less than 30 mg/L, indicating their suitability for restricted agricultural irrigation. However, only AIP and NGP are producing effluents with BOD and TSS concentrations less than 15 mg/L, the Saudi Arabian standard value for unrestricted agricultural irrigation. Ammonia nitrogen removal was in the range of 12% for RP to the max 40% for AIP, whereas, the lowest ortho-P removal was 3% for NGP to the highest 43% for MFP.

Keywords: wastewater, effluent quality, reuse, treatment plant performance, Riyadh.

INTRODUCTION

Wastewater is commonly treated with the objective of safe environmental disposal and/or reuse of treated effluent for landscape or agricultural irrigation, industrial purposes, or groundwater augmentation. Treatment systems are generally classified as preliminary, primary, secondary, or tertiary. This classification is dictated by the level of purification attained and the type of process involved.

Many cities in Saudi Arabia have experienced spectacular growth in the last few decades. The capital city, Riyadh, grew from a population of nearly 30,000 in 1930 to approximately 1.7 million in 1990 [1]. With the rapid increase in population, wastewater collection, treatment, and disposal has become a real challenge. To meet this challenge, however, wastewater treatment projects have been given priority in the Kingdom's development programs. The existing projects were expanded and new projects were established, providing secondary and tertiary treatment facilities so that the effluents can be reused for many beneficial purposes.

Research and study on the performance of these treatment schemes and the quality of effluents being produced can have significant bearing on designing new facilities or expansion of existing ones and for conservation, recycling and reuse of the Kingdom's limited water resources.

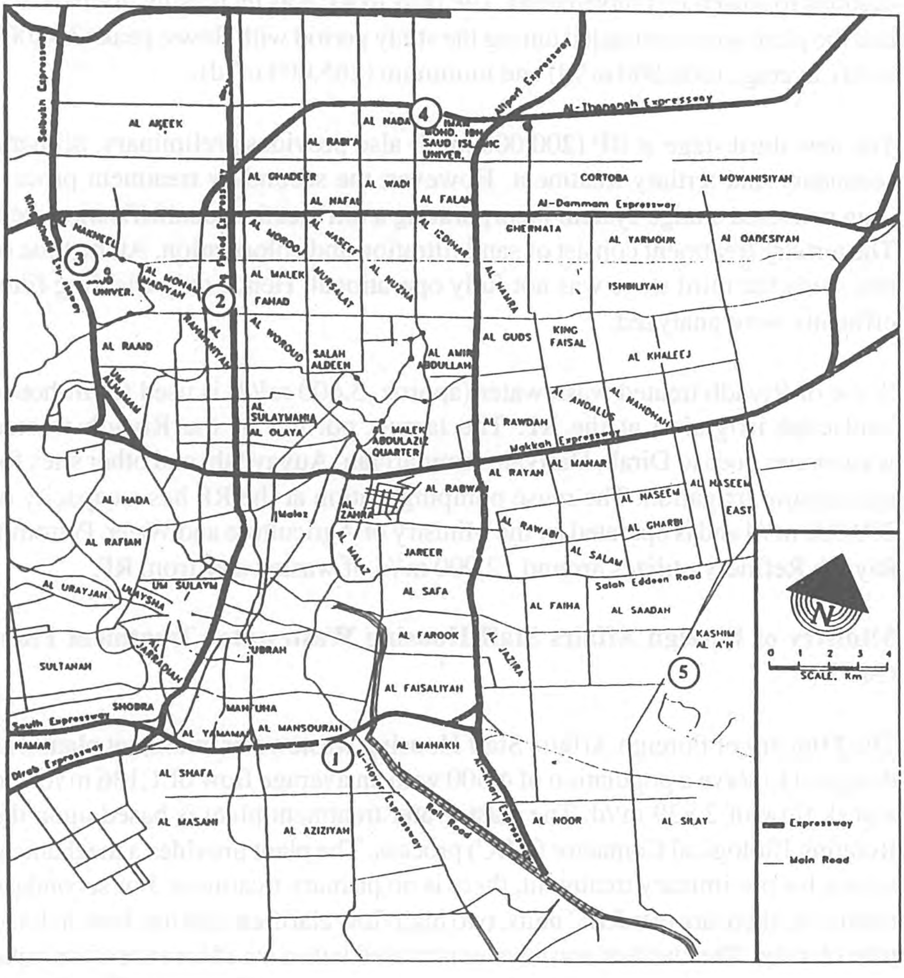
The aim of this paper is to present and discuss the findings of a research study conducted in order to evaluate the performance of five major wastewater treatment plants serving the city of Riyadh. The study did not rely on performance data recorded by each plant. Actual inspection of plants, sampling, and analysis of influents and effluents of the plants was performed by the investigators in this study. Effluent quality in each plant is discussed based on BOD, COD, TSS, nitrogen, and phosphorus concentrations. Effluent suitability for disposal and/ or reuse is also discussed in view of the treatment schemes involved.

WASTEWATER TREATMENT PLANTS IN RIYADH

The following paragraphs describe the capacities, processes and quantities of effluents reused at five major wastewater treatment plants in Riyadh [2,3]. The locations of the plants are shown in Fig. 1.

Riyadh Wastewater Treatment Plant (RP)

The Riyadh Wastewater Treatment Plant (RP) is the largest plant in the Kingdom of Saudi Arabia. It treats around 90% of wastewater collected in Riyadh Sewage



1. Riyadh Sewage Treatment Plant (RP).
2. Ministry of Foreign Affairs Staff Housing Wastewater Treatment Plant (WP).
3. King Saud University Wastewater Treatment Plant (KSP).
4. Al-Imam University Wastewater Treatment Plant (AIP).
5. National Guard Wastewater Treatment Plant at Khashm Al-Aan (NGP).

Fig. 1. Locations of Riyadh's Major Wastewater Treatment Plants.

Network. It has at present total average design capacity of 400,000 m^3/d; increased from 40,000 m^3/d of original plant in 1976. RP has three parallel stages. The first two stages with an average design capacity of 200,000 m^3/d uses the same process which are screening, aerated grit removal, primary sedimentation, high-rate trickling filters and secondary segmentation. The combined effluents of both stages are treated further in two-stage polishing lagoons followed by chlorination. The flow to RP was increasing dramatically and the plant was overloaded during the study period with flows; peak (360,000 m^3/d), average (308,000 m^3/d) and minimum (265,000 m^3/d).

The new third stage at RP (200,000 m^3/d) also provides preliminary, primary, secondary and tertiary treatment. However, the secondary treatment process is an activated sludge system incorporating a nitrification-denitrification step. The tertiary treatment consist of sand filtration and chlorination. At the time of this study the third stage was not fully operational. Hence only trickling filter effluents were analyzed.

Some of Riyadh treated wastewater (approx. 3,600 m^3/d) is used for in-house landscape irrigation at the RP. The largest portion of the Riyadh treated wastewater goes to Dirab, Dariyah, Ammariyah, Auyaynah, and other sites for agricultural irrigation. The reuse pumping station at the RP has a capacity of 200,000 m^3/d and is operated by the Ministry of Agriculture and Water. Petromin Riyadh Refinery utilizes around 12,000 m^3/d of wastewater from RP.

Ministry of Foreign Affairs Staff Housing Wastewater Treatment Plant (MFP)

The Ministry of Foreign Affairs Staff Housing wastewater treatment plant was designed to serve a population of 4,500 with an average flow of 1,136 m^3/d and a peak flow of 2,839 m^3/d. The wastewater treatment plant is based upon the Rotating Biological Contactor (RBC) process. The plant provides a mechanical screen for preliminary treatment, there is no primary treatment. For secondary treatment, there are two RBC units, two high flow clarifiers and one low inclined tube clarifies The clarified wastewater is treated with a small amount of chlorine before tertiary treatment which consists of two pressure filter units. The filtered water is then chlorinated before being stored in two concrete irrigation basins. The plant was designed to produce an effluent with a 10 mg/L BOD and 15 mg/L TSS. The entire plant's effluent is used for landscape irrigation on site.

King Saud University Wastewater Treatment Plant (KSP)

The King Saud University Wastewater Treatment Plant near Daraiyah was designed to treat an average flow of 10,000 m^3/d and serve a population of

45,000 persons. During this study it was operating at an average flow of 9,000 m3/d with peak and minimum flows of 12,000 and 7,000 m^3/d, respectively. The plant provides preliminary, primary, and secondary treatment as well as chlorination. The preliminary treatment includes preaeration, communitor, bar screen, and grit removal. The primary treatment consists of two plain sedimentation tanks, and the secondary treatment is provided by four trickling filters in conjunction with two final sedimentation tanks. The treated wastewater is also chlorinated before it is used for landscape irrigation or for water cooling tower use.

The plant was designed for a 93% removal of BOD and 90% removal of suspended solids (TSS). The effluent characteristics are to be 24 mg/L BOD and 41 mg/L TSS. Space has been left at the plant for tertiary treatment should wastewater of better quality be required. The treated wastewater from KSP is used on campus for power plant cooling (1,000 m^3/d) and landscape irrigation (5,000-6,000 m^3/d).

Al-Imam University Wastewater Treatment Plant (AIP)

This plant was designed to treat an average flow of 4,800 m^3/d and a peak flow of 11,520 m3/d and serve a population of 32,000 persons. The plant provides preliminary, primary, secondary and extensive tertiary treatment. The preliminary treatment consists of coarse and fine screens, preaeration tank and grit chambers. The primary treatment consists of two primary sedimentation tanks, while the secondary treatment consists of two aeration tanks (conventional activated sludge) in conjunction with two final sedimentation tanks. The tertiary treatment includes two sand filtration processes, one gravity and one pressurized. Also included in the tertiary treatment facilities are activated carbon adsorption and reverse osmosis. Disinfection can be provided before gravity filtration as well as part of the final treatment process for the water used in landscape irrigation.

This plant was designed for a BOD loading of 75 g/c/d with a 500 mg/L BOD in the influent. This plant is to produce an effluent with a BOD and TSS concentration of less than 10 mg/L. The reclaimed water from this plant is used for landscape irrigation on campus and for cooling tower water at the power plant.

National Guard Wastewater Treatment Plant at Khashm Al-Aan (NGP)

This wastewater treatment plant utilizes a 4-stage Rotating Biological Contactor (RBC) process and also provides rapid sand filtration and chlorination for the final effluent. This plant was designed to serve a population of 50,000 persons with an average flow capacity of 10,000 m^3/d. The plant was operating at an average flow of 9,900 m^3/d with a minimum of 7,000 m^3/d. The plant provides a mechanical screen, aerated grit chambers, bar screen, and two comminutors for preliminary treatment, two covered settling tanks for primary treatment, 10 aerated rotating biological contactors, (4 stage system) and 4 covered secondary clarifiers for secondary treatment and 3 rapid sand filters and chlorination for tertiary treatment. It was designed to produce an effluent with a BOD and TSS of less than 10 mg/L. The treated wastewater from this facility is used for landscape irrigation.

SAMPLING AND ANALYSIS

Twenty-four hour composite wastewater samples were collected from each of the five major wastewater treatment plants in Riyadh during the period Jumada II to Dhulqada 1414 H. (Dec. 1993 to May 1994). Composite samples were collected for both the influent (raw sewage) and effluent (plant's final effluent before chlorination) with sampling frequency of 3 hours i.e. 1 L each of influent and effluent was collected every 3 hours for 24-hours and was stored in 10 L containers kept in the refrigerator. Sampling at each plant was carried out once in a week for a period of four weeks.

Influent and effluent composite samples were then brought to the Environmental Engineering research laboratory of King Saud University (KSU). Samples were analyzed immediately for pH, Alkalinity, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Ammonia Nitrogen (NH_3-N) and Total Kjeldhal Nitrogen (TKN). The remaining samples were then stored in the refrigerator for the measurement of total suspended solids (TSS) and soluble Phosphorus (ortho-P), the following day. All detentions were performed in duplicates to ensure accuracy of the results. Analysis of all samples were performed according to Standard Methods [4].

RESULTS AND DISCUSSION

Organics (BOD and COD) Removal

Biochemical Oxygen Demand (BOD) is the most common parameter for defining the strength of treated and untreated wastewater. BOD is also the primary pollutant associated with depletion of dissolved oxygen, which is needed for the aquatic life in receiving waters [5]. Fig. 2 compares the influent and effluent BOD values from the five major wastewater treatment plants in Riyadh. The influent and effluent values are average of four composite samples collected over a span of one month.

As seen from Fig. 2 all plants have achieved good treatment efficiencies. The average effluent BOD concentration was 18 mg/L for RP, 21 mg/L for MFP and KSP, and 12 mg/L for AIP and NGP. These values are below United States Environmental Protection Agency (USEPA) standard values for disposal of 30 mg/L (monthly average) and 45 mg/L (7-days consecutive average) [6]. All the plants, except KSP, achieved more than 85% of BOD removal, another condition set by USEPA for secondary wastewater treatment. KSP's average BOD removal was 83% during the study period.

The average chemical oxygen demand (COD) values for the treatment plants are compared in Fig. 3. The mean COD removal was 80% for both RP and MFP, whereas it is 86% for NGP. AIP achieved high COD removal of 92% and KSP the lowest removal of only 68%.

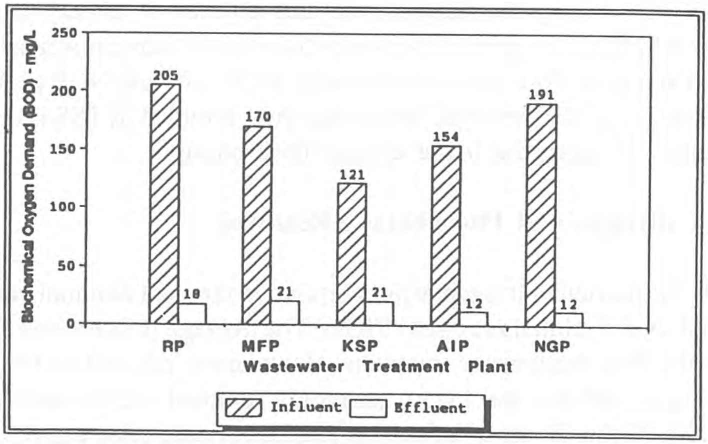


Fig. 2. Influent-Effluent BOD at Riyadh's Wastewater Treatment Plants.

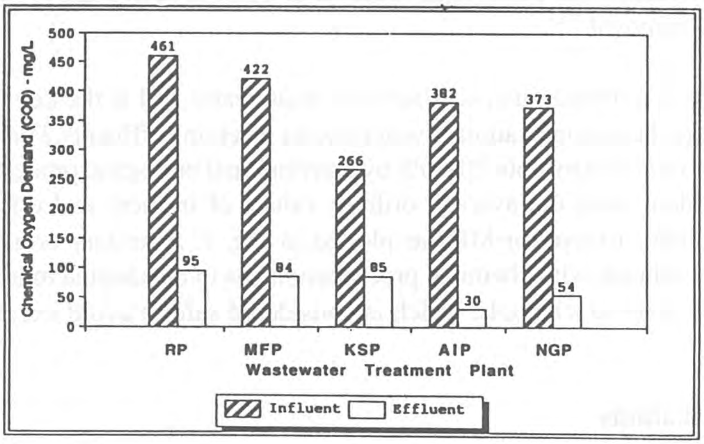


Fig. 3. Influent-Effluent COD at Riyadh's Wastewater Treatment Plants.

Suspended Solids (TSS) Removal

Suspended Solids (SS) is one of the most significant components of wastewater. After BOD, SS is the other basic design criteria in wastewater processing. High SS in the effluents discharged to water bodies interfere with the transmission of light and turbid water interferes with recreational use and aesthetic enjoyment [7]. Moreover, high SS can prevent pathogens inactivation in the disinfection process by shielding pathogens from the disinfectant. USEPA has established discharge limits of 30 mg/L (average monthly cone.) and 45 mg/L (average weekly cone.); the treatment plants should also achieve >85% SS removal [8].

Looking at the performance of treatment plants in Riyadh for TSS removal (Fig. 4), a good achievement can be noticed except for KSP. For KSP the average TSS removal is 80%. This low percentage of removal may be due to low influent TSS during the study period and absence of tertiary treatment scheme. RP which has an aerated lagoon as a tertiary treatment step achieved 85% of TSS removal. As expected, the plants MFP, AIP and NGP performed excellent in terms of TSS removal. More than 90% removal of TSS is obtained in these plants, obviously due to the tertiary filtration step.

Nutrients (Nitrogen and Phosphorus) Removal

In this study the nutrient, nitrogen, was measured in terms of ammonia nitrogen (NH_3-N) and total Kjeldhal nitrogen (TKN). The average influent and effluent NH_3-N for the five wastewater treatment plants are compared in Fig. 5. As shown in Fig. 5, RP has the lowest ammonia removal (12%) and AIP the highest (40%). Higher levels of influent ammonia concentration can be noticed in AIP samples. Fig. 6 shows the TKN values of influent and effluent of Riyadh's wastewater plants. The percentage removal of TKN in each plant is similar to the NH_3-N removal.

Phosphorus is a ubiquitous constituent of wastewater and is the key nutrient which causes the eutrophication of water bodies receiving effluents. Phosphorus can only be removed by upto 20-30% by conventional biological processes [91. This is evident from the average ortho-p values of influent and effluent of treatment plants except for MFP as plotted in Fig. 7. A tertiary or advanced wastewater scheme with chemical precipitation has to be adopted to lower the phosphorus level to <1 mg/L, which is considered safe to avoid excess algal growth.

pH and Alkalinity

pH value for the influent and effluent from all the wastewater treatment plants was near neutral (see Table 1) and was in the range of 6.0-9.0 which is recommended by the regulatory agencies for disposal and reuse. Alkalinity, used as a process control variable in treatment plants, reduced during the treatment processes at all the plants but only to a small extent as can be seen from Table 1. This is the normal reduction encountered at the treatment plants. Maximum levels of alkalinity have not been set by the regulatory agencies for discharge [10]. Table 1 also includes a summary of the average influent and effluent values and % removal of all the parameters studied.

Suitability of Effluents for Reuse

The quality criteria an effluent has to meet depends upon the purpose for which it is being reused. Here in Riyadh, more than 90% of reused effluent is for landscape and agricultural irrigation. Hence, the suitability of the effluent from the five major plants in Riyadh will be evaluated for agricultural use. The parameters that of most concern are BOD, TSS, pH, Colifoms and heavy metals. The measurement of coliforms and heavy metals is out of scope of this study. Hence, BOD, TSS, and pH values of effluents will be considered.

Table 2 shows the Saudi Arabian tentative water quality standards for restricted and unrestricted agricultural irrigation [11]. The quality criteria for BOD is 15 mg/L (weekly average) for unrestricted and 30 mg/L for restricted irrigation. From Fig. 2 it can be seen that the average BOD for effluents from all plants is below 30 mg/L, meeting the quality criteria for restricted agricultural irrigation. Further, the average BOD for AIP and NGP of 12 mg/L meets the quality criteria for BOD for unrestricted irrigation. The other BOD values of 18 and 21 mg/L for RP, MFP and KSP, respectively are not far from 15 mg/L. Moreover, the average 15 mg/L of BOD for unrestricted irrigation is based on weekly average. Here the BOD average values reported are based on four composite samples. If we go for higher sampling intervals, the average tends to decrease. Hence, it may be assumed that the effluent from all the five major wastewater treatment plants meets the quality criteria of unrestricted irrigation for BOD.

Referring to Fig. 4 and Table 1, the effluent from all the treatment plants meets the limit of 30 mg/L of TS S for restricted irrigation (Table 2). Also, KSP, AIP and NGP meets the TS S criteria for unrestricted irrigation (< 1 5 mg/L). RP and MFP having TSS concentration of 24 and 23 mg/L are exceeding the quality criteria for unrestricted irrigation. However, as stated before, more samples should be analyzed to reach to a definite conclusion. The pH values for all effluents is around neutral and it is well in the 6.0-8.4 Saudi Arabian standard range for irrigation.

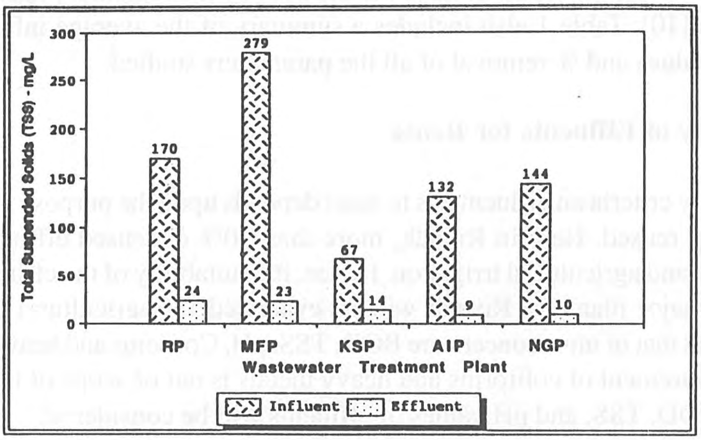


Fig. 4. Influent-Effluent TSS at Riyadh's Wastewater Treatment Plants.

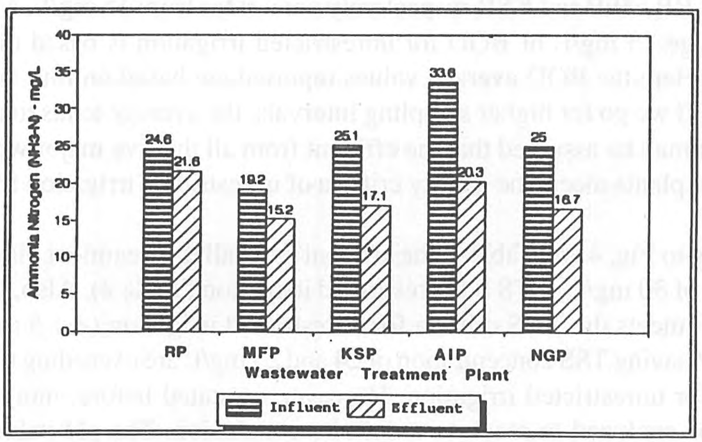


Fig. 5. Influent-Effluent NH_3-N at Riyadh's Wastewater Treatment Plants.

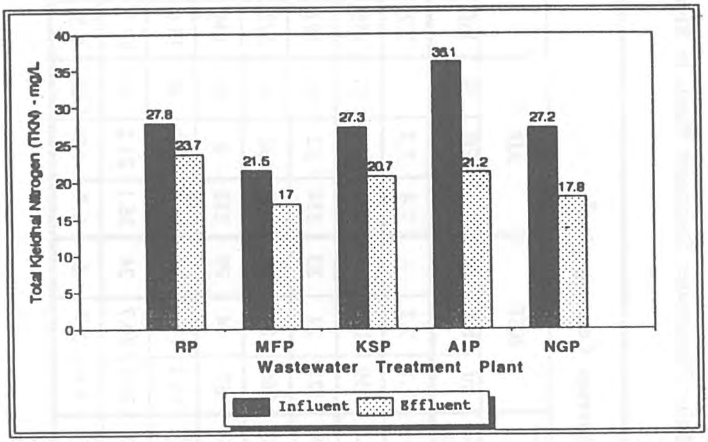


Fig. 6. Influent-Effluent TKN at Riyadh's Wastewater Treatment Plants.

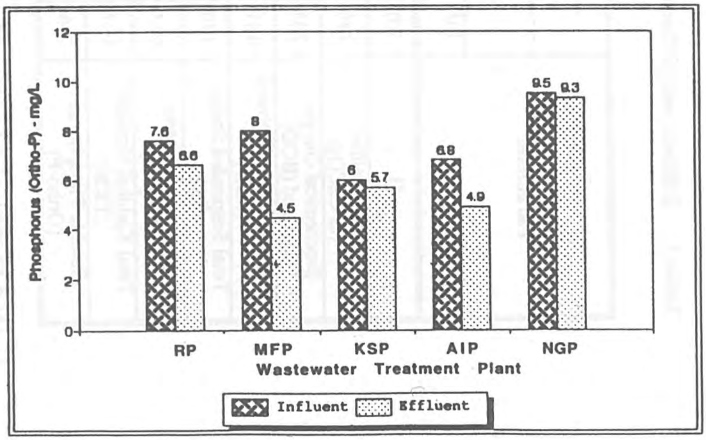


Fig. 7. Influent-Effluent Ortho-P at Riyadh's Wastewater Treatment Plants.

Table 1: Influent and Effluent Characteristics of Five Major Wastewater Treatment Plants in Riyadh

Parameter	Average Concentration*														
	RP			MFP			KSP			AIP			NGP		
	Inf	Eff	% Rem	Inf	Eff	% Rem	Inf	Eff	% Rem	Inf	Eff	% Rem	Inf	Eff	% Rem
pH	7.0	7.2	-	7.0	6.7	-	7.1	7.2	-	7.4	7.3	-	7.2	7.2	-
Total Alkalinity (as $CaCO_3$)	186	161	13	121	81	32	159	127	20	211	152	27	155	118	23
Biochemical Oxygen Demand (BOD)	205	18	91	170	21	88	121	21	83	154	12	92	191	12	94
Chemical Oxygen Demand (COD)	461	95	79	422	84	80	266	85	68	382	30	92	373	54	86
Total Suspended Solids (TSS)	170	24	86	279	23	92	67	14	79	132	9	93	144	10	93
Ammonia Nitrogen (NH_3-N)	24.6	21.6	12	19.2	15.2	21	25.1	17.1	32	33.6	20.3	40	25.0	16.7	33
Total Kjeldhal Nitrogen (TKN)	27.8	23.7	15	21.5	17.0	21	27.3	20.7	24	36.1	21.2	42	27.2	17.8	34
Soluble Phosphorus (Ortho-P)	7.6	6.6	14	8.0	4.5	43	6.0	5.7	6	6.8	4.9	28	9.5	9.3	3

Inf = Influent, Eff = Effluent, %Rem = %Removal

* All concentrations are in mg/L except for pH (pH units).

Table 2: Saudi Arabian Tentative Water Quality Standards for Agricultural Irrigation [11].

Wastewater effluent to be used for irrigation of any type of crop must meet the following quality standards.

Parameters	Maximum Contaminant Level (MCL)	
	Unrestricted Irrigation	Restricted Irrigation
BOD, Biochemical Oxygen Demand (mg/L)	10[a]	20[c]
TSS, Total Suspended Solids (mg/L)	10[a]	20[c]
Boron (mg/L)	0.7	0.7
Phenol (mg/L)	0.002	0.002
Oil and grease (mg/L)	absent	absent
Hydrogen-ion-concentration (pH units)	6.0-8.4	6.0-8.4
Intestinal nematodes (viable eggs/L)	1	1
Fecal coliforms (MPN/100 mL)	2.2[b]	100[c]
Turbidity (NTU)	2	2

a. Monthly average BOD and TSS concentration shall not exceed 10 mg/L each. Weekly average BOD and TSS concentration shall not exceed 15 mg/L each.

b. The wastewater effluent shall be considered adequately disinfected for unrestricted irrigation if the average fecal coliform organisms in the water does not exceed MPN 2.2/100 mL as determined from the bacteriological test results of the last 7 days, and the number of fecal coliform organisms does not exceed MPN 23/100 mL in any sample.

Wastewater effluent quality must meet or be better than the MCL 80% of the time, based on the last 20 consecutive samples.

Secondary level effluent can be used to irrigate trees, food crops which are consumed cooked or processed, and non-food crops such as fodder fiber and seed crops.

c. Monthly average BOD and TSS concentration shall not exceed 20 mg/L and fecal coliform organisms MPN 100/100 mL. Weekly average BOD and TSS concentration shall not exceed 30 mg/L and fecal coliform organisms MPN 200/100 mL.

Note: MCL's for heavy metals are not included.

CONCLUSIONS

The determination of some of the most important wastewater quality parameters like pH, alkalinity, BOD, COD, TSS, nitrogen, and phosphorus in the influents and effluents has given a clear picture of wastewater treatment and effluent quality of Riyadh's five major treatment plants. In general, all the treatment schemes were found to produce good quality effluent. The effluent from all the plants met very easily the disposal criteria set by the local and international regulatory agencies. The quality of effluents in Riyadh's wastewater treatment plants exceeds the water quality requirement for restricted agricultural irrigation. However, only two plants are producing effluents that are suitable for unrestricted agricultural irrigation. It should be noted that these general conclusions are based only on the parameters tested in this study. Other important quality parameters such as the pathogenic measures and heavy metals has to be studied in order to finalize these conclusions. Following are the specific conclusions of this study:

1. The average effluent BOD and TSS concentrations at RP during the study period were 18 mg/L and 24 mg/L, respectively. The plant achieved 91% of BOD removal and 86% of TSS removal. The effluent from the plant can be safely disposed or reused for restricted agricultural irrigation.

2. The Ministry of Foreign Affairs Treatment Plant (MFP) had BOD removal of 88% and TSS removal of 92%. The average effluent BOD and TSS concentrations were 21 mg/L and 23 mg/L, respectively. These concentrations are high for a plant having tertiary filtration step. The effluent is suitable only for restricted irrigation.

3. Effluent BOD and TS S concentrations at King Saud University Wastewater Treatment Plant (KSP) averaged 21 and 14 mg/L, respectively. The effluent is suitable only for restricted agricultural irrigation. The performance of the plant is reasonable since the plant does not have tertiary treatment facilities.

4. Al-Imam University Wastewater Treatment Plant (AIP) which has a tertiary filtration step is producing excellent effluent which is suited for unrestricted agricultural irrigation. During the study period the average BOD and TSS were 12 mg/L and 9 mg/L, respectively.

5. The average BOD and TSS were 12 mg/L and 10 mg/L, respectively, for National Guard Wastewater Treatment Plant at Khasham Al-Aan (NGP). The effluent is suitable for unrestricted irrigation. It has BOD and TSS removal efficiencies of 94% and 93%, respectively. All five plants are discharging effluents at around neutral pH values meeting the range of 6.0-8.4 for agricultural irrigation.

ACKNOWLEDGEMENT

The authors express their thanks and appreciation to the staff of all the five wastewater treatment plants studied for providing the necessary information and for their co-operation in composite sampling of wastewaters. Eng. Khaled Al-Huzaimi has analyzed for some of the parameters as part of his senior project.

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Slow Sand Filtration of Secondary Effluent - with and Without Chlorination

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SLOW SAND FILTRATION OF SECONDARY EFFLUENT - WITH AND WITHOUT CHLORINATION

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ABSTRACT

Headloss minimization in slow sand filters is one of the most important considerations for its longer, efficient and economic runs. Especially so when the slow sand filter is being used to treat nutrient rich secondary effluent. Previous studies on pilot filters have shown numerous complications in terms of short filter runs that result due to algal blooms and the uninhibited growth of the schmutzedecke layer. Chlorination of the secondary effluent prior to slow sand filtration is being studied as the solution to this problem. A pilot plant is constructed at the Al-Khobar Sewage Treatment Plant to study the effect of chlorination on slow sand filters. The pilot plant consists of a holding tank, a chlorination tank and two slow sand columns. Each filter has internal diameter of 2 m with sand depth of 1 m and effective sand size of 0.5 mm. Filters were operated at a constant flow rate of 10 l/min. Removal of six different group of organisms was investigated in this study. Preliminary data shows 96.7-99.9% removal of standard plate counts, 95-99.9% removal of total coliforms, 95-99.8% removal of fecal coliforms, 87.3-99.9% removal of fecal streptococci, 77.4-96.3% removal of Cl. perfringens and 69.1-99.8% removal of coliphages in chlorinated secondary effluent after slow sand filtration. The filter has been operating for over 100 days without interruption. Chlorination before slow sand filtration, seems to control the rapid growth of the *schmutzedecke* layer to an optimum limit that does not hinder micro-organism removal and also control the head loss. This study proposes to find the optimum chlorine dosage that will be effective in inactivation of micro-organisms and also prolonging the filtration run.

Keywords: Slow sand filters, prechlorination, headloss, colifoms, coliphage, tertiary treatment.

INTRODUCTION

Slow sand filtration has long been recorded as an economic and reliable treatment process for potable water treatment. Recent studies have shown that it is equally reliable in the treatment of wastewater (Ellis, 1985; Farooq and Al-Yousef, 1993a; Farooq et. al., 1993b). But slow sand filters also have some inherent disadvantages like rapid headloss build-up, and time variant removal rates due to filter ripening and uncontrolled growth of the *schmutzedecke* layer. A coordinated effort is required to develop and modify slow sand filters for its effective performce in microbial removal m secondary effluents.

Pre-chlorination of the secondary effluent prior to filtration has been recommended as a measure to reduce headloss, achieve greater viral and bacterial removals, and reduce the fluctuations in the performance of the slow sand filter (Ellis, 1984). A pilot-scale study is conducted at the Al-Khobar Sewage Treatment Plant, Eastern Province, Saudi Arabia, in order to generate detailed information about the effect of pre-chlorination of secondary effluents on the performance of slow sand filters with respect to the removal of microbial indicator organisms. The main emphasis of the study is to investigate and monitor the bacterial and viral removals through slow sand filters due to pre-chlorination of the secondary effluents under field conditions. Six different microbial parameters have been selected, namely standard plate counts, total coliforms, fecal coliforms, fecal streptococcus, *Cl. perfringens*, and coliphages (Kott et al., 1974; Geldreich, 1978; Cabelli, 1978; Scarpino, 1978; Borrego et. al., 1987), as these are widely recommended as indicators of pathogens in waters and wastewater.

LITERATURE REVIEW

Recent years have seen an increasing trend towards water reuse for agricultural purposes, ground water recharge, landscape development, toilet flushing etc. (Asano and Sakaji, 1990). Since human contact with this source of water is inevitable, there is an inherent danger in that the fecal-oral route is completed and there is a risk of transmission of water-borne diseases (Butler, 1981). With increasing volumes of treated waste water being targeted for reuse there is a need to develop reliable methods to mitigate the health safety risk caused by bacterial and viral infection. The mechanisms of virus removal by various disinfection processes were studied by Butler (1981). He regarded conventional wastewater treatment processes as highly inefficient and stressed the need for tertiary treatment and disinfection as a means of a more comprehensive virus removal. There is also the increased risk in allowing partially treated wastewater for reuse, as this will lead to the re-circulation of pathogens and thereby creating resistant strains. This makes it imperative for a total and comprehensive microbial removal in wastewater treatment so that pathogens do not survive. The need of the hour is the development of efficient, economic and reliable processes that will effectively reduce the health risk due to water reuse. Modifications and additions to existing treatment works for the complete removal of pathogens are the order of the day.

Ellis (1984), made an extensive review of the history, performance, influence of various physical, chemical and biological parameters, extent of research etc., on slow sand filters. He concluded that slow sand filters have all the advantages of being an efficient, economic and reliable water treatment process. The use of slow sand filters for treatment of secondary effluents is a recent concept that was examined and explored by Ellis (1985) in the mid 80's. Ellis found that results of previous studies on the viability of slow sand filtration as a tertiary treatment process gave a conservative picture of the treatment efficiency of slow sand filters. Studies using a slow sand filtration unit of 140 mm dia. perspex cylinder, 2.65m in height and 950 mm sand depth of fine sand was used. The sand size was initially 0.3 mm and later changed to 0.6 mm. At treatment rates of 3.5 md^{-1} and 7.5 d^{-1} the slow sand filter was able to remove at least 90% of suspended solids, more than 65% of the remaining BOD and over 95% of the coliforms.

A comprehensive study on the effect of sand sizes and filter depths on the treatment efficiency of slow sand filters was conducted by S. Farooq et al. (1993b). The filter depths investigated were 135, 105, 55 cm and two sand sizes of 0.31 and 0.56 mm elective size. It was found that the removals of BOD, COD, standard plate counts, nitrate, phosphate, and sulfate vary from 79-92%, 40-60%, 88-93%, 17-30%, 8.3-84% and 5-10% respectively at various sand depths for two different sizes of sand. They concluded that the percent removals of different parameters investigated in the study decreased by decreasing the sand depth and/or by increasing the sand size. Therefore it was suggested that sand of coarser size with deeper bed be used in contrast to finer sand of shallow bed in order to get desired efficiency.

Bellamy et al. (1985) conducted experiments on six parallel pilot slow sand filters and observed the effect of temperature, sand bed depth, sand size, disinfection and biological activity on the treatment efficiency of slow sand filters. The study demonstrated increasing efficiency with increased temperatures, negligible effect of sand depth, increased efficiency with smaller sand size and increased microbial removals with greater biological activity.

Surprisingly there is no single study that deals with the direct comparison of the microbial removals in slow sand filters with and without pre-chlorination. Historically chlorination of the supernatant waters, in a slow sand filter, have generally been restrained because of its perceived detrimental effect on the *schmutzedecke* layer (Ellis, 1984; Reisenberg et. al., 1995). Ellis however recommends pre-chlorination in situations where the chlorine demand is sufficiently high enough, so as not to effect the *schmutzedecke*. Pre-chlorination has also been used to prevent algal blooms in the filters, as a shock treatment to clean filter media and prevent fouling-up (Schuler et.al., 1991), or as a means of suppressing biological activity (Bellamy et. al., 1985).

MATERIALS AND METHODS

Two modular slow sand filters, one settling tank and one chlorination tank were constructed in the field at the Al-Khobar Sewage Treatment Plant. Their layout is shown in Fig 1. Each modular slow sand filter unit consists of a 4 m deep, 2 m internal diameter cylindrical filter box placed 1-1.5 m into the ground. A sand layer of elective size 0.5 mm with a uniformity coefficient of 1.6 and a depth of 1 m was placed on a gravel media. Peizometers attached to the filters are used to measure the headloss at different depths. The headloss in both the test and control filters were measured daily. The hydraulic loading to the filters is constantly adjusted to around 2.3 m/d using the outflow valves. The holding tank is a cylindrical structure designed to hold the secondary effluent for an average detention time of about 4 hr. It is 4 m deep with an internal diameter of 2 m. The secondary effluents from the treatment plant are first pumped into the settling tank. The settled secondary effluent is then divided into two streams. One goes to the control filter and the other is chlorinated in the chlorination tank, with a chlorine dose of 5 mg/l, before being introduced into the test filter. Both the filters and the tanks have outlets through which the treated samples are collected.

The samples for the microbial analysis were collected from the settled secondary effluent, chlorination tank outlet, and the outlets from the test and control filters respectively. The method of collection of samples was as outlined in the *Standard Methods*. Microbial analysis of chlorinated and unchlorinated secondary effluents includes the detection and enumeration of standard plate counts, total coliforms, fecal coliforms, fecal streptococcus, *Cl. perfringens*, and coliphages. The detection and enumeration of standard plate counts, total coliforms, fecal coliforms, fecal streptococci and coliphages were as recommended by *Standard Methods*. *Cl. Perfringens* was enumerated by the process outlined by the *International Standards Organization for the Examination of Drinking Water.* The analysis for all the parameters was carried out weekly to monitor the removal of the microbial indicator organisms and filter efficiency.

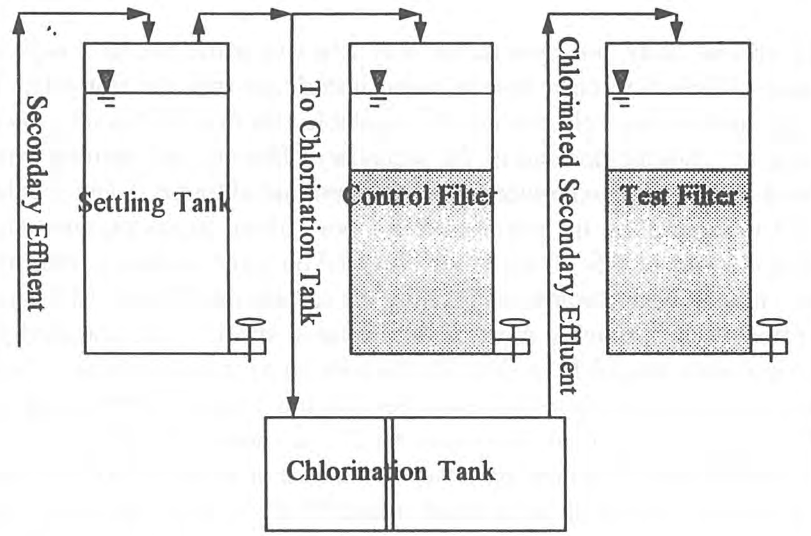

Fig 1: Schematic Layout of Pilot Slow Sand Filters

RESULTS AND DISCUSSION

The microbial data was generated under four different set of conditions, i.e., disinfection at a chlorine dosage of 5 mg/l, microbial removal in control filter, microbial removal in test filter, and the overall microbial removal in the test filter incorporating the combined effect of chlorination and slow sand filtration. The results in terms of average percent removals along with their ranges for all organisms under four conditions are given in Table 1. However, their variations with respect to time are shown in respective Figs. 2-7. In the case of the control filter, percent values were calculated using the difference in microbial populations in the settled secondary effluent and at the filter outlet. The effect of chlorination is obtained as the percentage difference of the microbial parameters in the settled secondary effluent and at the outlet of the chlorination tank. The chlorinated secondary effluents then formed the influent to the test filter. The removals in the test filter were calculated as the percentage difference of the microbial populations in the chlorinated secondary effluents and at the outlet of the test filter. The overall microbial removal in the test filter is evaluated as the percent difference of the microbial populations in the settled secondary effluent and at the outlet of the test filter. The results of these conditions for different microbial indicators are given in Figs 2-7.

Effect of Chlorination Alone

In the present study, pre-chlorination was achieved at the rate of 5 mg/l, in a separate chlorination tank, before being introduced into the test filter. This had the dual purpose of utilizing the available chlorine exclusively towards meeting the chlorine demand of the secondary effluents, and thereby causing minimal harm to the *schmutzedecke*. The residual chlorine if any would be utilized in controlling the schmutzedecke population. In the present study a residual chlorine of 0.5-1.0 mg/l was observed on some occasions, but mostly all the chlorine went towards disinfecting the secondary effluents. Chlorination was effective in removing most of the bacterial species. The standard plate count removals ranged from 76.6-98.9% with an average removal of 90.4%. Total and fecal coliforms had removals ranging from 47.1-85% and 70.5-95.5%, and averaged at 71.8 and 85.2% respectively (Figs 2, 3, 4). Chlorination showed variable removals in the case of focal streptococci having a range of 46.2-94% with an average around 75.8% (Fig 5). Removals of *Cl. perfringens* showed marked variability with a range of 12.9-80.8% and averaged around 44.5% (Fig 6). This is an expected result as *Cl. perfringens* is a spore-former and has high resistance to disinfectants. Due to its exceptional resistance to chlorination it has been recommended by Cabelli (1978) as an indicator of fecal pollution in extreme environments, where the traditional indicators like coliforms are likely to give erroneous interpretations.

The coliphage reactivation data showed marked variability with a range of 24.4-80.6% and an average around 49.2% (Fig 7). Coliphages are more resistant to chlorination than most enteroviruses. In a study of the chlorination experiments on f2 and MS_2 coliphages, attenuated with Polio I strain, Kott et al. (1974) have reported that the coliphages were more resistant than the attenuated Polio I virus. This study recommends that bacteriophages, particularly coliphages serve as viral pollution indicators in wastewater treatment involving chlorination. Thus chlorination alone is inadequate for the removal/inactivation of viruses. The large fluctuations in the removal/inactivation percentages, could be due to the large chlorine demand of the secondary effluents, and the protection offered to the micro-organisms by turbidity and flocs.

Microbial Parameters	Population in Settled Secondary Effluent	Percent Removal/Inactivation							
		Chlorination (5mg/l)		Control Filter		Test Filter		Overall Test Filter Chlorine+Filtration	
		Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
1. Standard Plate Count	$3.55*10^4$/ml	76.6-98.9	90.4	80.5-99.2	93.6	80.0-99.3	88.5	96.7-99.9	98.9
2. Total Coliform	$5.87*10^5$MPN/100ml	47.1-85.0	71.8	58.3-99.4	82.8	66.7-99.4	93.4	95.0-99.9	98.4
3. Fecal Coliform	$3.48*10^5$MPN/100ml	70.5-95.5	85.2	50.0-99.7	82.8	74.0-99.4	91.9	95.0-99.8	98.8
4. Fecal Streptococcus	$5.33*10^4$MPN/100ml	46.2-94.0	75.8	38.2-99.8	87.3	33.3-99.1	85.5	87.3-99.9	97.5
5. *Cl. Perfringens*	$1.24*10^2$/100ml	12.9-80.8	44.5	47.4-91.3	78.1	44.8-90.7	78.9	77.4-96.3	89.5
6. Coliphages	$7.7*10^2$/100ml	24.4-80.6	49.2	60.3-94.5	80.1	36.2-99.7	79.3	69.1-99.8	91.3

Table 1: Microbial Removal Efficiencies in Chlorination, Control Filter, Test Filter and Overall Test Filter

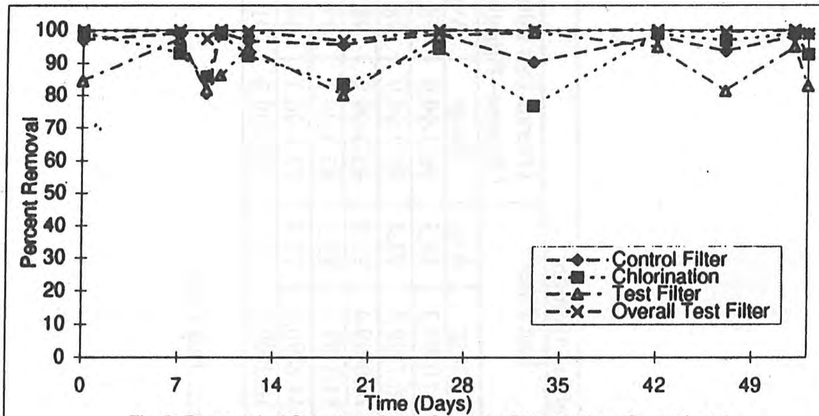

Fig 2: Removal of Standard Plate Count in Chlorination, Control and Test Filter

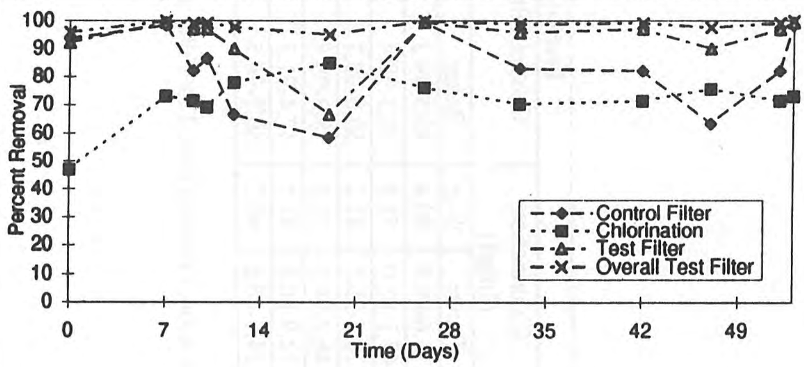

Fig 3:Removal of Total Coliform in Chlorination, Control and Test Filter

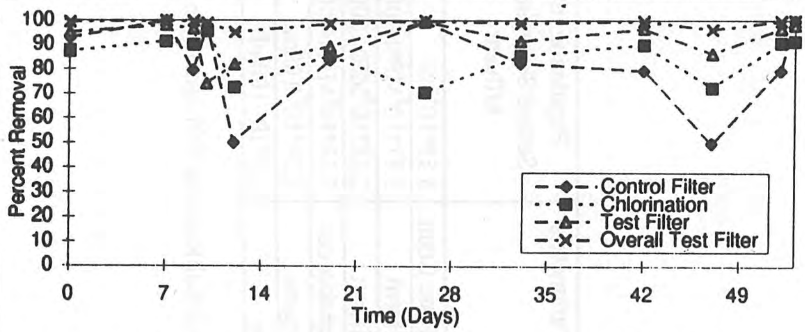

Fig 4: Removal of Fecal Coliform in Chlorination, Control and Test Filter

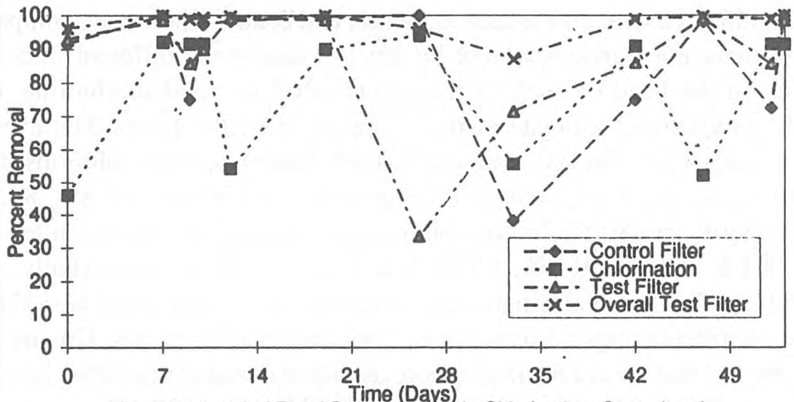

Fig 5: Removal of Fecal Streptococcus in Chlorination, Control and Test Filter

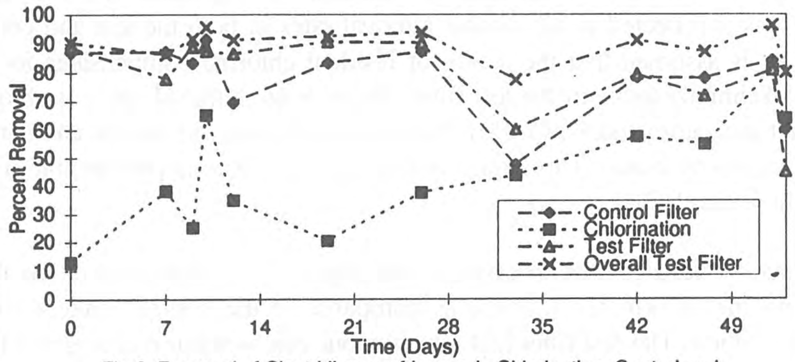

Fig 6: Removal of Clostridium perfringens in Chlorination, Control and Test Filter

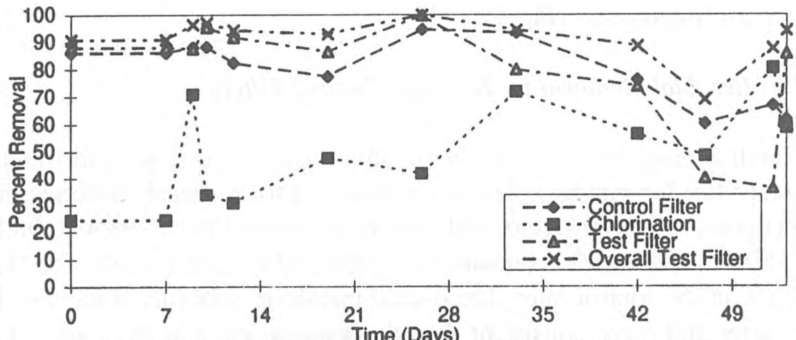

Fig 7: Removal of Coliphage in Chlorination, Control and Test Filter

Effect of Pre-chlorination on Filter Efficiency

The microbial removal efficiencies in the test and control filters were compared. Though these comparisons cannot be precise, due to the different microbial influents at the head of each filter and the effect of residual chlorine, they provide a reasonable estimate of the performance of the filters. The average removal ranges for standard plate count, total coliforms, fecal coliforms, fecal streptococcus, *Cl. Perfringens* and coliphages were 93.6%, 82.8%, 82.8%, 87.3%, 78.1% and 80.1% in the control filter, whereas in the test filter they were 88.5%, 93.4%, 91.9%, 85.5%, 78.9%, and 79.3% respectively, (Fig 2,3,4,5,6,7). The removal efficiencies of all the micro-organisms was similar in both the filters except perhaps for the total and fecal coliforms. This may be due to the fact that the coliforms are more readily reactivated than other indicator organisms. This has lead to a demand for viral indicators other than coliforms in chlorination studies. Ellis (1984) has reported that a pre-chlorination dose of even 8.8 mg/l did not significantly change the performance of a slow sand filter. This is reflected in the similar removal rates in both the test and control filters. It is assumed that the action of residual chlorine compensates for the loss of Schmutzedecke in the test filter. The average removal rates of chlorine resistant indicators, that is, *Cl. Perfringens* and coliphage, in the test and control filter are nearly equal. This indicates that the test filter is performing at par with the control filter.

The major difference was observed in the length of the operations of the filter fed with the chlorinated influent as compared to the control filter with no prechlorination. The test filter had a continuous run, without reaching headloss even after a period of 100 days (Fig 8). The control filter on the other hand, had a run time of 48 days, after which a five day period was required for its cleaning and maturation (Fig 9).

Overall Microbial Removal in Test and Control Filters

The overall average removals, including chlorination and slow sand filtration, in the test filter for standard plate count, total coliforms, fecal coliforms, fecal streptococcus, *Cl. Perfringens* and coliphages were 98.6%, 98.4%, 98.8%, 97.5%, 89.5% and 91.3%, compared to 93.6%, 82.8%, 82.8%, 87.3%, 78.1% and 80.1% in the control filter. The overall microbial removals in the test filter by far better and more consistent than the removal rates in the control filter. This was especially so for *Cl. perfringens* and coliphages, indicating that a combined disinfection and filtration action was more efficient than disinfection or filtration alone. This is in conformance with the study carried out by Goldgrabe et.al., (1993), on the particle removal efficiencies in prechlorinated and nonchlorinated filters. She reports the particle removals in pre-chlorinated filters (1 mg/l residual chlorine) to be greater than the non-chlorinated filter by log 0.5-0.6. In a comparative study of pre-ozonation, pre-chlorination and pre-chloramination, Le Chavellier et.al, (1992), found that AOC (Assimilable Organic Carbon) reduction occurred even in the presence of a disinfectant residual. This implies AOC utilization by the indigenous filter biota even in the presence of disinfectants. However, the impermeable, gelatinous slime formation on pre-chlorinated filters that were reported by Ellis (1984) was never observed throughout the filter run. This may have been due to the absence of clay particles in the filter influents.

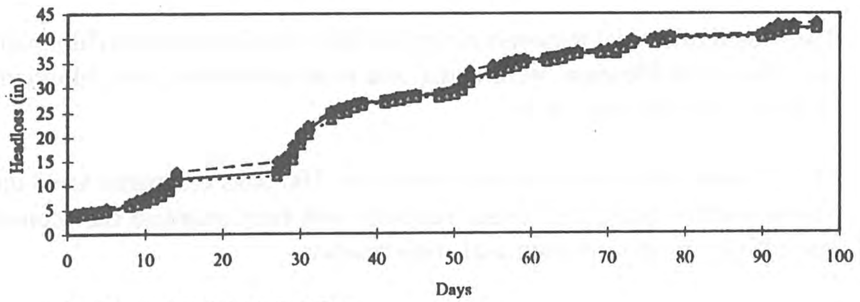

Fig 8: Headloss Variation in Test Filter

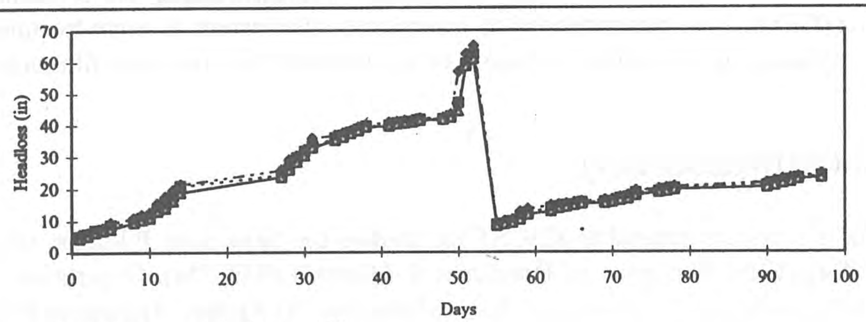

Fig 9: Headloss Variation in Control Filter

CONCLUSION

The following specific conclusions may be drawn from the results of the operation of the pilot plant with respect to pre-chlorination studies in slow sand filters.

- Chlorination of secondary effluents alone, as is commonly practiced, is highly inadequate for the removal of spore former like *Cl. Perfringens* and chlorine resistant viruses like coliphage. This is evident from their highly variable removal efficiencies.

- The efficiencies of microbial removals in the test and control filter were similar. This indicates that a pre-chlorination dose of 5 mg/l does not adversely effect the filter operations or the *schmutzedecke* layer.

- The overall microbial removals in the test filter, that incorporates chlorination and slow sand filtration, were better and more consistent than chlorination or slow sand filtration alone.

- The runtime of the test filter was more than 100 days compared to 48 days for the control filter. The longer runtimes will help maintain the economy and efficiency of operation and maintenance.

- Based on the superior results obtained by pre-chlorinating the secondary effluents, it is recommended to incorporate chlorination as a pre-treatment measure in the tertiary treatment of wastewaters by slow sand filtration.

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“Nanofiltration/bioreactor” and “Nanonfiltration/ Crystallization” - Two Examples for the Potential of Nanofiltration in Wastewater Treatment

Robert Rautenbach and Thomas Linn

"NANOFILTRATION/BIOREACTOR" AND "NANOFILTRATION/CRYSTAILIZATION" - TWO EXAMPLES FOR THE POTENTIAL OF NANOFILTRATION IN WASTE WATER TREATMENT

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ABSTRACT

Nanofiltration membranes can fractionate effectively

* dissolved organic components of different molecular mass and
* mono- and bivalent anions such as chloride and sulfates in aqueous solutions.

This feature makes NF a very promising candidate for the treatment of industrial effluents.

The paper discusses 2 successful process combinations containing nanofiltration as an essential step. Both processes have been developed for the treatment of dumpsite leachate, an effluent severly contaminated by organics and inorganics. The essential feature of the combination "bioreactor-nanofiltration" is the recycling of the nanofiltration concentrate into the bioreactor.

Due to the selectivity of nanofiltration the concentration of (high molecular) recalcitrants in the loop is significantly increased resulting in turn in a higher rate of biodegradation without increasing the hydraulic residence time of the bioreactor.

Pilot plant tests on 4 dumpsites, each over a period of 6 months, demonstrated the reliability of the process. Compared to a process without nanofiltration, the elimination rate of the bioreactor increased between 9% and 17%.

In the second example, nanofiltration allowed the design of a "pure" membrane process with a water recovery rate of 97.5%. A high water recovery rate is mandatory for all waste water treatment processes. In essence, the nanofiltration/ crystallisation stage removes the scaling agents such as calcium sulfate and the

organics from the concentrate of the 1. RO stage.

Since the NF permeate contains almost only chlorides, this can be concentrated without danger of scaling by the final high-pressure RO stage.

The process is in operation since October 1994 and has demonstrated its reliability and low specific energy consumption at several dumpsites.

INTRODUCTION

In aqueous solutions, nanofiltration can fractionate effectively

* dissolved organic components of different molecular mass and
* mono- and bivalent anions such as chlorides and sulfates.

This feature makes nanofiltration a very promising process for the treatment of multicomponent industrial effluents.

The paper discusses 2 successful process combinations containing nanofiltration as an essential step. Both processes have been developed for the treatment of dumpsite leachate, an effluent severly contaminated by organics and inorganics.

NANOFILTRATION

Nanofiltration is a pressure driven membrane process 1/1. Regarding driving force and rejection of organic components in aqueous solutions, nanofiltration is somewhere between reverse osmosis and ultrafiltration (tab. 1).

	pressure [bar]	**cut-off [g/mol]**
reverse osmosis	30 - 70 (200*)	< 200
nanofiltration	3 - 60	200 - 1.000
ultrafiltration	2 - 10	1.000 - 100.000

Tab. 1: Driving force and selectivity of reverse osmosis, nanofiltration and ultrafiltration.

Like reverse osmosis, nanofiltration is based on solution-diffusion as major transport mechanism. But contrary to reverse osmosis nanofiltration membranes contain fixed (negatively) charged functional groups. As a consequence, the selectivity of NF for monovalent and bivalent anions is significantly different. Tab. 2 shows results of experiments with binary aqueous solutions. Typically the rejection for chlorides and nitrates is about 50%, but for sulfates 96-98%.

	reverse osmosis		nanofiltration	
	membrane	rejection rate [%]	membrane	rejection rate [%]
chloride (monovalent)	FllmTec FT30 SW	99.1	FilmTec NF45	55
	Desal 3 S	99.2	Desal 5K	50
	Toray UTC 80	99.4	Toray UTC 60	60
	Nitto NTR 759 H	99.5	Nitto NTR 7450	50
sulfate (bivalent)	FllmTec Fr30SW	> 99.8	FimTec NF45	98.5
			Desal 5K	96.4 - 98

Tab. 2: Charateristics of reverse osmosis and nanofiltration membranes

In turn, this different rejection of mono- and bivalent anions permits the realisation of the Donnan Effect: In a multicomponent system containing among others sulfate- and chlorideions, the chloride rejection is shifted towards negative figures with increasing concentration of the sulfateions (fig. 1) - chlorides are forced into permeate with increasing sulfate concentration.

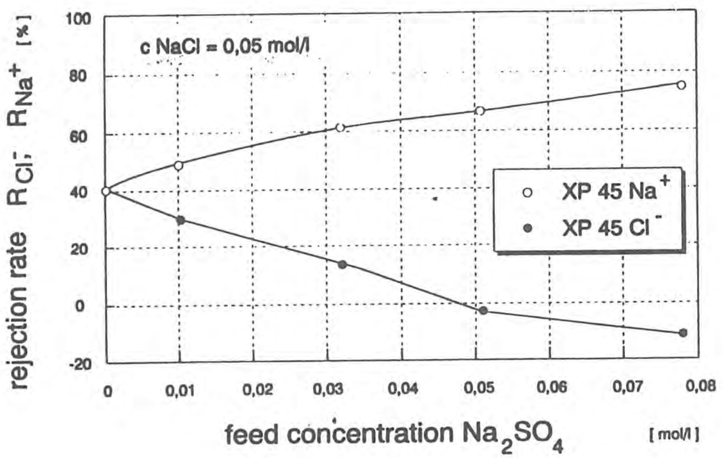

Fig. 1. Influence of sulfate feed concentration on chloride rejection

With respect to organic dissolved components, the difference between reverse osmosis and nanofiltration is only of quantitative nature; whereas components of a molecular mass of about 150 kg/kmol are almost totally rejected by reverse osmosis, the "cut-off" of nanofiltration is above 300 kg/kmol.

PROCESSES

The processes discussed in this paper have been developed originally for the treatment of dumpsite leachate. They are, however, suitable in general for the treatment of effluents containing inorganic and organic contaminants.

Dumpsite leachate is a direct consequence of rainfall. The average leachate production of a dumpsite in western Europe is about 5 M^3/ha d but in rainy periods this figure can be exceeded by a factor of 3 - 4.
Leachate water contains a rather complex mixture of components (fig. 2):

* organics, measured by the sum parameters COD, AOX and TOC
* nitrogen as NH_3/ NH_4 +
* inorganic dissolved solids such as HCO_3-, Cl-, SO_4^{2-}, Na+, K+ and Ca^{2+}
* metal ions

Tab. 3 shows the presently valid allowable discharge figures for the treated water and, correspondingly, the required minimal performance of the treatment process. According to tab. 3 leachate treatment must achieve a reduction of

* COD of 95 - 99%
* NH_4+ - N of 96 - 98%
* AOX of about 80%.

Metal ions pose no problem since their concentration in leachate is usually well below the allowable discharge figures.

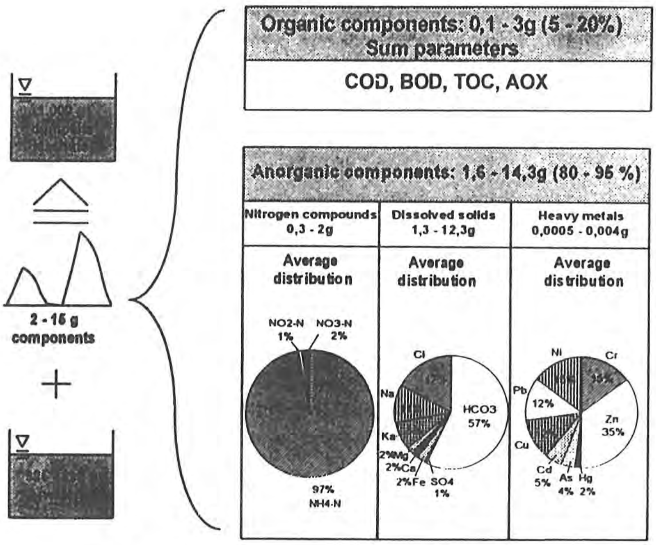

Fig. 2: Average composition of dumpsite leachate /2/

parameter	unit	concentration range	required cleaning performance relative to maximum allowable discharge figure (§ 7a WHG) %
COD	[mg/l]	100 - 10000	0 - 95
BOD	[mg/l]	20 - 5000	0 - 99
NH_4+-N	[mg/l]	50 - 2500	0 - 98
AOX	[mg/l]	0,1 - 5	0 - 90
fish toxicity	1-1	2 - 100	0 - 98
conductivity	[µS/cm]	2000 - 25000	-
dry residue	[mg/l]	1000 - 15000	-
ash residue	[mg/l]	800 - 10000	-

Tab. 3: Allowable discharge figures for dumpsite leachate

With respect to inorganics salts, the situation is presently not clearly defined in Germany. They must be removed if they effect the fish toxicity otherwise they can be discharged. The situation is different in other EU countries. In Italy for example a maximum allowable discharge figure for NaCl is defined (law Merli of 1976) resulting in a required reduction of about 80% in case of dumpsite leachate.

Combination of bioreactor / nanofiltration

A conventional biological treatment of effluents containing high amounts of recalcitrants requires high residence times i.e. voluminous biologies. In such cases, the combination of a nanofiltration with a biology as shown in fig. 3 can lead to surprising results. Recalcitrant organics are mostly larger molecules which are rejected by nanofiltration membranes whereas the biologically degraded substances and salts will permeate.

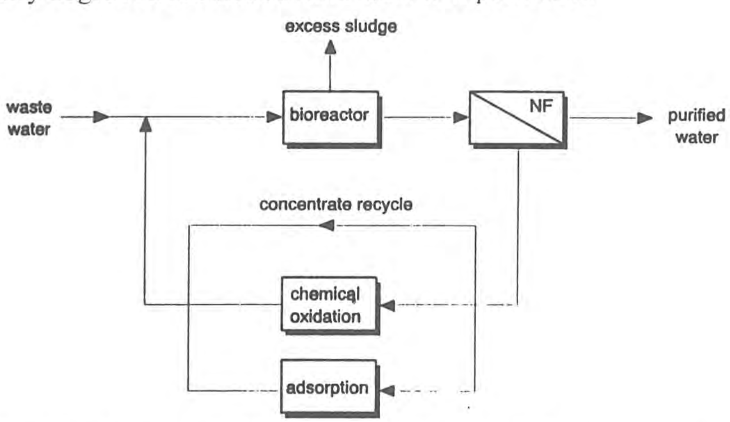

Fig. 3. Combination of nanofiltration and activated sludge bioreactor
Optional: partial treatment by chemical oxidation or adsorption

By recycling the nanofiltration concentrate to the bioreactor, the residence time and the concentration of the recalcitrants are substantially increased without increasing the volume of the bioreactor /3/. As a consequence the reaction rate i.e. the rate for biodegradation of recalcitrants is increased. According to the Monod-equation it increases with concentration until stopped by the eventual increase of toxic substances /4/. Depending on the composition of the waste water to be treated, the unavoidable discharge of reactor effluent with the excess sludge will be sufficient for a stable unpoisoned operation of the system on a high concentration level. In case where the bleed with the excess sludge is not sufficient for a stable operation, a partial reduction of COD by either chemical oxidation or adsorption is recommended. Compared to an installation behind a conventional biology there are the following advantages.

* Since the stages are fed with the concentrate of the nanofiltration, they are operating at high concentrations i.e. very effectively.
* The operation of the chemical oxidation /5/ or adsorption /6/ is not determined by the low concentrations which must be guaranteed before discharge.
* With chemical oxidation, a partial oxidation of nondegradable components to biodegradable substances is possible since the effluent of the oxidation is recycled to the bioreactor.

Based on our pilot experiments, there are presently 3 large scale installations commissioned (Cronheim, Luneburg, Berg).

Results of pilot plant experiments

Biology

In all cases where the dumpsite is operating in the "stable", methane producing state, a conventional biological treatment achieves a COD reduction of about 50-60%. In our experiments on different sites, COD reductions between 46% and 62% have been observed (tab. 4).

COD elimination [%]	Alsdorf-Warden	Berg'91	Sinsheim	Eiterkbpfe	Berg'92/'93
straight through operation	59	58	74	62	46
concentrate -recycling	-	75	86	71	53

Tab 4: COD elimination of "straight-through" operated biology vs. nanofiltration concentrate recycle

The exception is dumpsite Sinsheim but this dumpsite had not yet reached the "stable" state.

Straight-through operation without nanofiltration defined the reference points. In addition, the maximum possible flow rate defined by a stable nitrification has been determined by this mode of operation.

In the recycling mode, the effluent of the bioreactor is treated by nanofiltration. The NF-concentrate was recycled to the bioreactor without further treatment until the COD concentration of the permeate started to exceed the permitted concentrations. Then part of the NF concentrate was either treated by chemical oxidation or by activated carbon before recycling or withdrawn from the loop (bleedtreatment).

As listed in tab. 4, the COD elimination rate increased significantly - as expected. Due to the higher concentration of recalcitrants in the loop, not only the fast biodegradable components but also part of the recalcitrants are eliminated.

COD concentration in the bioreactor increases substantially by the recycling of NFconcentrate as shown in fig. 4.

But even at concentrations of 10 000 mg COD/1 or more the bioreactor was not affected by the recycling of the NF-concentrate as indicated by the stable nitrification during the whole pilot plant operation.

The stable and complete nitrification is an excellent indicator for the proper operation of the bioreactor since the nitrifying bacteria nitrosomas and nitrobacter are very sensitive to toxic components.

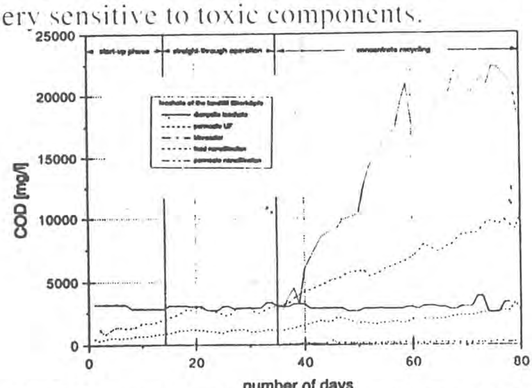

Fig. 4. Increase of COD concentration during start up of recycle operation

Nanofiltration

The hybrid process bioreactor/nanofiltration requires nanofiltration membranes with a high rejection rate for organics and a low rejection rate for inorganics. Based on extensive laboratory tests, we selected the Desal 5 K which showed a high rejection rate for organics and a high permeate flux.

In addition to these laboratory tests pilot plant experiments on the site are required for a reliable design of the NF stage.

As shown in fig. 5, the permeate fluxes observed in continuous on-site pilot plant experiments are significantly lower than in case of batch experiments with biologically treated leachate.

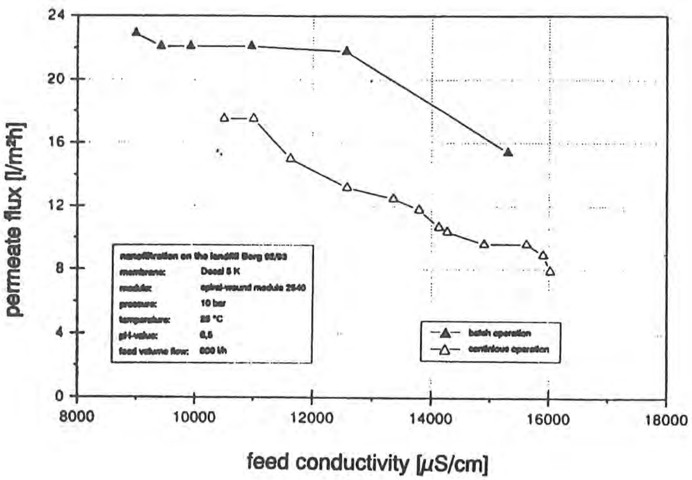

Fig. 5. Comparison of batch and continuous experiments

Plant design should never be based on batch experiments with their limited fouling potential. If batch experiments have to be used because continuous experiments are not possible, a safety factor of at least 1.5 has to be employed!

Furthermore the on-site pilot plant experiments demonstrated that cost-effective spiral wound modules can be used if - as has been the case in our experiments- ultrafiltration is used instead of sedimentation for the retention of the biomass.

The pH in the nanofiltration feed was adjusted by hydrochloric acid dosing. Sulfuric acid which is preferable with respect to costs and handling was not chosen in order to avoid increase in sulfate concentration and, as a consequence, $CaSO_4$ scaling.

The rejection rate with respect to COD increased from 97% to 99% during the recycle start up corroborating our assumption that recalcitrants, i.e. components with higher molecular mass are accumulated by nanofiltration.

Simultaneously the concentration of sulfate ions increased from about 1000-1500 mg/l in the straight-through reference operation to 4000-6000 mg/1 resulting, in a significant decrease of the rejection rate for chloride from 50% to 11% due to the Donnan exclusion.

Despite the high sulfate concentrations in the loop, scaling has not been observed. After about 70 days steady state conditions were reached: the amount of sulfate contained in the raw leachate was equal to the amount of sulfate discharged with the permeate (tab. 5).

sulfate [mg/1]	dumpsite A	dumpsite B
dumpsite leachate	57	129
UF permeate	377	1111
NF concentrate	2331	4693
. NF permeate	53	111

Tab. 5: Sulfate concentrations in the bioreactor/NF system after 70 days of operation (steady state)

Reverse osmosis/nanofiltration/crystallisation

A successful alternative to the biological treatment of dumpsite leachate is the treatment by reverse osmosis in combination with further concentration steps.

Reverse osmosis has proved its reliability and economics in sea- and brackish water desalination. There is, however, a fundamental difference between waste water treatment and desalination. Whereas water recovery rates of about 50% are optimal in seawater desalination, the recovery rate in waste water treatment must be as high as possible since the disposal of the residues is always expensive.

As shown in fig. 6 the RO-concentrate is usually concentrated further by evaporation and, finally, dried where the disposal of a dry residue is demanded.

Furthermore, the process must contain a step for the separation of NH_3/ NH_4+- either a stripping unit or a biology. This process combination can be considered as state of the art.

Disadvantageous are the high specific energy consumption and the high specific investment costs of evaporation / dryer stages.

limiting factor for concentration by RO. Rochem DT modules are now available for operation pressures of 120 and 200 bar. The disc tube modules are also relatively insensitive to fouling. By implementation of these modules into the process the evaporation stage can be eliminated. Instead of concentration factors of 2-3, concentration factors up to 10 can be achieved by the RO stage /8/.

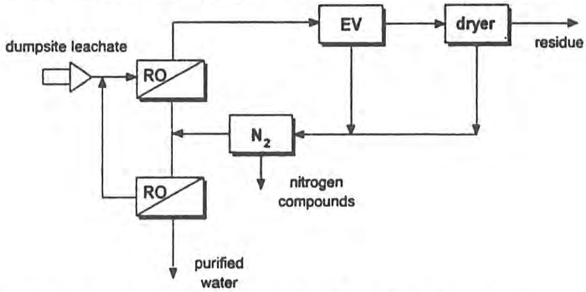

Fig. 6. Leachate treatment - standard technology

Nevertheless the process must contain a drying stage (and a stage for NH_3/NH_4+ separation) for the separation of the residual - 10% of water. Since the drying step separates only small amounts of water but causes 35-38% of the overall treatment costs it must be questioned whether this process combination can be improved.

A simple further increase of the water recovery rate by RO can not be expected for 2 reasons:

* the danger of calciumsulfate scaling and
* unacceptably high membrane compaction at transmembrane pressure differences above ΔP = 200 bar.

The implementation of a nanofiltration stage into the treatment process can extend the limits of RO set by scaling and/or osmotic pressure considerably.

Fig. 7 shows the flow diagram of our process. The 2-stage RO in operating at 60 bar and 120 bar in the first stage and 60 bar in the second stage. The concentrate of the 120 bar RO-stage is treated by a combination of NF/ crystallisation /9/. At moderate transmembrane pressure differences of 20-50 bar the nanofiltration unit produces a permeate containing mainly chlorides. This permeate can be concentrated further without danger of scaling by a 200 bar HPRO.

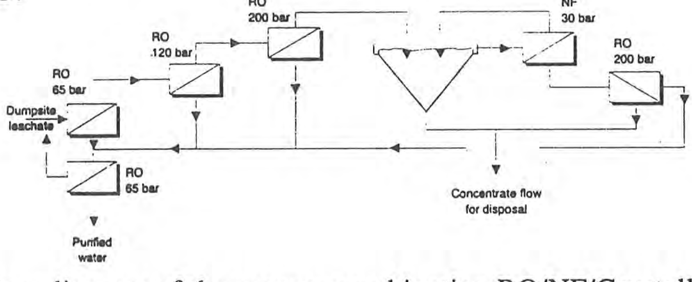

Fig. 7. Flow diagram of the process combination RO/NF/Crystallisation

Essential for the process is the operation of the NF/Crystailizer cycle in the range of supersaturation with respect to calcium sulfate and at high concentrations of organics. For this reason the success of the process depends to a large extent on a proper module design - the modules must be insensitive to fouling and the presence of crystals. Such modules have been developed by Rochem, Germany (fig. 8). Stacks of rectangular membrane cushions and matching spacer plates are arranged in series in the pressure vessel in such a way that stagnant areas are avoided and internal friction losses are minimized. Feed flow is strictly parallel to the vessel axis, the velocity in the feedsite module channels is about 1.5 m/s.

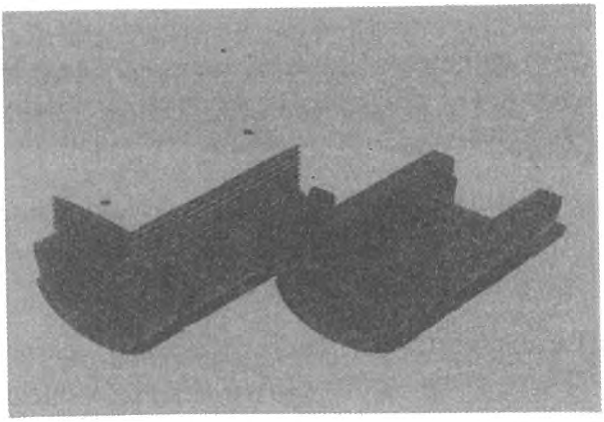

Fig.8. ROCHEM DTF-Module

In cooperation of the Rochem company and the Institut fur Verfahrenstechnik, RWTH Aachen, the process has been installed and tested on a technical scale at the dumpsite 1Wenberg. A nanofiltration stage consisting of 4 blocks with 9 modules each and total membrane area of 180 m^2 (fig. 9) has been added to the existing RO-HPRO combination and commissioned in September 1994. The unit is designed for the treatment of about 4 m^3/h RO concentrate of a concentration factor of

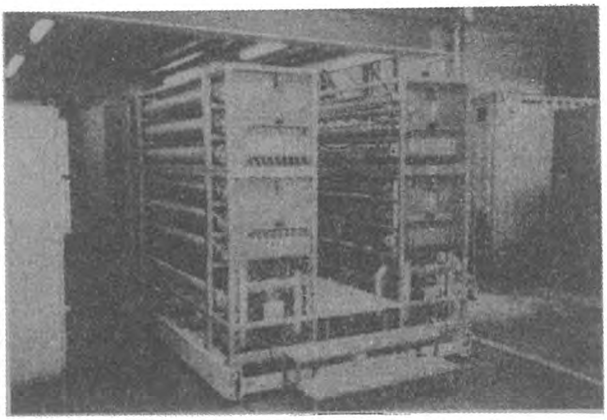

Fig. 9. Nanofiltration blocks at the dumpsite Ihlenberg

Depending on the concentration factor of the 60 and 120 bar RO-stage, the NF-stage achieves a further concentration of

$$CF_{V\,RO} = \left(\frac{\dot{V}_F}{\dot{V}_R}\right)_{RO} = 10$$

A sludge consisting of organics, precipitated inorganics and water is discontinuously withdrawn from the bottom of the crystailizer/sedimentation tank.

With the added concentrate of the subsequent 200 bar HPRO stage this concentrate is disposed of at Ihlenberg by solidification with fly ash and final storage at the dumpsite.

Cleaning of the NF- modules consists of flushing with feed at zero transmembrane pressure difference for 30 sec. every hour and an alcaline cleaning every 250-300 hours.

Fig. 10 shows the results obtained in the operation period September - December 94. After startup, an average permeate flow rate of 3.6 m^3/h is achieved at transmembrane pressure differences of, initially 20 bar, increasing to 40 bar before cleaning.

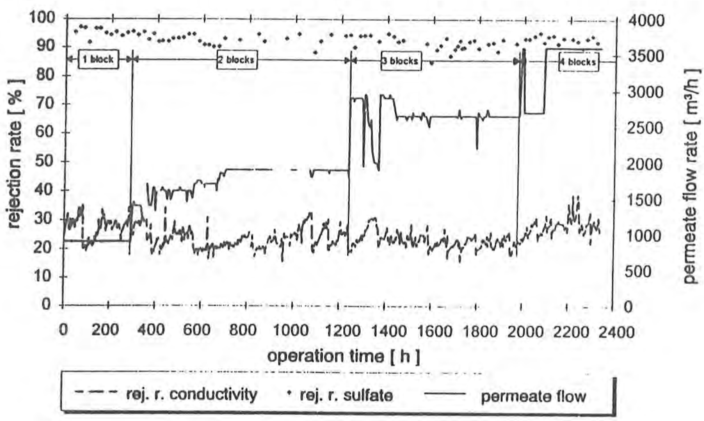

Fig. 10. Operation data of the NF-plant on dumpsite Ihlenberg

The rejection rate for sulfates is 92-95%, for the dissolved solids (conductivity) 20-35%. Tab. 6 lists the data for other relevant parameters. Interesting are the high rejection of organics (COD) of about 92% and the unexpected high rejection of about 40% for NH_3/NH_4+.

At the dumpsite Ihlenberg (tab. 7) the specific energy consumption of the NF and the subsequent 200 bar RO stage is 32 kWh/m^3 permeate. This figure is a direct consequence of the untypical leachate composition of the Ihlenberg dumpsite. But with figures of 8.5 kWh per m^3 of totally produced permeate and an overall water recovery rate of 97%, the overall specific power consumption of the process is extremely low compared to other processes.

This process, with respect to water an almost zero-discharge process, is presently, developed and studied at our institute and several dumpsites in Germany.

Rejection rate on the dumpsite Ihlenberg

Parameter	Unit	Feed	Permeate	Rejection rate [%]
BOD	[mg /I 02]	480	280	41.67
COD	[mg /I 02]	17.000	700	95.88
Ammonia	[mg/l]	3.350	1.420	57.61
Sulfate	[mg/l]	31.200	2.345	92.48
Chloride	[mg/l]	12.760	17.730	**-38.95**
Calcium	[mg/l]	2.670	187	93.00
Magnesium	[mg/l]	1.030	72.7	92.94
Sodiwn	[mg/l]	10.900	5.010	54.04
pH-value		6.3	6.4	
Conductivity	[mS/cm]	61	43	29.5

Rejection rate on the dumpsite Halle-Lochau

Parameter	Unit	Feed	Permeate	Rejection rate [%]
BOD	[mg/l 02]	591,4	239.6	59.49
COD	[mg/1 02]	6,400	600	90.63
Ammonia	[mg/l]	2,260	1.020	54.87
Sulfate	[mg/l]	40,000	3.000	92.5
Chloride	[mg/l]	29,780	35.629	**-19.64**
Calcium	[mg/l]	243	31	87.24
Magnesium	[mg/l]	952	133	86.03
Sodium	[mg/l]	41,000	20.390	50.27
pH-value		6.23	6.31	
Conductivity	[mS/cm]	110	95	12.5

Tab. 6. Analysis of the dumpsite leachate and the rejection rates of nanofiltration

Specific energy consumption of the "Ihlenberg" leachate treatment plant (Capacity: 50 m³/h dumpsite leachate)			
	Reverse osmosis / High pressure reverse osmosis		
		Process stage	Total plant
Part of plant	Permeate flow rate [m³/h]	Spec. energy consumption [kWh/m³ permeate]	Spec. energy consumption [kWh/m³ feed]
60-bar-RO	35	4	2,8
HP-RO	11	17	3,74
	Nanofiltration / High pressure reverse osmosis		
NF RO	2,7	32	1,73
Total plant:	Water recovery:	97,40%	8,27

Tab. 7: Specific energy consumption of the process

CONCLUSIONS

Nanofiltration membranes can fractionate effectively

* dissolved organic components of different molecular mass
* mono- and bivalent anions such as chlorides and sulfates

This feature makes NF a very promising candidate for the treatment of effluents.

In long time pilot plant experiments it could be proved that the efficiency of a bioreactor with respect to the elimination of recalcitrants can be significantly increased by addition of a nanofiltration and recycling of the NF concentrate to the bioreactor. This is a direct consequence of the increased concentration of recalcitrants in the loop and the accordingly increased rate of elimination (Monod equation!).

Non-degradable organic components in the loop must be removed from the system either by chemical oxidation or activated carbon. Again the high concentration and the recycling operation are favorable - compared to a "straight-through" operation where discharge figures must be met the specific ozone or activated carbon consumption is significantly reduced.

In combination with reverse osmosis and high pressure reverse osmosis, nanofiltration results in a simple process which can produce water of almost any desired quality - if necessary by a staged RO and, even more important, a water recovery rate of almost 100%.

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Water Reclamation in Salalah, Sultanate of Oman

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WATER RECLAMATION IN SALALAH, SULTANATE OF OMAN

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Sultanate of Oman

ABSTRACT

Faced with mounting water quality and quantity problems brought about by growing population pressures upon limited natural water resources, the Dhofar Municipality is implementing an innovative wastewater management program that will provide beneficial use of treated wastewater in the city of Salalah. This conversion of waste product to valued resource will allow the Municipality to meet its water supply demands well into the next century, and serve as a model for other communities in the Middle East and Gulf regions that are facing similar water resource problems. The centerpiece of this program is an advanced water reclamation plant that will treat wastewater to meet stringent Omani Regulations for Wastewater Reuse and Discharge. Construction of the US$32 million water reclamation plant is funded jointly by the United States Agency for International Development (USAID) and the Government of Oman. The plant will begin operation in August, 1998.

BACKGROUND

The Municipality of Salalah is located in the southern region of the Sultanate of Oman as shown in Figure 1. Salalah is located on a high quality, fresh water aquifer that is replenished during the annual khareef, or monsoon, season. The residents of Salalah have traditionally used this aquifer as the sole source of water for all agricultural, potable, and non-potable needs. Historically, the population of Salalah has been fairly small, and demands on the aquifer were in balance with its recharge capacity. However, increases in national wealth over the last 25 years have resulted in dramatic improvements to public health and quality of life, resulting in a significant increase in population. Oman now has the highest population growth rate of any country in the world, and Salalah has grown to a community of approximately 77,000 population, with current projections indicating that Salalah's population will exceed 200,000 by the year 2020.

This rapid rise in population has severely taxed water resources in the Salalah area. In the 1980s, significant decreases in the Salalah aquifer water level were recorded, and evidence of saltwater intrusion due to over-abstraction of groundwater became apparent in coastal areas. In addition, water quality problems developed as failing or inadequate on-site septic systems and waste water holding tanks resulted in groundwater contamination. By the end of the 1980s, it had become clear that the Salalah aquifer could not support anticipated growth rates unless progressive water management and reuse practices were implemented.

The Salalah Wastewater Project was conceived in response to this need. The project includes three distinct elements:

- A wastewater collection system to serve the most densely populated areas of Salalah;
- An advanced water reclamation plant that will meet stringent national effluent reuse standards; and
- An effluent recharge system that will inject treated effluent back into the Salalah aquifer.

These facilities will serve to alleviate both water quantity and quality problems by returning treated wastewater to the aquifer, thereby balancing aquifer supply and demand, and eliminating pollution resulting from failing on-site wastewater treatment systems and holding tanks. This "closed loop" approach to water management is shown schematically in Figure 2. This approach provides maximum benefit to the community in terms of resource conservation and avoids the need for development of more costly water supply options such as desalination plants. Ultimately, sludge solids from the water reclamation plant will be stabilized and made available as a fertilizer source for local agricultural and amenity plantings, thereby providing beneficial use for both treated effluent and residual sludge solids.

The key to any successful water reuse scheme is a wastewater treatment system that is both highly efficient and highly reliable. Details of the Salalah treatment system are provided herein.

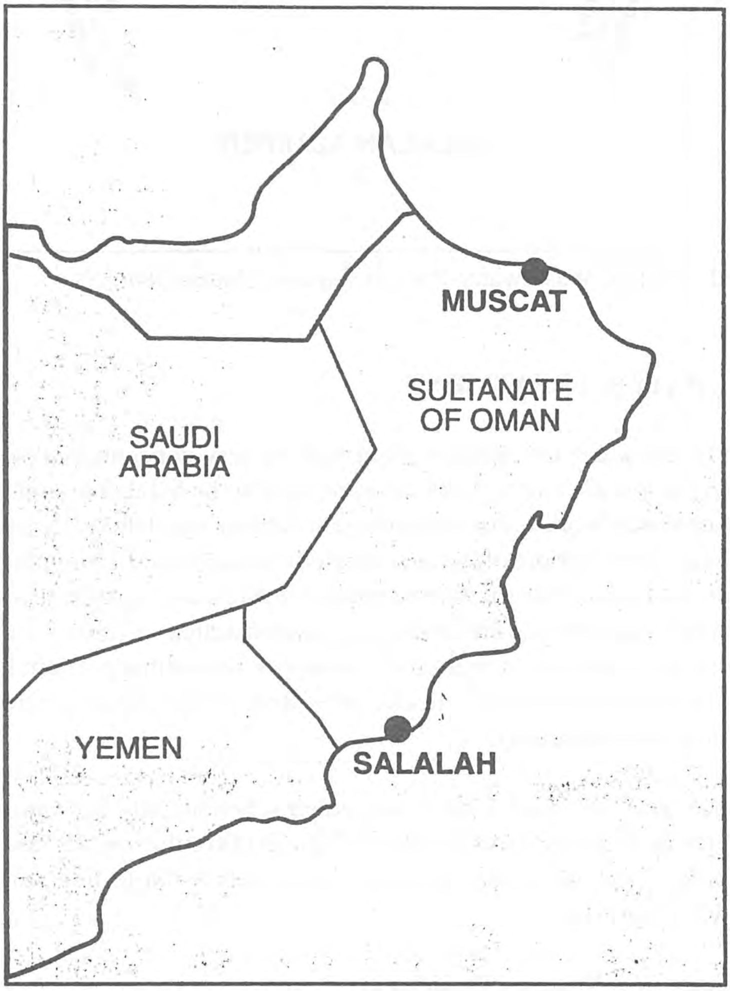

Figure 1. Location Plan

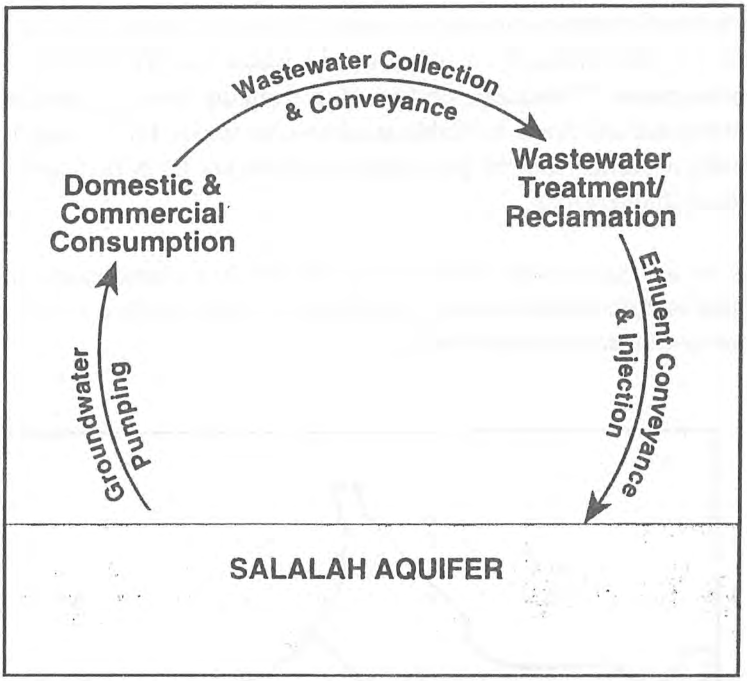

Figure 2. Salalah Wastewater Project Aquifer Water Balance

WASTEWATER TREATMENT

Influent to the water reclamation plant will be very concentrated because of the relatively low per capita water consumption in the Salalah region. Effluent from the treatment works must meet stringent national regulations for wastewater reuse. This combination of a high strength influent and stringent effluent requirements means that the recommended wastewater treatment train must achieve very high removal efficiencies, as demonstrated in Table 1. In addition to regulatory concerns, community concerns regarding potential aquifer contamination in the event of a treatment system failure creates a strong need for overall system reliability.

The wastewater treatment train is presented schematically in Figure 3. The initial capacity of the treatment works will be 20,000 cubic metres per day (m^3/day) average flow, with provisions for future expansion to treat an average flow of 40,000 m^3/day.

Preliminary and Primary Treatment

Preliminary treatment will be provided with mechanically cleaned screens and forced vortex grit removal basins, with both screenings and grit conveyed to a local landfill for disposal. Due to the high strength and septicity of the influent, channels and tanks in the headwords area will be lined with PVC for corrosion protection and covered to allow for collection and treatment of exhaust gases.

Primary treatment was included in the treatment train to maximize the low cost, physical removal of pollutants and to improve sludge handling characteristics.

Activated Sludge Process

Selection of an activated sludge arrangement was based on the need to achieve very high nitrogen removal efficiencies in a cost-effective manner. After evaluation of several process alternatives, a two stage system with anoxic and aerobic zones and internal recycle was recommended.

In the aeration zone, influent nitrogen is converted to nitrate (nitrification) to meet ammonia discharge requirements. An internal recycle stream returns nitrified effluent from the first aeration zone to the first anoxic zone for denitrification, with secondary influent providing the carbon source necessary to fuel the denitrification process. Fine bubble diffused aeration supplies oxygen to the aerobic zone, and mechanical mixers keep the mixed liquor in suspension in the anoxic zone.

Salalah Water Reclamation Plant
Influent Characteristics and Effluent Requirements
Table 1

Parameter	Influent Concentration (mg/1)	Effluent Concentration (mg/l)	Required Removal Efficiency (%)
Biological Oxygen Demand (BOD)	370	15	96
Total Suspended Solids (TSS)	440	15	97
Ammonia Nitrogen	45	5	89
Organic Nitrogen	30	5	83
Nitrate Nitrogen	0	10 (1)	87 (2)
Total Kjeldahl Nitrogen (TKN)	75	10	87
Total Nitrogen	75	20	73

(1) Equivalent to 45 mg/1 as nitrate
(2) Assumes all influent nitrogen is nitrified
(3) Influent and effluent concentrations are average values

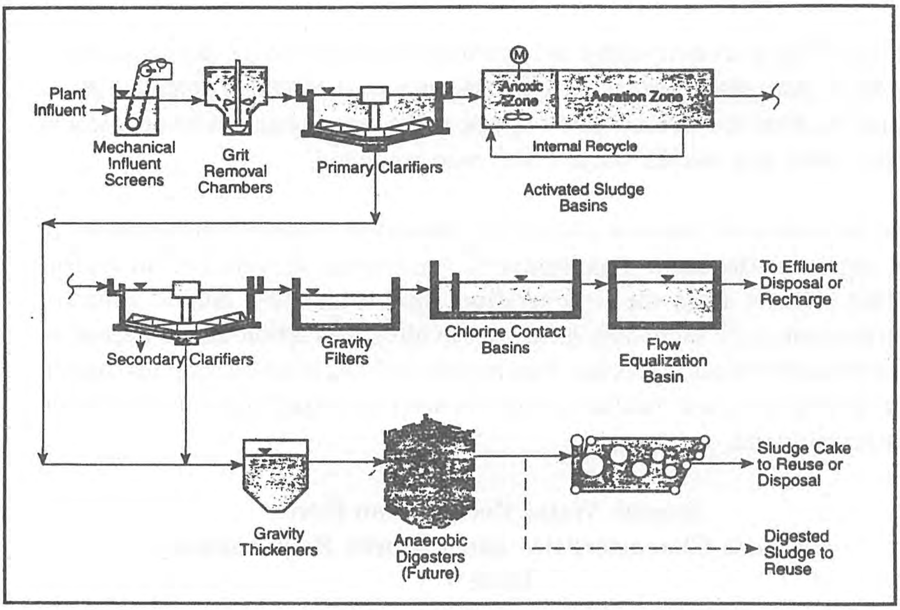

Figure 3. Salalah Water Reclamation Plant Process Train

In many two-stage activated sludge arrangements, oxygen carryover from the aeration zone to the anoxic zone via the internal recycle stream has been a problem, especially during the early years of operation when organic and nitrogen loads are below design levels. This oxygen carryover makes it difficult to maintain true anoxic conditions in the first zone, thereby interfering with the denitrification process. To address this problem, each aeration basin was designed with three diffuser grids and a mechanical mixer was provided at the effluent end of each basin. This arrangement allows the operator to turn off the diffuser grid at the effluent end of each aeration basin during periods of low loading and use mechanical mixing to maintain solids suspension. This serves to prevent excessive aeration and the resultant oxygen carryover within the internal recycle stream.

Filtration/Disinfection

Tertiary filtration is required to meet the 10 mg/1 discharge standard for suspended solids and gas chlorine will be used for disinfection. Gas chlorine selected due to the required scale of operation and the local availability of a reliable chlorine chemical supply. In addition to application as a disinfectant, chlorine will be used as a scrubbing chemical for odor control and, if necessary, for prechlorination. Chlorine safety equipment includes an emergency scrubber that will automatically neutralize building exhaust in the event of a chemical leak.

Flow Equalization

A flow equalization tank has been provided to dampen the fluctuations in effluent flow and thereby reduce water hammer effects within the effluent recharge system and allow the effluent recharge system to be sized for a reduced peak flow. Under design year conditions, the equalization volume provided will allow the projected peak flow of 58,000 m^3/day to be dampened to 37,000 m^3/day.

Effluent Recharge or Disposal

Under normal operating conditions, treated effluent will be discharged to a system of injection wells for aquifer recharge. The primary wells have been strategically placed along the coastline to reduce the impacts of saltwater intrusion from the Arabian Sea. A second string of wells is located further inland to provide redundancy and operational flexibility in managing the groundwater aquifer.

In addition to the recharge system, a direct pipeline to a major wadi adjacent to the treatment works has been provided for effluent disposal. In the event of a plant upset, monitors will alert operators to a degradation of effluent quality and flow will be transferred from the recharge system to the effluent disposal system, thereby protecting the aquifer from potential contamination.

SOLIDS HANDLING

Fundamental to the Municipality's sludge management strategy is the desire to ultimately provide beneficial use of the treated sludge solids. Historically, Salalah has been the center of a successful agricultural industry. In addition, amenity plantings in public areas are given high priority by both the local and national governments. Providing an inexpensive, high-quality fertilizer product for these agricultural and amenity plantings benefits the local community and is in keeping with the Municipality's stated goal of maximizing available natural resources.

The solids train is presented schematically in Figure 3. The selected unit processes are well established, simple to operate and maintain, and provide a viable beneficial use end product. Provisions will be made for withdrawal of either a stabilized liquid sludge product (4 to 6 percent solids) or a stabilized sludge cake. This flexibility will allow the characteristics of the product to be modified to suit the requirements of the end user. Due to cost constraints, anaerobic digesters were not included in the first phase of construction, but will be added at a later date.

Sludge Thickening

Thickening of both the primary and waste activated sludges is essential to reduce the size and improve the efficiency of subsequent sludge handling processes. At some installations, thickening of primary sludge can be satisfactorily accomplished in the clarifiers, thereby eliminating the need for a separate thickening process. However, under the warm climatic conditions of Salalah, primary clarifiers will likely be operated with a thin sludge blanket, producing a relatively dilute primary sludge that will require additional thickening.

Gravity thickeners will be used to thicken both the primary and secondary sludges. The gravity thickeners will be covered, with off gases treated for odor control. It is anticipated that the solids concentration of the sludge feed will be in the range of 1 to 2 percent solids, and a thickened solids concentration of about 5 percent solids will be achieved.

Sludge Stabilization

Given the desire to apply the sludge in a beneficial use application, it is essential that the recommended stabilization process be highly reliable and provide a well stabilized end product. Anaerobic digestion was selected based on its demonstrated performance and cost effectiveness at facilities of similar size. The digesters are of conventional concrete design with floating covers. Digester gas will be used to meet the internal digester heating requirements, and excess gas will be flared. Mixing will be provided by a gas "bubble generator" system. As noted previously, digesters not included in the current construction contract due to cost constraints, but will be added at a future date.

Sludge Dewatering

Belt filter presses were selected as the optimum sludge dewatering technology due to their simplicity and cost effectiveness. Sludge cake will be land applied or landfilled locally with little transport or application cost. Therefore, there is no economic benefit to application of more capital intensive technologies that produce a drier sludge cake. Polymer conditioning of the press feed will be provided. It is anticipated that a sludge cake concentration of 20 to 22 percent solids will be achieved. During initial years of operation, sludge cake will be sent to a local landfill for disposal. After addition of anaerobic digesters, beneficial use land application will become the preferred method of sludge management.

SUMMARY

The Salalah water reclamation plant is a model for resource conservation. The plant will ultimately provide the local community with two valued commodities - usable water and a high quality fertilizer product - through innovative application of advanced treatment technologies. By maximizing its natural water resources through conservation and reuse, the Municipality of Salalah will ensure itself of a dependable, high quality water supply for the foreseeable future and avoid the need for development of other more costly water sources.

Preliminary Selection of Suitable Sites for Sewage-Based Irrigation in Egypt

Akram Fekry and Fatma A.R. Attia

PRELIMINARY SELECTION OF SUITABLE SITES FOR SEWAGE-BASED IRRIGATION IN EGYPT

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ABSTRACT

Egypt is faced by limited surface water resources and a continuous increase in population. The present geographic distribution of the population is governed by the availability of water resources. Since the main source of water is the Nile water, about 99% of the population and related economic activities are confined to the areas served by Nile water, namely the Nile valley and delta, covering about 11% of the country surface area. The generated sewage effluent is presenting a nuisance to the country; while it may represent an additional source of water if properly used. The present rate of generated treated waste water amounts about 1.8 billion m^3/year and is expected to become 4 billion m^3/year by the year 2001.

On the other hand, groundwater, especially on the fringes of the Nile valley and delta, is threatened by various types of deterioration, namely, depletion and increased salinity. For these reasons, investigations are going on for solving the dual problem of groundwater deterioration and economic reuse of treated sewage water. One of the possible schemes is augmentation of depleted aquifers through controlled recharge with treated sewage. The bases for the selection of suitable sites for controlled groundwater recharge include, among others: (1) distances from treatment facilities; (2) present groundwater use; (3) vulnerability of groundwater to pollution; (4) initial depth to and quality of groundwater; (5) sites suitability for artificial recharge; and (6) present and future development plans. Results indicated that the most initially suitable locations are those located along the fringes of the Nile system and, possibly, along the Mediterranean coast. In the first category, the main aim would be to augment groundwater potential while achieving additional treatment. In the second, the main aim would be to reduce sea water intrusion into agricultural lands. Further investigations are needed to ensure the technical and economic feasibility of such activities, which may be achieved on pilot schemes.

INTRODUCTION

Physical Setting

Egypt covers an area of about one million square kilometers (Figure 1). It is divided geographically into four regions: (i) the Nile Valley and Delta, including Cairo, Giza, El Fayum depression and Lake Nasser; (ii) the Western Desert, including the Mediterranean littoral zone and the New Valley; (iii) the Eastern Desert, including the Red Sea littoral zone, the islands and the high mountains; and (iv) Sinai Peninsula, including the littoral zones of the Mediterranean, the Gulf of Aqaba.

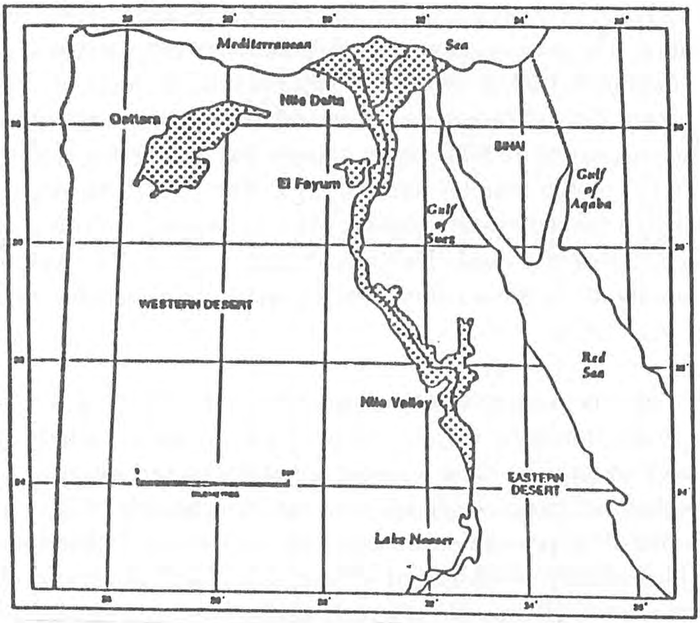

Figure 1. Geography of Egypt

The country lies for the most part within the temperate zone, and the climate varies from and to extremely arid. The air temperature frequently rises to over 40°C in daytime during summer, and seldom falls to zero in winter. The average rainfall over Egypt as a whole is only 10 mm/year. Along the Mediterranean, where most of the winter rain occurs, the annual average rainfall is less than 200 mm/year, decreasing rapidly inland. The evaporation rates are high, being in excess of 3,000 mm/year.

The hydrography of Egypt comprises two systems: (i) a system related to the Nile; and (ii) a system related to the rainfall in the past geological times, particularly in the Late Tertiary and Quaternary.

Egypt's population is estimated at 62 million (1996), increasing at an average rate of 2.6% per annum (varying between 1.4% and 3.5% in Port Said and North Sinai, respectively). About 99% of the population is concentrated over 11% of the country physical area, in the Nile Delta and Valley, Cairo, and Giza. This situation resulted in: (i) a continuous pressure on the agricultural land and Nile water resources; (ii) a continuous degradation of land and water resources; (iii) an unhealthy life style; and (iv) generation of increasing amounts of sewage.

Main Aquifer Systems

The hydrogeological framework of Egypt comprises six aquifer systems (RIGW, 1993), as shown in Figure 2: (i) the Nile aquifer system, assigned to the Quaternary and Late Tertiary, occupying the Nile flood plain region and the desert fringes; (ii) the Nubian Sandstone aquifer system, assigned to the Paleozoic-Mesozoic, occupying mainly the Western Desert; (iii) the Moghra aquifer system, assigned to the Lower Miocene, occupying mainly the western edge of the Delta; (iv) the Coastal aquifer systems, assigned to the Quaternary and Late Tertiary, occupying the northern and western coasts; (v) the karstified Carbonate aquifer system, assigned to the Eocene and to the Upper Cretaceous, predominating in the northern part of the Western Desert; and (vi) the Fissured and Weathered hard rock aquifer system, assigned to the Pre-Cambrian, predominating in the Eastern Desert and Sinai.

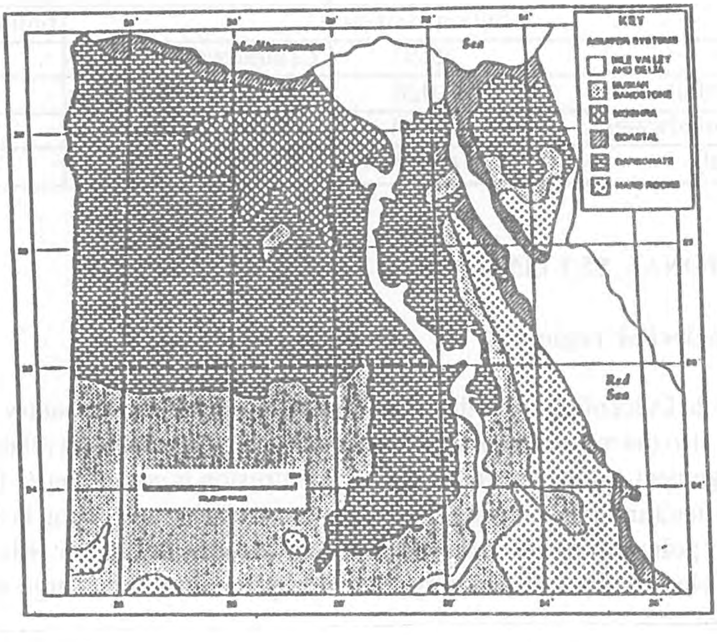

Figure 2. Main Aquifer Systems

Egypt water resources

The main source of water in Egypt is the Nile which originates outside the country and is shared by eleven riparian countries. Rainfall is very limited with respect to its geographical and temporal distribution, and rates. The other source of water in the country is groundwater in the aquifers underlying the deserts, mainly represented by the Nubian sandstone which considered almost non-renewable water. On the other hand, groundwater in the Nile aquifer system can not be considered a resource in itself as it is mainly recharged as a result of irrigation activities based on the Nile water. Other possible sources of water can be obtained through recycling, as shown in Table 1 [1].

The increasing population and economic activities are generating increasing amounts of waste water; which is presenting a nuisance to the country while it may represent an additional source of water if properly used. Possible uses include direct irrigation and recharge of groundwater. The last may represent a better option due to the possible additional treatment during the infiltration of water through the soil.

Table 1. Foreseen Original and Recycled Water Resources in Egypt (Year 2007)

Original		Recycled	
	billion m3/year		billion m^3/year
Nile	55.50	Groundwater	6.30
Rainfall	020	Agricultural drainage	7.00
Groundwater	480	Sanitary drainage	4.00
Total	60.50	Total	17.30

REGIONAL SETTING

The selected region

The Nile Delta of Egypt is the most populated region of the country (Figure 3), being also the region encompassing various types of problems related to water management. Along the coast, sea water intrusion is continuously threatening the agricultural lands. Along the fringes, groundwater depletion is threatening the on-going economic development. For these reasons, the Nile Delta has been selected for experimenting controlled groundwater recharge with treated sewage.

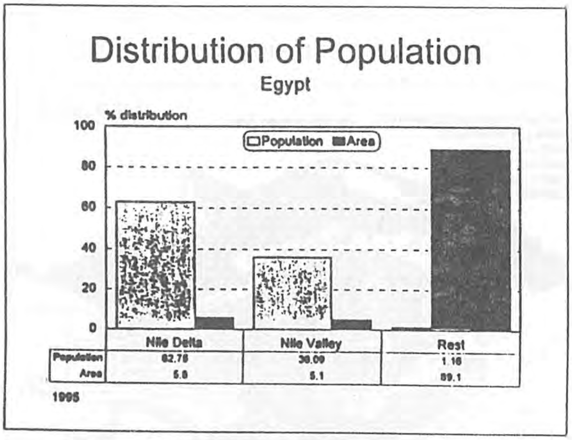

Figure 3. Population Distribution In Egypt

Hydrogeology

The Nile aquifer system consists of Pleistocene graded sand and gravel, while its extension in the desert fringes comprises Plio-Pleistocene sediments. In the censer of the flood plain, the aquifer is serni-confined (10 m average thickness of silt clay); becoming phreatic on the edges and desert fringe. The aquifer is underlain by Pliocene marine clays. The saturated thickness of the aquifer ranges between few meters to 800 m, in the fringes and censer, respectively. The aquifer transmissivity ranges from 20,000 m^2/day in the censer of the floodplain, to less than 500 m^2/day at the edges.

The main source of recharge is percolation from irrigation water. Recharge varies according to the type of soil, source of irrigation water, irrigation method, and the availability of artificial drainage networks. In sandy areas with basin irrigation diverted from the river and no artificial drainage, percolation losses vary between 1 and 2.5 mm/day. In silty areas with artificial drainage, percolation losses may be less than 0.5 mm/day [2]. Discharge from the aquifer is through seepage to the river or groundwater extraction by wells. The total annual extraction from the Nile aquifer system and desert fringes is about 3 billion m^3 [3]. Discharge from the aquifer also takes place by upward groundwater leakage in the north of the Delta [4].

Groundwater quality

Groundwater quality depends to a large extent on the land use and quality of the recharge water. In the flood plain and desert fringes the main source of groundwater recharge is irrigation water percolating through agriculture soils. Locally, seepage from carbonate and sandstone rocks or from sewage water may occur. From surface water to groundwater the total dissolved salts (TDS) in water increases from an average of 250 ppm to an average of about 600 ppm in the southern part of the Delta; while in the northern part groundwater becomes brackish to saline due to sea water intrusion (see Figure 4).

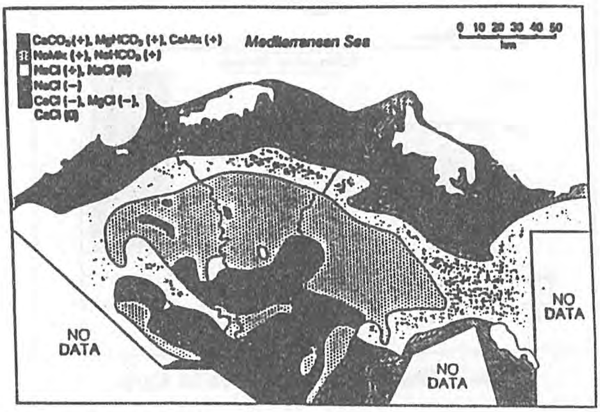

Figure 4. Groundwater Types in the Nile Delta

Groundwater vulnerability to pollution

The vulnerability of groundwater to pollution is largely determined by the soil leaching capacity (intrinsic vulnerability), depth to groundwater, and direction of natural vertical groundwater flow. In the Delta, four areas are distinguished (see Figure 5): (i) the reclaimed desert areas with moderate to high vulnerable groundwater, due to the presence of sandy formations with high infiltration and low adsorption capacities, although groundwater is relatively deep; (ii) the traditionally cultivated area with moderate to low vulnerable groundwater due to the presence of a clay cap; (iii) the transition zone between the old land and the reclaimed areas with highly vulnerable groundwater due to the presence of sandy soils and shallow groundwater table; and (iv) the northern part with very low vulnerable groundwater due to the presence of a top clay cap and upward groundwater flow.

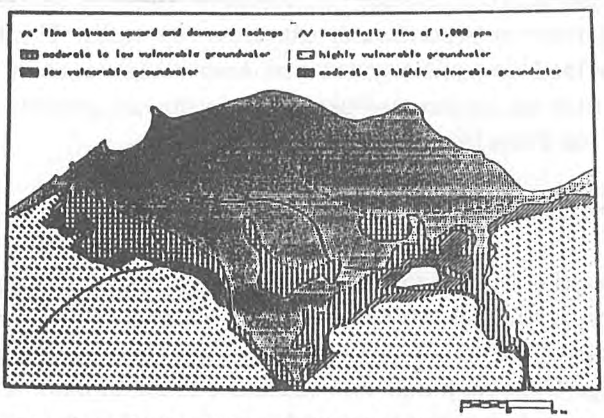

Figure 5. Groundwater Vulnerability to Pollution in the Nile Delta

Land and groundwater use

On the basis of land use, the Nile Delta Region can be subdivided into three major areas: (1) agricultural land, including sub-urban and rural areas (40%); (2) the wet lands (20%); and (3) the desert 40%. Groundwater is used for various purposes in the region. The main groundwater user sector is the agricultural sector where groundwater is either used as a supplementary source of irrigation (flood plain) or the only source (fringes). Groundwater use for domestic purposes comes next, but is expected to increase in the future. The present rate of groundwater withdrawals for irrigation and domestic purposes amount 2.2 and 1 billion m^3/year, respectively.

PRELIMINARY SITE SELECTION

Introduction

The most important factors governing the selection of sites for controlled recharge with sewage water are: (1) groundwater use; (2) vulnerability of groundwater to pollution; (3) initial depth to and quality of groundwater; (4) sites suitability for artificial recharge; and (5) present and future development plans.

Locations

Within the desert fringes of the Western Nile Delta Region, groundwater is of limited potentiality due to the characteristics of the aquifer system. In this region, large development schemes are taking place, essentially for land reclamation. Results have already been observed in the form of large drawdowns and increased groundwater salinity. The most suffering areas are those located along the Cairo-Alexandria desert road (see Figure 6), namely, Abu Rawash, west gabal El Mansuryia, Wadi El Farigh, and southwest El Sadat City.

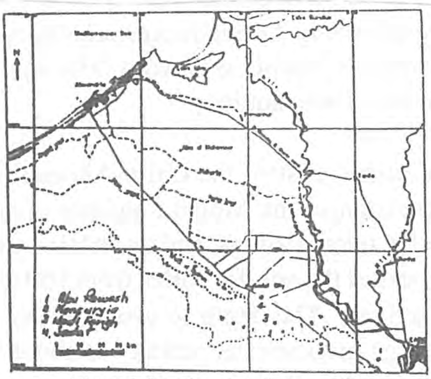

Figure 6. Location of Preliminary Sites

Hydrogeology

Figure 7 illustrates typical lithological sections in the four sites. From this figure and other available information, the following can be concluded:

1) In Abu Rawash area, the land surface slopes from 20 to 80 m towards the Cairo Alexandria desert road. The aquifer belongs to the Moghra formation, consisting of graded sand and gravel (about 150 m thick) with some clay intercalations, and is underlain by Oligocene basalt or shale. The aquifer is highly effected by faults. The main fault is separating this part of the aquifer from the Nile Delta aquifer, thus constraining groundwater exchange. The depth to groundwater vanes between 10 and 50 m, in the east and west, respectively. Groundwater salinity increases from 700 to 5,000 ppm in the east and west, respectively.

2) Gabal El Mansuryia area is located west of Cairo-Alexandria desert road. The ground elevation varies between 100-125 m, increasing to the south and southwest. The aquifer constitutes the southern border of the Moghra aquifer. It consists of Lower Miocene sand and gravel with limestone. The thickness of the water bearing formation reaches 200 m, underlain by Oligocene basalt. The aquifer is partly confined with clay. The depth to water reaches more than 110 m. Aquifer transmissivity vanes from 2000 to 4000 m^2/day; and groundwater flow direction is from north-east to south-west. Groundwater salinity varies between from 1000 to 2500 ppm.

3) Wadi El Farigh area is located to the west of Cairo-Alexandria desert road. The ground level varies from 60 to 80 m. The aquifer belongs to the Moghra, and consists of graded sand and gravel with clay intercalations. The saturated thickness of the aquifer reaches about 150 m, increasing west and north-west, with a bottom formed of Oligocene basalt or shale. The depth to groundwater varies from 60 to 80 m in the east and west, respectively. Groundwater salinity is generally less than 500 ppm, but increases sharply westward. The aquifer is hydraulically connected to the Nile Delta aquifer,

4) Sadat city is located east of the Cairo-Alexandria desert road. The aquifer is an extension of the Moghra aquifer, consisting of sand and sandstone with clay intercalations, and underlain by Oligocene basalt or shale. The thickness of the aquifer varies from 100 to 300 m in the south and north, respectively. The depth to groundwater varies between 40 and 100 m. Average groundwater salinity is about 500 ppm, and may increase to 2,000 ppm locally.

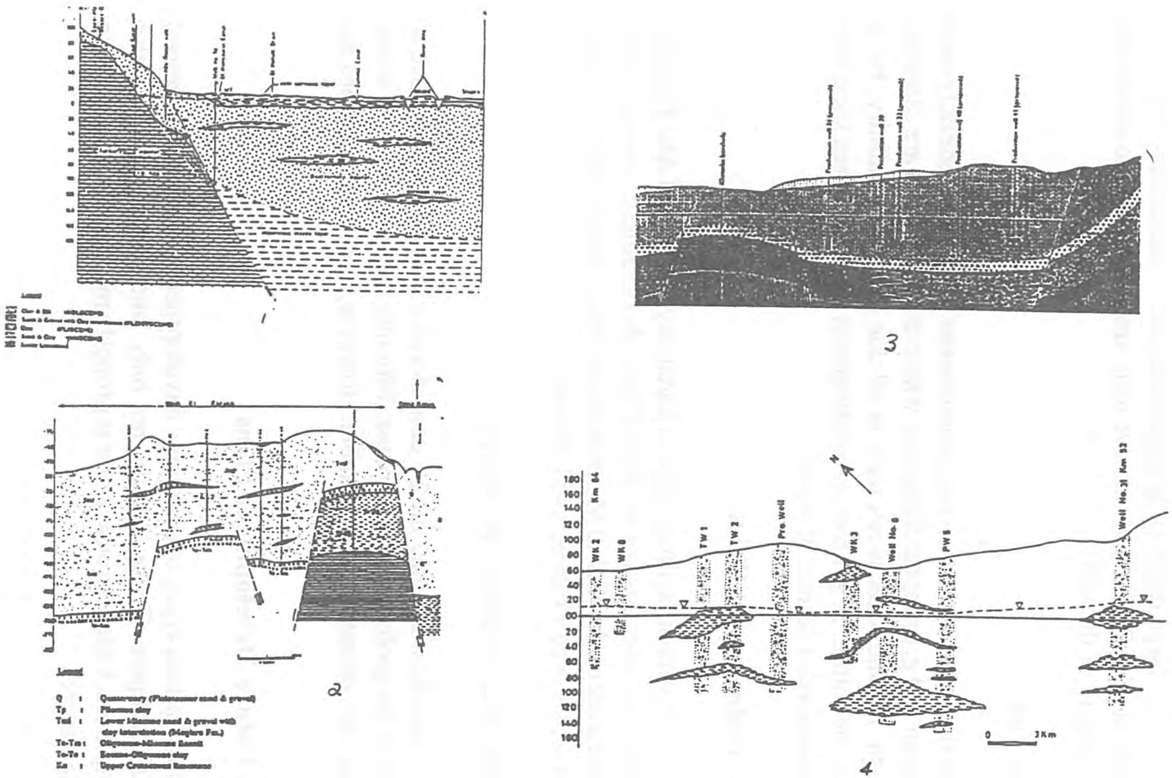

Figure 7. Hydrogeology of Initial Sites: (1) Abu Rawash; (2) Mansuryia; (3) Wadi Farigh; (4) Sadat

Groundwater Vulnerability to Pollution

In general terms, the groundwater vulnerability to pollution is moderate to low, due to the presence of clay covers, except at Abu Rawash where the clay cap is absent. Due to the large depth to groundwater, the vulnerability may even decrease, except at Abu Rawash. Extensive tests are still needed to determine the leaching capacity of the soil.

Groundwater Use

At all the sites, the only water source is groundwater. Wells are generally used for both irrigation and g, except at Sadat city where drinking wells are separate. At Abu Rawash, groundwater is not used at all due to its high salinity; but it may be used in the future. In general, groundwater in the whole area should be considered an important source of water.

Distance to Treatment Facilities

The only existing treatment facilities exist in Sadat city (local) and Abu Rawash, which accommodates the sewage of West Cairo. Accordingly, sewage water will have to be transferred to Gabal Mansuryia and Wadi Farigh; while in Sadat, locally treated waste water can be used directly.

Sites Suitability For Artificial Recharge

In this respect, Abu Rawash may not be considered a feasible location due to the complexity of the geology that may pause difficulty in the recovery of water. The three other sites seems initially suitable. However, local investigations are still required.

Present and Future Development Plans

In general terms, various types of economic development schemes are planned in the West Delta region. These include, not only land reclamation, but also industrial complexes. Unless groundwater is properly managed, such plans can never be implemented.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Groundwater in Egypt has always been considered a secondary source of water.

However, with the continuous increase of population and their concentration along the river Nile, officials started to realize that the only means of population redistribution is through spreading in the desert. Realizing that groundwater is the only source of water in the desert, groundwater research has received increasing attention.

With the continuous pressure on groundwater, the resource started to suffer from degradation. Since Egypt is an and country with very little rain, the only possible recharge source of recharge water is drainage, both agricultural and municipal.

In the first experimental sites where artificial recharge is under testing, Nile water is used. However, in the future only treated waste water will be available. Four sites have been selected for this reason, and preliminary feasibility assessed.

RECOMMENDATIONS

The following recommendations may be considered relevant:

1) In the year 2000, the total generated treated waste water will reach about 4. billion m^3/year. The treated waste water should be considered part of Egypt's water resources, and as such be included in the overall water management system.

2) The infiltration of the secondary treated waste water into the soil may result in additional treatment. However, caution and small scale experiments should be applied before any large scale project is implemented.

3) In this respect proper monitoring, including periodic sampling and analysis are the bone for decision making.

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Environmental consideration of Brine-Water Disposal from Desalination Plants

Hosny Khordagui

ENVIRONMENTAL CONSIDERATION OF BRINE WATER DISPOSAL FROM DESALINATION PLANTS

Hosny Khordagui
U.N. Economic & Social Commission for Western Asia

ABSTRACT

GCC countries are mostly devoid of rivers, have harsh climates, experiencing accelerating economic growth, facing large urban expansion, and depend mainly on limited fossil groundwater and non-conventional water resources for their requirements. The problem of water shortage had been complicated with the high growth rates of the indigenous population and the successive waves of foreign settlers captivated by the wealth of the discovered oil reserves in the region. Despite the dependency on desalinated water has substantially increased during the last 15 years in most countries of the region, the environmental implications associated with the discharge of reject brine from desalination process has not been given adequate considerations by concerned authorities. The main objective of the present study is to fill this gap by identifying the environmental problems associated with brine water disposal from (sea & brackish) water desalination plants, assessing their environmental impacts and proposing measures for the alleviation or minimization of these impacts.

The problems that have been addressed within the context of their impact on the environmental compartments of concern include the following:

1. Problems associated with the discharge of brine water to the near-shore marine environment from desalination plants situated on coastlines and using seawater as feed and cooling water.
2. Environmental problems associated with the discharge of brine water to land from in-land Reverse Osmosis (RO) desalination plants using brackish ground-water as feed-water.

The major addressed problems include the following:

1. Thermal pollution resulting from brine disposal
2. High salt content of brine water.
3. Pre-and post-treatment chemicals which might include antiscaling agents, antifoaming agents, polyphosphates, coagulant aids, residual chlorine and acids.
4. Corrosion products (heavy metals) such as Ni, Cu, Zn, Mo and others.

Conventional and state-of-the-art control measures applicable to countries of the region were addressed, reviewed and discussed taking into account the environmental advantages, limitations and economic considerations.

INTRODUCTION

GCC countries are mostly devoid of rivers, have harsh climates, experiencing accelerating economic growth, face large urban expansion, and depend mainly on limited fossil groundwater and non-conventional water resources for their requirements. The problem of water shortage had been complicated with the high growth rates of the indigenous population and the successive waves of foreign settlers captivated by the wealth of the discovered oil reserves in the region.

Owing to such rapid increase in demand for water in the GCC Countries, where conventional water resources such as fresh surface water and renewable groundwater are extremely limited, other alternatives such as waste-water reclamation and desalination have been adopted since the 1960s. Additional but less realistic non-conventional water resources alternatives encompassing iceberg towing, transport by large tankers, towing of large capacity rubber (Medusa) bags and finally, the transport of Turkish water resources through a 20 billion US dollars pipeline to the Arabian Gulf were contemplated.

Transporting water across international boundaries cannot be politically or economically justified. The Peace Pipeline proposed by Turkey to deliver 2.5 mcm of water to many cities in the Arabian Peninsula at a capital cost estimated at $20 billion is considered by some experts in the field as an illusion. At the same cost (using the 1993 prices), it is possible to build a number of desalination plants and the electric power plants required for their operation to produce potable water at a capacity of 7.5 mcm/day.

Furthermore, ocean shipping by using tankers or Medusa bags cannot compete with large scale desalination processes. When all associated cost at terminal points are considered, desalination usually cost only a fraction of the cost of ocean shipping.

Transportation of icebergs may still be considered as a cost competitive non-conventional water resource. However, the very high capital cost in addition to the constraints associated with its untested and pioneer application place desalination again as the technology of choice.

Review of non-conventional water production schemes in the Arabian Gulf indicates that desalination followed by water reuse are be the most cost-effective alternatives to water shortage (Khordagui, 1996). Currently, desalination technology has been perfected to the point where it can provide a reliable source of water at competitive costs. In the GCC countries, desalination from dual-purpose plants (co-generation) has proven to be a more economical alternative than constructing new dams or extending pipelines to supply water from other regions, taking into consideration required water quality standards, social acceptability, and political vulnerability.

The total number of desalination plants in operation (as of 1992) has reached a total of 45 with 23 in Saudi Arabia, eight in the UAE, six in Kuwait, three in Bahrain, and two each in Oman and Qatar. Out of 15.58 million cubic meters per day worldwide installed desalination capacity, GCC countries contribute almost half (49.5%) of the total. Saudi Arabia alone houses about half of the GCC desalination capabilities amounting to about 25% of the world capacity. Despite the fact that dependency on desalinated water has substantially increased during the last 15 years in most countries of the GCC Region, the environmental implications associated with the discharge of reject brine water from desalination processes have not been given adequate considerations by concerned authorities. The main objective of the present study is to fill this gap by identifying the environmental problems associated with brine water disposal from (seawater & brackish groundwater) water desalination plants, assessing their environmental impacts and proposing measures for the alleviation or minimization of these impacts.

PROPERTIES OF BRINE WATERS

Desalination is a process by which TDS are separated from salty water to render it useable. The extracted salts will concentrate in the reject brine solution. During the process of desalination, the physical and chemical properties of the brine reject change significantly. The characteristics of the reject brine was found to be a direct function of the quality of the feed water, the desalination technology used, the percent recovery, the chemical additives used within the process, the construction material and proficiency of the operators. The general characteristics of the reject brine from some GCC desalination plants are provided in Table 1.

Table 1: Characteristics of reject brine water from some GCC desalination plants

Parameters	Abu-Fintas Doha/Qatar	BWRO Ajman	BWRO UmQuwain	Quidfa I Fujairah Seawater	Quidfa II Fujairah Seawater
Temp. °C	40-44	30.6	32.4	32.2	29.1
pH	8.2	7.46	6.7	6.97	7.99
Cond.US/cm	—	16,490	11,325	77,000	79,600
Ca++ ppm	1300-1400	312	173	631	631
Mg++ppm	7600-7700	413	282	2025	2096
Na+ppm	—	2756	2315	17294	18293
HCO_3ppm	3900	561	570	159	149.5
SO_4-ppm	3900	1500	2175	4200	4800
Cl-ppm	29000	4572	2762	30487	31905
TDS in ppm	52,000	10,114	8,276	54,795	57,935
Tot.Hard ppm	—	—	32	198	207
Free C12ppm	Trace	—	0.01	—	—
SiO2ppm	—	23.7	145	1.02	17.6
Langlier S.I.	—	0.61	0.33	—	—
Cu in ppb	<20	—	—	—	—
Fe in ppb	<20	—	—	—	—
Ni in ppb	Trace	—	—	—	—
Antiscale ppm	0,8-1.0	—	—	—	—
Antifoam ppm	0.04-0.05	—	—	—	—

— = not prepared

ENVIRONMENTAL IMPACT OF BRINE DISPOSAL ON THE NEARSHORE MARINE ENVIRONMENT

The amount of salty feed water that must be provided to the desalination plants for each unit of product water has an important environmental consideration. According to ESCWA (1993), SWRO will consume 2-3 m³ for each m³ of product water. However, distillation processes would typically involve a somewhat higher ratio. For instance Effects Desalination (MED) requires 4.5 m³of salty water to produce 1 m³ of desalinated water.

The environmental impact of brine water discharge to the nearshore marine environment might be expressed in one or more of the following forms :

- Physical Impact : Resulting from the discharge of hot from thermal desalination plants.
- Chemical impact : Resulting from chemical agents remaining in the brine

water and added within the process for the control of biofouling (chlorination), control of calcium carbonate scale formation (sulphuric acid, polyphosphates and recently polyelectrolytes) and antifoaming agents. Additionally, SVVRO necessitates an exhaustive pretreatment of the feed water to avoid accelerated fouling and scaling of the RO membranes. This pretreatment involves prechlorination, coagulation using coagulants (alum $Al_2(SO_4)_3.18H_2O$ or ferric chloride sulphate Fe $ClSO_4$)) and coagulant aids (polyelectrolytes), sedimentation, clarification, sand filtration and dechlorination using sodium bisulphate before conveyance to the RO membranes.

Biological Impact: Biological impact is the secondary effect of oxygen demand exerted by the natural and induced organics in the brine water. Relatively higher levels of Biochemical Oxygen Demand (BOD) are commonly observed in the desalination plant effluents. The impact of BOD demand for Dissolved Oxygen (DO) associated with lower levels of DO in brine waters due to higher salt content and temperature will ultimately reduce the level of DO in seawater adjacent to the brine water outfalls.

Environmental Impacts of Increased Salinity on Open Seawaters

There has always been a misconception among some environmentalists that the concentrated salt content of the brine water disposed of by seawater desalination plants will inflict significant damage to the open nearshore marine environment. Fortunately, this is not the case for the following reasons:

1. The amount of seawater withdrawn for desalination is relatively minute when compared to the water mass of the open sea.
2. The amount and nature of salts discharged with the brine are identical to the salt content of the open sea.
3. The concentration factor increase by no more than two. In case brine is discharged after blending with power production cooling waters for dilution, this ratio of two will significantly drop to near one.
4. In order to avoid recirculation of plant effluents to the intakes of the desalination plants, the outlets are specifically designed to discharge in coastal areas where maximum circulation patterns and hydrographic currents can easily disperse and dilute the brine.

It is then safe to assume that the increase in salinity of the open seawater in the vicinity of large seawater desalination plants is immaterial, and should not give reasons for concern, particularly when nearshore hydrographic circulation patterns are considered in the design of the plants outlets.

Environmental Impacts of Increased Salinity on Semi-Enclosed Marine Environment:

The discharge of brine water in shallow and relatively stagnant nearly-landlocked coastal areas such as bays, khours, harbours, etc. might result into a more pronounced impacts on the encircled marine environment.

The percent recovery attainable from the desalination of sea water ranges from 20% to 65% (ESCWA, 1993) depending on the process used in the desalination giving rise to concentration ratio of 1.25 to 3. It is important to note that higher recovery reduces the volume of brine water discharged, yet it will increase the salt content by the same ratio. Reciprocally, lower recovery will reduce the salt content and increase the volume of brine water discharged. In this respect it is the mass of the discharged salt that counts rather than its concentration per liter.

Semi-enclosed and shallow embayments in the Arabian Gulf (AG) are naturally characterized by a higher salt content due the accelerated rate of evaporation and restricted dispersion and dilution. In some nearshore localities of the AG, the average salinity in summer can reach some 48 Part per Thousand (ppt), as compared to 37 ppt in winter. These natural cycles of higher salinity are several order of magnitudes what is being discharged from desalination plants. Nonetheless, very limited environmental impacts were documented in literature associating natural cycles of higher salinity with negative ecological implications, Hence, the increase in salinity in the proximity of points of brine water discharge might be of limited impact on the marine ecology.

Environmental Impacts of Thermal Pollution from Brine Water

The temperature of the brine water effluent resulting from thermal desalination processes is typically above the feed water temperature by 5 to 8°C. However, Altayaran & Madany (1991) have reported 10 to 15°C above the naturally occurring temperatures in summer and winter seasons in Bahrain. The degree of damage to the biota present in the vicinity of the point of discharge is a function of its type, the temperature levels (levels of exposure) and duration of thermal inputs (duration of exposure).

According to ESCWA (1993), if the environment is open and well mixed, then the effects will only be noticeable to within 300 meters from the discharge point. This statement has been confirmed in the study conducted by Altayaran and Madany (1992) in which they discovered that at 160 meter seaward from the point of discharge from Sitra power and desalination plant in Bahrain, no discernible pattern of temperature, salinity or DO differences were noticed.

The impact of thermal pollution in enclosed areas might be more significant and could be manifested by changes in community structure such as types of dominating organisms and by changes in the characteristics of the individual species such as lower tolerance and/or adaption. Thermal pollution will lower the amount of DO, increases bacterial and aquatic invertebrate activity which in turn will diminish already lowered DO, increases the growth rate of microscopic plants and fish and increases sensitivity of aquatic life to toxic elements.

Environmental Impacts of Residential Chlorine Oxidants in Brine Water:

The discharge of residual chlorine oxidants is exclusive to desalination processes other than SWRO. It is a common practice to dechlorinate the feed water to SWRO to avoid their detrimental impacts on the RO membranes.

In an effort to control biofouling, chlorine is added continuously at the desalination plants intakes at concentrations ranging from 2 to 4 ppm. Shock doses are also added every 8 hours for 20 minutes at 8 to 10ppm. The common practice is to maintain a 0.5 ppm of residual chlorine at plant outlets to avoid any risk associated with biofouling (Khordagui, 1992a).

The discharge of residual chlorine even at very low fraction of one ppm levels have come under fire by environmentalists due to their determental and toxic implications on the nearshore environment (Morris,1983 and Hester, 1985). According to USA-EPA, (1986), fish and invertebrates are more sensitive to residual chlorine oxidants than aquatic plants.

Eventhough, chlorine is considered as the most economical and effective antifouling measure, its usefulness has been significantly compromised by stringent discharge regulations in the developed world (Khordagui, 1992b). Under the current USA-EPA regulations that is mostly derived from the US-EPA Quality Criteria Water (1986), the discharge of residual chlorine in seawater should not affect unacceptably if the 4-day average concentration of chlorine produced oxidants does not exceed 7.5 Microgram per liter i.e. Parts Per Billion (pbb) more than once every 3 years on the average and if the one hour average concentration doesn't exceed 13pbb more than once every year 3 years on the average. The recommended exceedence frequency of 3 years is the EPA's best scientific judgment of the average amount of time it will take an untressed system to recover from pollution event in which exposure to chlorine exceeds the criterion. Given these facts, it appears that the discharge of trace levels of residual chlorine oxidants either in open or enclosed seawaters will be very detrimental to aquatic life in the nearshore marine environment.

Formation of Trihalomethanes (THMS) in Brine Water:

The formation of trihalomethanes in brine water is a direct consequence of the chlorination process in which free chlorine reacts with the natural organics occurring m seawater to form THMs (Khordagui & Mancy, 1983). Some of the volatile THMs species were found to be carcinogenic and mutagenic to humans (Cantor,1983).

According to Ali & Riley (1986), Out of 20 possible THMs only 4 were consistently detected in brine waters. Brominated species were dominating the formation distribution, with Bromoform (CHBrs) accounting for more than 90% of the total THMs followed by dibromochloromethane (CHBreCI). The detected levels of total THMs in Kuwait ranged from 90 ppb in the immediate vicinity of the point of discharge to less than 1 ppb within few kilometers seaward (Ali & Riley, 1986). Currently there is growing concern within the scientific community about possible damage to the nearshore marine ecology into which chlorinated brine are discharged. Except in the immediate vicinity of the brine water point of discharge, it is very unlikely that the concentrations of trihalomethanes are significant enough to pose any ecological threat.

The problem is further complicated by the fact that low boiling point THMs can reach the desalination plant intakes and recirculate within the system. Once in the intakes, THMs will evaporate with the steam, then co-distill and concentrate in the potable water condensate. The possible appearance of THMs in desalinated water can pose a serious public health threat to consumers.

Environmental Impacts of Trace Metals in Brine Water

In thermal desalination plants, it is plausible to find corrosion products in brine waters resulting from the effect of water flow, dissolved gases and treatment chemicals (acids) on the alloys utilized in the construction of desalination pipes and equipments. The corrosion products may include harmful heavy metals such as Nickel (Ni), Copper (Cu) and Molybdenum (Mo) and less toxic metals such as Iron (Fe) and Zinc (Zn). The amount of these metal ions is directly related to the redox potential, pH and the material in contact with water during the desalination process.

As conservative pollutants, metals will last in different compartments of the marine environment for ever. However, their ultimate sink is the marine sediment. The level of metals in sediments and water reflect the general status of the environment but they don't necessarily reflect the biological availability of these metals. After 25 years of practising large scale seawater desalination, studies conducted in the nearshore of Kuwait revealed that local fish and shrimp species were not contaminated by heavy metal (Anderlini, 1982).

Fortunately, most of the reported data indicates that the levels of heavy metals associated with brine water disposal are minimal and often below the detection limits of the standard analytical procedures. This has been particularly true after blending brine water with large volumes of cooling water used in power production. When comparing the mass and nature of heavy metals released with brine water to the amount of heavy metals being released from landbased industrial wastewater, atmospheric fallout and crude oil spills, it is thought over as negligible.

Environmental Impacts of Anti-Sealants in Brine Water

In order to control calcium carbonate scaling, concentrated sulphuric acid (93%) is added to the feed water. The addition of sulphuric acid breaks down the bicarbonate alkalinity and prevent the calcium carbonate scales from forming. Additionally, calcium, barium and strontium sulphate scales can also be formed, particularly after the addition of sulphuric acid to control carbonate scaling. A threshold scale inhibitor such as sodium hexametaphosphate is added at a dose ranging from 4 to 6ppm to hamper the growth of carbonate and/or sulphate crystals.

The extremely large carbonate buffering capacity of the seawater minimizes the impact of acids on the environment and renders it negligible. Altayaran and Madany (1992) were unable to detect any discernible pH variation in nearshore seawater in the proximity of Sitra Power and Desalination plant in Bahrain.

The greatest environmental impact of polyphosphate in reject brine on the nearshore marine environment lies in its nutritional value. When present with other nutrients, phosphate causes an overabundant growth of plants that are unusual or nonindigenous to the area. This excessive plant growth usually means a reduction in diversity of species, and result in an imbalance of food chain materials essential for intermediate organisms. In turn their demise means an increase in BOD and turbidity of water.

ENVIRONMENTAL MEASURES FOR BRINE WATER DISPOSAL IN THE NEARSHORE MARINE ENVIRONMENT

In most of the cases, high salinity reject brine is simply returned to the nearshore marine environment. Several methods have been suggested to alleviate or minimize the impact of reject brine disposal on the nearshore marine environment. Most of the suggested methods focused on making optimum use of tidal flushing, dispersion, dilution and reduce the contaminants to stay within the assimilation capacity of the overall system. The introduction of treatment methods that greatly reduce the impact of reject brine on the marine environment should not be neglected.

Introduction of chemicals to control scale formation has witnessed significant technological advancements. Numerous polyelectrolytes (polymers) were developed and marketed to replace acids and polyphosphates as antiscalants. These polymers are claimed to be biodegradable and with much less lower environmental impacts than polyphosphates.

The amount of heavy metal ions is directly related to the pH of the water, and the material used in they construction of the desalination machinery. Consequently, in order to limit potential for adverse effects on nearshore marine ecosystems, it is advisable to closely monitor and control the pH of the water passing through the different stages of the process, and adjust it at the end so that its value at the discharge point becomes as close as possible to its value at the intake. Build up of heavy metals in brine water should be prevented by using corrosion inhibitors or by using more resistant construction material. The level of heavy metals concentration in the effluent should be limited and depends upon the characteristics of the local environment. From earlier discussions it appeared that the major problems associated with reject brine discharges are mostly thermal pollution and residual chlorine.

Control of Thermal Pollution:

In order to minimize the environmental implications associated with thermal pollution, it is customary to select the plant site and design the brine disposal system such that dissipation of thermal input takes place rapidly. The maximum allowable increase in the weekly average temperature beyond 300 meters seaward from the point of discharge is 1.0°C. In addition, daily temperature cycle should neither change in frequency nor in amplitude (ESCWA, 1993). When designing for brine water outfalls, it is strongly recommended to avoid nearshore enclosed areas and /or khors.

In the event an environmental damage directly resulting from thermal discharges becomes evident, it will be necessary to pass the hot reject brine through a separate cooling pond or cooling tower before final disposal in the near shore. Past experience in the GCC countries indicates that there is no real demand for these add-on brine water cooling systems.

Control of Residual Chlorine (Dechlorination):

The strict ban on residual chlorine discharges in seawater and the adoption of a near-zero discharge standards compelled the power and desalination industries in the West to search for solutions. The efforts to eliminate the environmental impacts of residual chlorine discharge included the following :

1. Optimization scheme : this included targeted chlorination, chlorine minimization and off-line control.
2. Chlorination Alternatives : this included bromine, bromine chloride, ozone chlorine dioxide, UV and ferrate.
3. Chlorination/Dechlorination : this included chlorine/activated carbon, chlorine/ SO_2 and chlorine/holding ponds.

In a design of a conceptual approach to select a control measure for residual chlorine discharge in Kuwait Bay, Khordagui (1992a) indicate that out of the 12 different residual chlorine control alternatives, chlorination/dechlorination using regenerated SO_2 emitted from thermal power plants was found to be the most cost-effective and feasible technique to be implemented. It is generally believed that decholorination is beneficial, especially because it reduces acute toxicity (Sopocy et al., 1985; Neiheisel et al., 1988) and even mutagenecity (Wilcox & Denny, 1984) associated with chlorinated water. In addition, dehalogenation will prevent further formation of THMs in nearshore seawaters.

The chemical reactions involved in the SO_2 dehalogenation are given as follows:

$$SO_2 + H_2O \longrightarrow H_2SO_3 \quad \text{.................} \quad (1)$$

The sulphurous acid reacts with the various chlorine residual (Bromine residual) species as follows :

$$HOCl + H_2SO_3 \longrightarrow HCl + H_2SO_4 \quad (2)$$
$$NH_2Cl + H_2SO_3 + H_2O \longrightarrow NH_4Cl + H_2SO_4 \quad (3)$$
$$NHCl_2 = 2H_2SO_3 + 2H_2O \longrightarrow NH_4C1 + HCl + 2H_2SO_4 \quad (4)$$

The reactions prescribed by equations 1 to 4 are complete in a matter of less than 10 seconds. For each part of chlorine removed, 2.8 mg/1 alkalinity as $CaCO_3$ is consumed. Theoretically, no significant physical or chemical degradation should be found in reject brine following dehalogenation using SO_2 Fig. 1 provides a layout of the suggested dechlorination facility (Khordagui, 1992 b).

ENVIRONMENTAL IMPACTS OF BRINE DISPOSAL ON LAND

In many instances, RO desalination plants are located at inland sites, where the disposal of reject brine is in some cases the most critical economic and environmental problem. In these inland locations, brackish groundwater resources are used as feed water for desalination. The Brackish Water Reverse Osmosis (BWRO) is used to desalinate groundwater of much lower salinity than seawater,

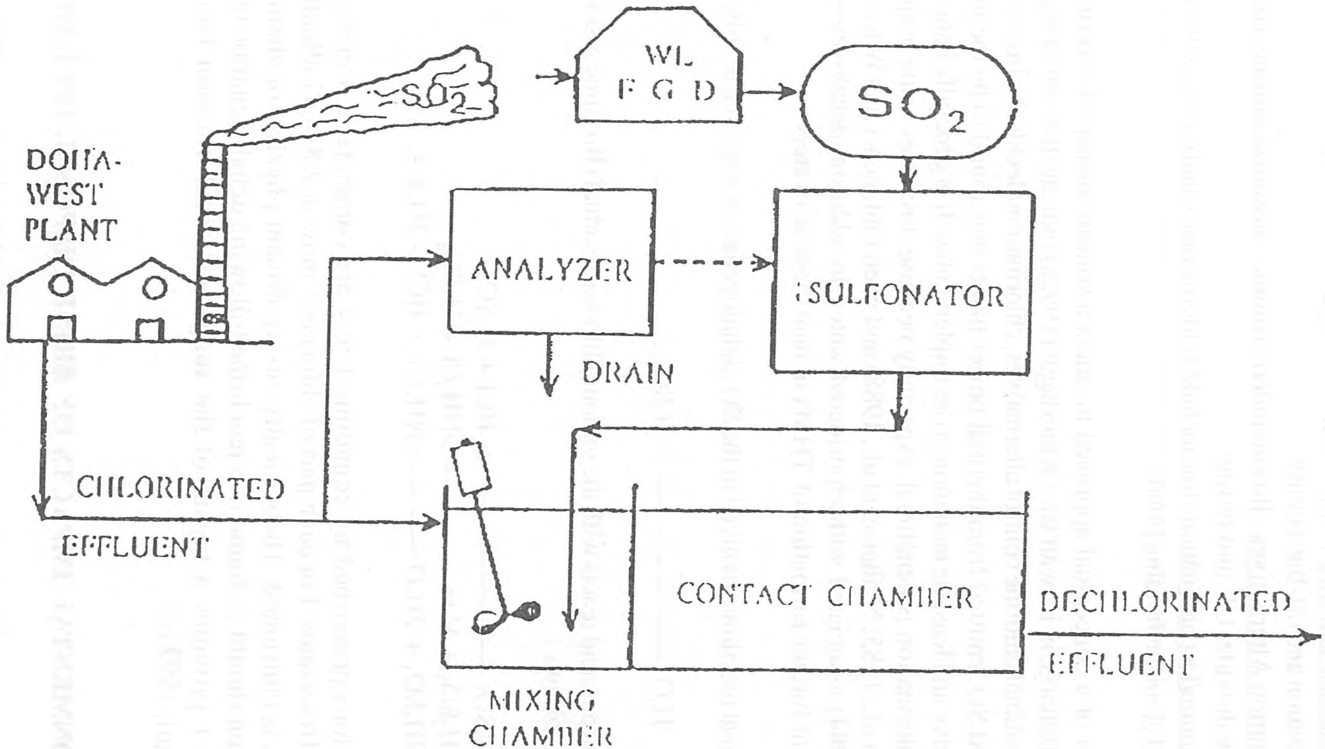

Fig. 1. Simplified layout of proposed dehalogenation facility (Source: Khordagui, 1992b).

Typically the Total Dissolved Solids (TDS) will range from 2000 to more than 8000 as compared to 45,000 for seawater.

High salinity brine water resulting as a by-product from the desalination processes is considered as one of the major factors determining the location, capital cost and operation cost of BWRO desalination facilities. The brine in BWRO plant can amount 20% of the water produced and, where it can be discharged to the sea or a smaller saline water body, it is generally not a problem. Ordinarily, the rejected brine cannot be disposed economically to a distant sea or reused for agriculture or other applications and the brine disposal problem becomes a critical drawback in exploiting desperately needed brackish groundwater resources.

Brine reject if not disposed properly has a good potential for polluting the same groundwater resources used as feed water for RO systems. High salt contents in reject brine can reach ground water by percolation if improperly disposed on land. Productivity of agricultural lands can deteriorate by the deposition of air-borned salts from dried brine. However, the environmental problem associated with thermal desalination such as residual chlorine, heavy metals and thermal pollution etc. are not usually transpired in BWRO.

Although conceptually there is an economic incentive to use high recovery system reduce energy consumption and decrease brine water volume, these advantages must be weighed against disadvantages. The two major drawbacks are the increased sophistication of the RO system including complexity of pre-treatment of feed waters and the increased potential for fouling and scaling of membrances owing to precipitation of carbonates and sulphates. The potential for scale formation augments as the concentration of brine increases for each successive RO stage. This is, of course, highly dependent on the chemical constituents in each individual water resource and must be examined on case by case basis. Apart from economics, other factors contributing to the desirability for investing in higher recovery include the scarcity of brackish groundwater resources.

Using the high recovery approach, Glueckstern and Pricl (1996) were able to reach a 92% recovery for a 300 m^3/h brackish groundwater by using three brine stage BWRO system. A simplified diagram of the high recovery plant is illustrated in Fig. 2. Out of the 300 m^3 only 206 m^3 of brackish feed is desalted. The limiting factor in this case was the 250% oversaturation of calcium sulphate in the reject brine. The total related water supply (following blending) amounts to about 284 m^3/h, and the disposed brine to 16 m^3/h.

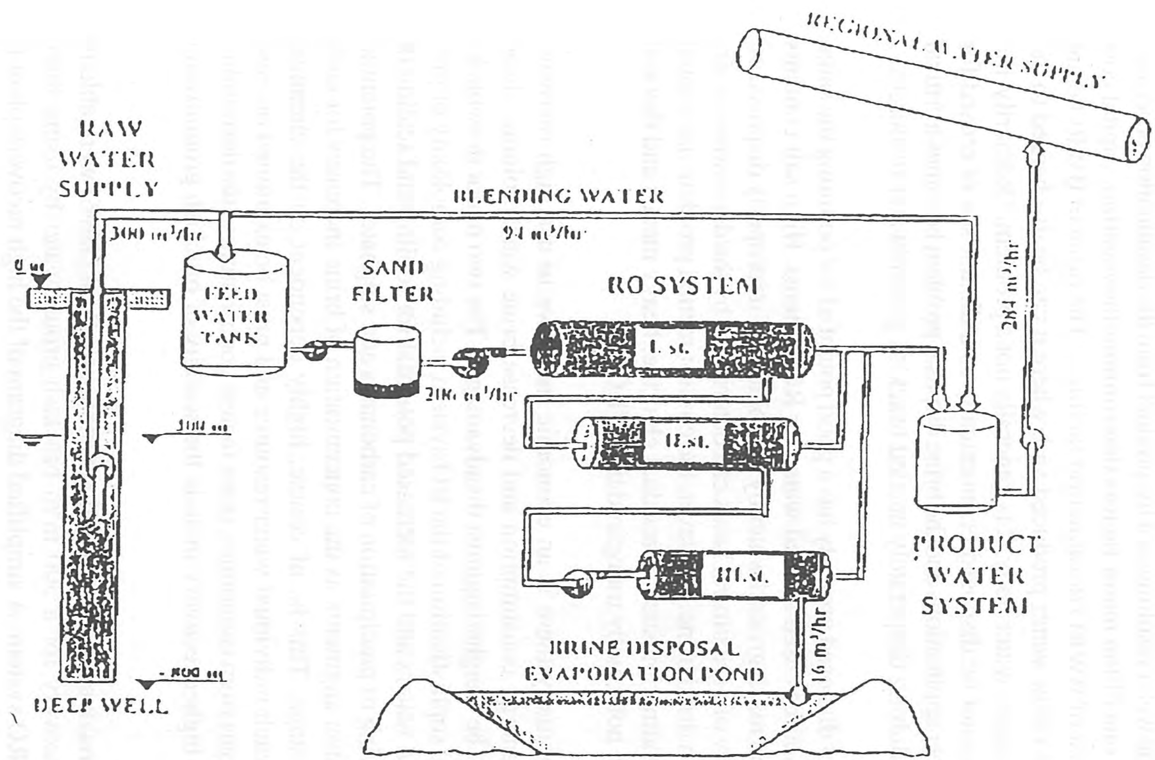

Fig. 2. Simplified flow diagram of typical high recovery BWRO.
(Source: Glueckstern and Priel, 1996).

ENVIRONMENTAL MEASURES FOR INLAND BRINE WATER DISPOSAL

Since the reject brine has the potential of causing serious environmental problems if discharged improperly, its disposal should be carefully considered. The necessity for a special disposal techniques could make the system very costly. According to ESCWA (1993), cost plays an important role in selecting the method of reject brine disposal. This cost ranged from 5 to 33% of the total cost of desalination. The cost has always before disposal, means of disposal and the nature of the disposal environment. Glueckstern & Priel (1996) revealed that despite the differences in system capacity and feed water salinity, the total desalination cost for a typical inland BWRO desalination plant is much higher than that of disposing its reject bring into a nearby sea.

For the GCC Countries, the options available for the disposal of reject brine from BWRO are a s follows :

1. Pumping into lined evaporation ponds
2. Injection into deep underground formations
3. Discharge through pipelines to sea other water bodies.

It should be recognized that with all types of land disposal procedures, there will always be the potential risk of ground water contamination. However, this risk becomes much lower when reject brine is concentrated into solid salts.

The facile and common practice of disposing high salinity brine water particularly from small (skid) RO units in municipal sewerage in some GCC countries will ultimately lead to the rise of TDS in domestic sewage. The expensive biological methods used in these countries for the treatment of their domestic wastewater does not remove TDS and will render the needed treated effluent inappropriate for reuse in agriculture. Diversion of reject brine to the sea throughout storm water collection system is another option to be considered and subject to its availability.

Pumping Into Lined Evaporation Ponds:

Reject brine resulting from inland BWRO can be pumped into a lined and sealed pit or pond and left to evaporate. In most of the GCC Countries, the prevailing warm weather and excellent solar radiation, and the availability of land at reasonable prices, enable the use of evaporation ponds. However, in order to reduce the land requirement and construction costs, it might be essential to consider the design of BWRO system with the maximum possible product recovery ratio as illustrated in Fig. 1. If the bottom of the pond is well sealed and evaporation is at least equal to the influent, such impoundment may receive and hold reject brine for long years. However, seals may break down leading to groundwater contamination, rain storms and/or flush floods may cause overflows. According to Giuekestem & Priel (1996), for a typical 300 m^3/h. BMWRO discharging a reject brine of 16 m^3/h, the required evaporation pond area for 6,500 hours operation time is 65,000 m^2. The cost of brine disposal including land cost amounted to 8.5 cent/m^3. Dependent on the value and availability of land, properly constructed and managed lined evaporation ponds may cost more than deep well injection. According to ESCWA (1993), the concentration of reject brine into solid salts using solar evaporation may cost U.S.$ 1.15 to 1.88 per 1000 gallons of desalinated water using 1985 U.S.$ value. Glueckestem and Priel (1996) estimated the cost of disposal of reject brine in an evaporation pond by 15% of the total desalination cost.

Deep Well Injection:

Disposal of treject brine by injection into deep wells has been successful in areas of low or non-existent assimilating water bodies. To be elective, the brines must be placed in a geological formation which prevents its migration to the surface or ground water supplies. The rock types most frequently used are the more porous ones such as limestone's, sandstone's and dolomites, since the porosity may help develop a filter cake which plugs the well. Other factors to be considered are the depth and diameter of the well, injection pressure to be applied, and the volume and characteristics of the brine to be disposed. The BWRO design engineer should work closely with a geologist familiar with the subsurface formations in the area in order to select the proper reject brine disposal zone. A testing well should be drilled and core samples should be analyzed for specific characteristics such as permeability and reactivity with the brine. Tests should be carried out to determine the injection pressure required at various reject brine flows. Certain procedures such as fracturing and acidizing, may be used to improve the soil premeability and thus reduce energy cost of the injection pressure required at various flows.

Reject brine may be injected into a downhole formation located at a minimum of 100 meters below the deepest fresh water sand into a dry porous strata separated from deep groundwater by a thick impervious layer. In theory, the reject brine pumped into the well soak into the porous material and remain isolated from groundwater's by the impermeable overhead layer. It is important to note that it is impossible to guarantee that fractures in the impermeable layer resulting from earthquakes, strong vibrations, etc. will not eventually permit brine water to leak-out and contaminate groundwaters. Indeed, stresses produced by the introduction of the reject brine may even cause such a fracture. Other ways in which can escape into strata containing fresh groundwater include corrosion of the casing and inadequate seal following the boring of the well.

The estimated cost for the disposal of reject brine by deep well injection ranges from U.S $ 0.1 to 1.15 per 1000 gallons of desalinated water at the 1985 U.S.$ value (ESCWA, 1993).

Disposal into the Sea :

Under certain conditions, discharge into the sea might be one of the best cost-effective available alternatives. Special considerations should be given to the siting of the point of discharge to avoid any impact of environmentally sensitive areas such as mangroves, coral reefs, nesting areas, sea grass areas, breeding areas, etc. The outfall for brine disposal should avoid mud flats and should be selected at a point where nearshore currents are significant to ensure maximum blending, dilution and dispersion of the released salts and make optimum use of tidal flushing. The distance of BWRO from the point of discharge on the sea shore is a vital factor in the capital and operations costs of the desalination process.

CONCLUSIONS

- The characteristics of the reject brine directly depends on the quality of the feed water, the desalination technology used, the percent recovery, the chemical additives used within the process, the construction materials and the proficiency of the operators.
- Open sea is generally less vulnerable than enclosed bays and sounds to many impacts of brine water disposal. This can be attributed to the large volume and free exchange of water. Open sea currents and circulation patterns have a considerable capacity to transport, disperse, and dilute brine water constituents.
- It is then safe to assume that the increase in salinity of the open seawater in the vicinity of large seawater desalination plants is immaterial, and should not give reasons for concern, particularly when nearshore hydrographic circulation patterns are considered in the design of the plants outlets.
- In some nearshore localities of the AG, the average salinity in summer can reach some 48 Part per Thousand (ppt), as compared to 37 ppt in winter. These natural cycles of higher salinity are several order of magnitudes what is being discharged from desalination plants.
- If the nearshore marine environment is open and well mixed, then the effects will only be noticeable to within 300 meters from the discharge point.
- The impact of thermal pollution in semi-enclosed nearshore areas might be more significant and could be manifested by changes in community structure such as types of dominating organisms and by changes in the characteristics of the individual species such as lower tolerance and/or adaption. Thermal

pollution will lower the amount of DO, increase bacterial and aquatic invertebrate activity which in turn will diminish already lowered DO, increase the growth rate of microscopic plants and fish and increase sensitivity of aquatic life to toxic elements.

- The discharge of trace levels of residual chlorine oxidants either in open or enclosed seawaters will be very detrimental to aquatic life in the nearshore marine environment.
- Except in the immediate vicinity of the brine water point of discharge, it is very unlikely that the concentrations of trihalomethanes are significant enough to pose any ecological threat.
- The low boiling point THMs discharged with the brine can reach the desalination plant intakes, and recirculate within the system. THMs can evaporate with the stern, then co-distill and concentrate in the potable water condensate. The possible appearance of THMs is desalinated water can pose a serious public health threat to consumers.
- Most of the reported data indicated that the levels of heavy metals associated with brine water disposal are minimal and often below the detection limits of the standard analytical procedures.
- The extremely large carbonate buffering capacity of the seawater minimizes the impact of sulphuric acid (added to avoid scaling in the desalination plants) and renders it negligible on the marine envirorment.
- The amount of heavy metal ions is directly related to the pH of the water, and the material used in the construction of the desalination machinery. Build up of heavy metals in brine water can be prevented by using corrosion inhibitors or by using more resistant construction material.
- Chlorination/dechlorination using regenerated SO_2 emitted from thermal power plants was found to be most cost-effective and feasible technique to eliminate the damaging environmental impacts of residual chlorine. Dechlorination is beneficial, especially because it reduces acute toxicity and even mutagenecity associated with chlorinated water. In addition, dehalogenation will prevent further formation of THMs in nearshore marine environment.
- If not disposed properly, brine reject has a good potential for polluting the same groundwater resources used as feed water for RO systems. High salt contents in reject brine can reach ground water by productivity of agricultural lands can deteriorate by the deposition of air-borned salts from dried brine.
- The environmental problem asssociated with thermal desalination such as residual chlorine, heavy metals and thermal pollution etc. are not usually transpired in BWRO.
- The facile and common practise of disposing high salinity brine water particularly from small (skid) RO units in municipal sewerage in some GCC Countries will ultimately lead to the rise of TDS in domestic sewage and render the treated effluent inappropriate for reuse in agriculture. Diversion

of reject brine to the sea throughout storm water collection system is a valid option to be considered by the industry.

- Reject brine resulting from inland BWRO can be pumped into a lined and sealed pit or pond and left to evaporate. In most of the GCC Countries, the prevailing warm weather and excellent solar radiation, and the availability of land at reasonable prices, enable the use of evaporation ponds.
- The concentration of reject brine into solid salts using solar evaporation may cost U.S $ 1.15 to 1.88 per 1000 gallons of desalinated water using 1985 U.S.$ value. The estimated cost of disposal of reject brine in an evaporation pond is 15% of the total desalination cost.
- The estimated cost for the disposal of reject brine by deep well injection ranges from U.S. $ 0.1 to 1.15 per 1000 gallons of desalinated water at the 1985 U.S.$ value.

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The Gulf Sea Basin: A Clean Water Supply Intake or A Dumping Sink?

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THE GULF SEA BASIN: A CLEAN WATER SUPPLY INTAKE OR A DUMPING SINK?

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ABSTRACT

Use of desalination technology renders sea water an unlimited supply of fresh water to energy-rich, water-poor regions such as states in the Arab Gulf. Seawater quality requirements in the Gulf basin are in conflict due to competitive uses. Although it is a source of raw fresh water supply, the sea is also a sink for urban and industrial wastes, polluted river discharges, and repeated accidental hydrocarbon spills. The western coastline of the Gulf contains the largest number and greatest production capacities of sea water distillation plants in the world. Sea water intakes as a point source of supply are at risk due to spills of oil and chemical pollutants, thus imposing hazards to health, and the environment. Pollutants' transport and mixing are affected by general circulation pattern in the Gulf basin, ocean dynamics at the intakes, water column depth, mixing process, and shoreline slopes. This paper discusses Gulf sea water circulation patterns and identifies pollution sources in the Gulf basin. An environmental risk model is also applied considering the characteristics of the water supply systems in the region. It is concluded that an integrated regional approach is needed, together with stringent environmental protection standards. This paper concludes that risk assessment should be adopted as a tool to be incorporated in decision-making affecting water resources & environmental planning in the region.

Keywords: Gulf Water Resources, Pollution Sources, Gulf Hydrodynamics and Risk Models.

INTRODUCTION

Along the coastline of the Arabian Gulf, the life of just about every resident is affected by its hypersaline waters in one way or another. Lapping the shores of Iran(l259 km), Iraq (90 km), Kuwait (350 km), Saudi Arabia (790 km), Bahrain (126 km), Qatar (700 km), UAE (650 km), and Oman (60 km), it is the prime source of a basic commodity, fresh water. Its subsoil contains vital hydrocarbon assets (oil and gas). Although the Gulf basin is relatively small in size compared to other oil producing seas such as the North Sea, twice its size, or the Gulf of Mexico, five times as large, it is the center of the world oil industry (Fig. 1). Onshore and offshore oil and gas fields are clustered around the Gulf coastline. Its oil reserves constituted 65% of the international constituted oil reserves in 1990 [1]. It is interesting to note that the Gulf basin harbours three strategic fluids: oil, gas and desalinated water. The largest onshore oil field (Ghawar), the largest offshore oil field (Safania), the largest non associated gas field (North field) and the largest desalination plant (Al Jubail) are all within Gulf circumference.

No single resource has such a tremendous impact on people, society and environment as oil. The flow-out of oil from the Gulf generated in return a flow in of what we call the 3M'S: Money, Men workers and Marine pollution. While It is possible to quantify Gulf oil revenues and labor immigrants with marginal accuracy, with marine pollution this is not the case.

In one lifetime, the stress on the Gulf marine environment has been immense due to intense activities in the coastal zone. Populations of coastal cities increased manifold after oil discovery with considerable expansion of commercial and industrial activities. The Arabian side of the Gulf supports a greater population than that of the Iranian side. Table (1) shows a comparison.

Table (1) Gulf population of coastal urban centers [15], [38]

Arabian Coast		Iranian Coast	
Country	**Population (year)**	**Cities & Towns**	**Population (year)**
Qatar	(640,846) (1995)	Bandarabbas	252,743 (1991)
		Hajabad	11,915 (1991)
Saudi Arabia (Eastern Province)	(3,030,765) (1985)	Bandar Lenge	19,367 (1991)
		Bandar Khamir	6,447 (1991)
		Bandar Kang	11,475 (1991)
Bahrain	(508,037) (1991)	Bastak	5,216 (1991)
		Gheshm	11,802 (1991)
Kuwait	(1,690,535) (1995)	Bousher	120,787 (1986)
		Kangan	12,298 (1986)
UAE	(2,230,000) (1994)	Mashahr	74,910 (1991)
		Imam Khomini	58,833 (1991)
		Korramshahr	34,752 (1991)

The water column of the Gulf basin supports a multi-uses with conflicting quality requirements. Being a water supply intake for desalination plants cannot coexist in harmony with its use as a dumping sink for waste pollutants. Waste pollution is a by-product of the urbanization and industrialization that is taking-place along the Gulf coastline.

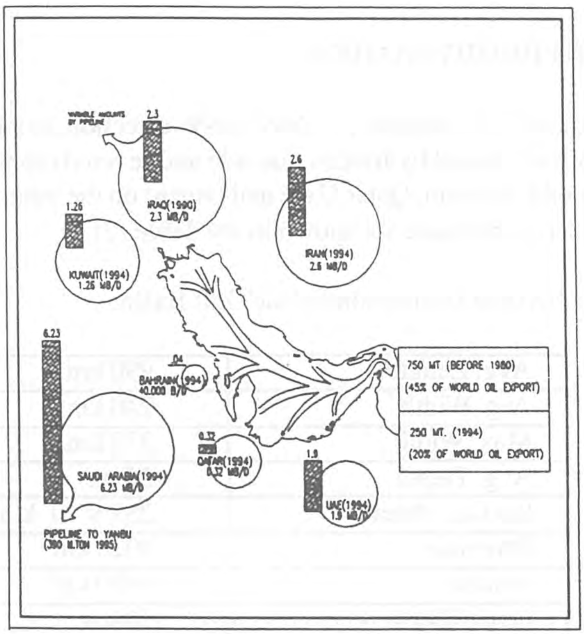

Fig. 1. Oil export from the Gulf

Considering Gulf waters as a primary fresh water resource one may consider the following:

1. The complete dependence on desalting sea water (Multi-Stage Flash Process) as the freshwater supply system for Arab Gulf States. The installed capacity is in excess of five Gega liter per day [2].

2. Gulf sea water is in use as environmental cleanser. Chemical, oil and oil derivatives are primary pollutants. Consequently pollutant source, thereby creating risk. An assessment of the level of environmental risk should be made.

3. The circulation system on the Arabian coastline, where desalination intakes are in place, has known features that impact pollutants' transport (vertically and horizontally) : 1. An anticyclonic pattern 2. shallow water depth. 3. minimum freshening sources (i.e. River inflow and fresher ocean water through the strait) with the exception of the Kuwaiti coast.

In view of the new international environmental perspective in the context of sustainable development after the Rio Conference, we need to examine the water - supply system in the Gulf region using a holistic integrated approach and point out to key questions that need to be raised for further research. This is the mission of this paper.

GULF HYDRODYNAMICS

The Arabian Gulf, oriented in a NW to SW direction, is a roughly rectangular body of water, shared by Iran on one side and seven Arab States (Iraq, Kuwait, Saudi Arabia, Bahrain, Qatar UAE and Oman) on the other. The main physical dimensions of the basin are shown in the Table (2).

Table (2) Physical Dimensions of the Gulf Basin:

Avg. Length	990 km.
Avg. Width	240 km.
Max. Width	338 km.
Avg. Depth	36 m.
Surface Area	239×10^3 km^2
Shoreline	4025 km
Volume	8630 km^3
Strait Width	56 km.
Strait Depth	100 m.

The Strait of Hormuz is the single outlet for exchange of mass and energy with the Indian Ocean. The bathometery of the Gulf (Fig.2) shallows on the flat Arabian side and deepens gradually toward the Iranian in the transverse section. Along the major-axis, the bottom topography is shallow at the head and deepens along the Iranian side toward the strait which is about 100m depth, then drops suddenly to ocean depth in the Gulf of Oman.

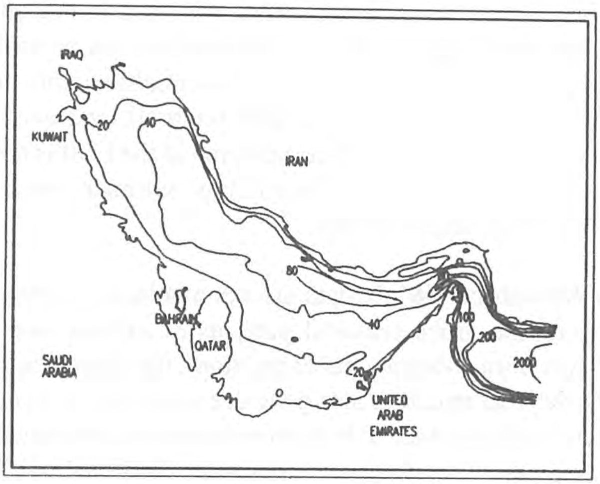

Fig. 2. Bathymetric map of the Gulf (depth in meters)

Advective and diffusive mechanisms - Gulf seawater flow is forced by Tides, Winds and a Pressure gradient due to density differences caused by the evaporation process. Its inflow is affected by the rotation of the earth (Coriolis Force) and modified by bottom topography (friction force). Scales of length, time, and typical current speed of the three forcing mechanisms are shown in table (3). The interaction between these forces is nonlinear and the significance of each component depends on the phenomenon under consideration.

Table (3) Gulf circulation Forcing Mechanisms with length, time and velocity scales.

Force	**Time Scale**	**Horizontal Length Scale**	**Typical Sea-Current Velocity**
Tidal Flow	< 24 hrs.	< 10 kin	> 100 cm/s
Wind Driven Flow	Days	Fetch Length	(100 - 30) cm/s
Density driven Flow (Residual Flow)	Seasonal	Basin Length	(30 - 10) cm/s

Tidal flow, the largest, is significant in vertical mixing, stirring, and transport due to stoke's drift but the tidal component in residual circulation is small [3].

Wind forcing is an important factor in the Gulf dynamic system. Ekman transport generated by wind stress on the water surface has a dispersion and drift mechanism, consequently it plays significant role in the movement of surface pollutants.

Density currents (residual flow) are important in the distribution and removal of pollutants from the Gulf region. Density driven flows are normally small but consistent in direction. Mixing processes and vertical structure are due to the forcing of tides, winds, waves, (surface and internal), and evaporation. The time scale for vertical mixing in the water column in the Gulf is about 3 days in winter and 17 days in summer [4]. The longer summer time is caused by stratification effects that inhibit mixing.

Hydrographic Structure - While data are not available to describe all areas during all seasons, the gross seasonal patterns of salinity and temperature structure are known from observational expeditions, the latest being Mt. Mitchell in 1992 [5]. The thermal structure along the deep axis during summer shows a strong themodine with a surface to bottom temperature difference of 11°C [6]. Typical mean summer surface temperature in the Gulf is about 33°C. During winter, the water column tends to be isothermal, and surface temperature shows a cooling trend towards the head of the basin (From 21°C at the strait to 15°C at the Kuwait coastal waters).

Unlike temperature, salinity distribution is fairly consistent throughout the year. It rises from 36.7% at the entrance to about 41% off the Saudi Shores. Fig. 4 and Fig. 5 show surface temperature and salinity for winter and early summer from Mt Mitchell Cruise [7]. Residence time is the ratio of volume of water to the volume of exchange rate assuming steady state and perfect mixing (in or out of the Gulf). It is estimated to be in the range of 2 - 5 years [8]. In addition to the uncertainty in these low rates of water exchange estimates, the strait of Hormuz has no constricting sill at its exit and thus the circulation through the strait is not restricted vertically. Consequently, the outflow currents carrying pollutants are flushed regularly with no restriction.

Water circulation - The physics of Gulf water circulation is not very well understood. However, general features of the circulation patterns are described from observational data [9] and modeling efforts [10].

The Gulf is similar to a land-locked sea, in that it has a negative water balance; evaporation exceeds the total input of fresh water [11]. Throughout the year, relatively low-salinity water from the Gulf of Oman enters the Gulf through the Strait of Hormuz and flows northward, against the prevailing winds, due to evaporative loss in this and area and buoyancy flux. The inflow of light water is deflected to the right due to the Coriolis effect, giving a surface flow along the Iranian coast. As these waters move north, they become cooler and more concentrated (saline), which produces a southward deep flow of denser water that creates subsurface current toward the Strait and out of the Gulf below incoming water.

Measurements and models so far agree on the followings features: (Fig. 5)

a. The inflow current along the Iranian coast is weakened by Shamal winds in the winter, but in the summer it strengthens and extends almost to the head of the Gulf.

b. A cyclonic circulation gyre fills the southern Gulf and is driven by the inflowing surface water through the Strait of Hormuz.

c. Runoff from Shatt Al-Arab in the northwest Gulf maintains a cyclonic circulation there that would otherwise be anti-cyclonic [12].

d. A southward coastal jet exists between the head of the Gulf and Qatar, and extends east of Qatar, depending on the wind.

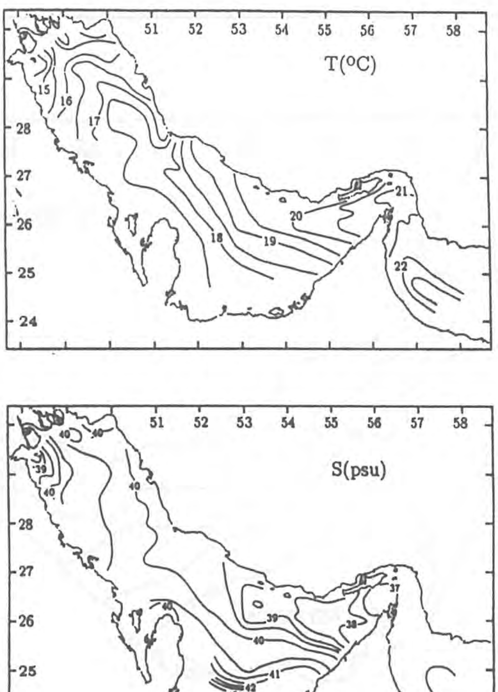

Fig. 3. Maps of surface temperature and salinity for winter [3]

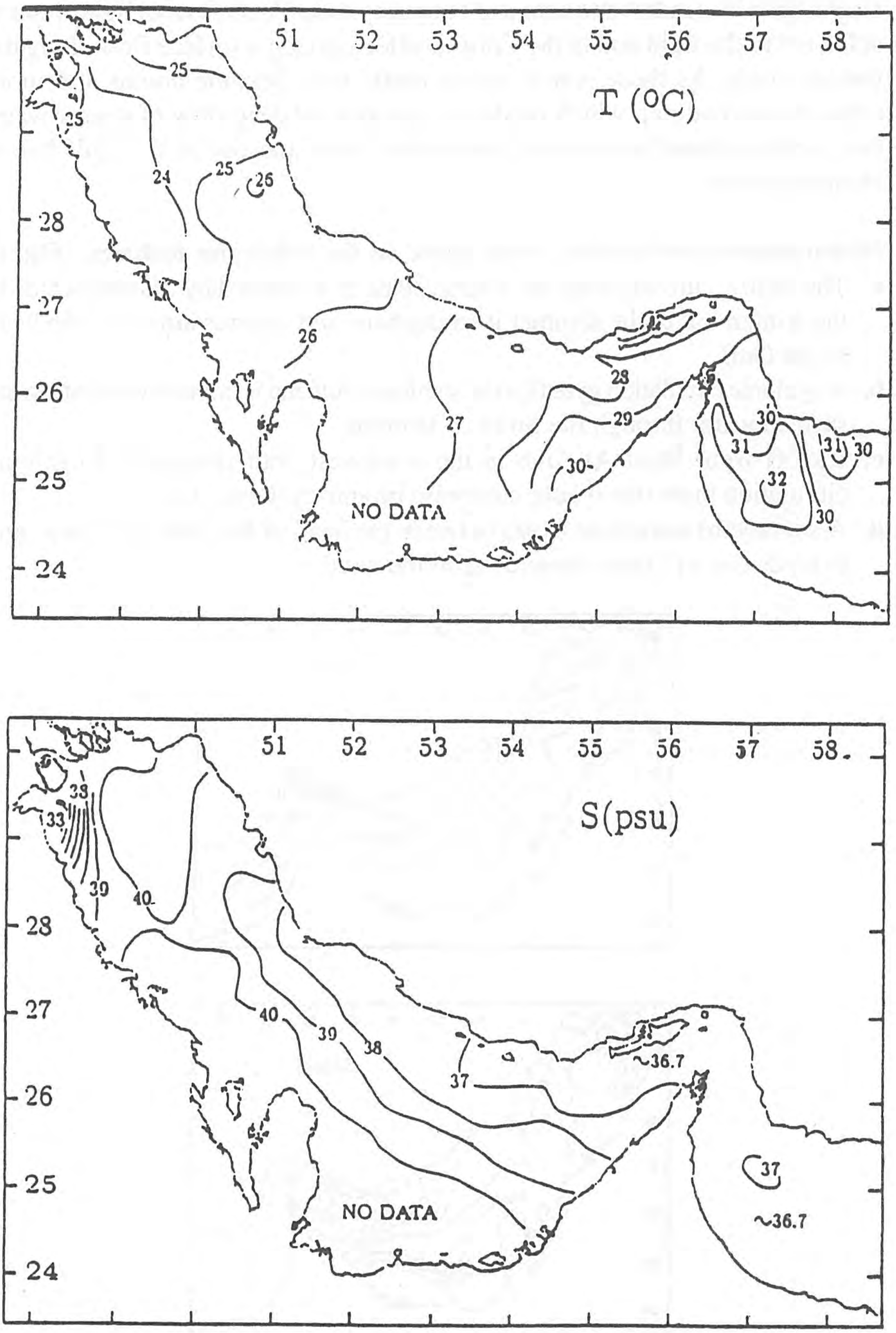

Fig. 4. Maps of surface temperature and salinity for early summer [3]

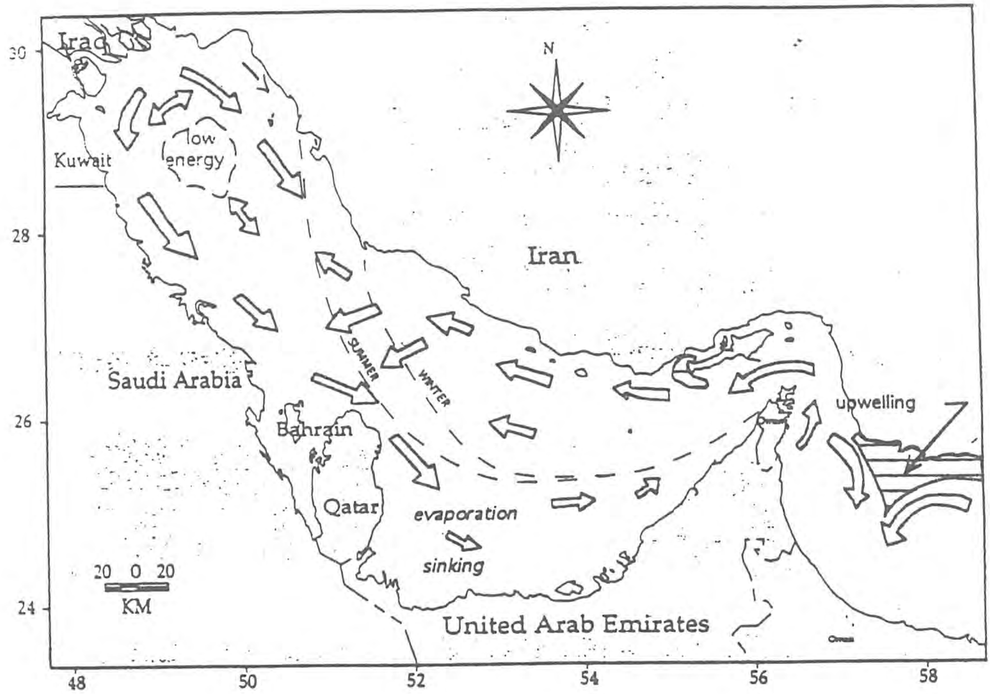

Fig. 5. Schematic of surface currents and circulation processes [3]

THE GULF BASIN AS A WATER-SUPPLY SOURCE

Natural Hydrological Cycle - The local hydrological cycle of the Gulf Basin is dominated by an invisible evaporation process. Estimates of evaporation vary from 144 cm/yr [13] to 500 cm/yr [14]. Total River inflow into the basin is equivalent to 46 cm/yr of depth. Annual rainfall is in the order of 7cm/yr. Low rainfall is due to hyper-arid conditions and the sparseness of natural vegetation. Ocean evaporation rate is a derived quantity that is estimated theoretically, while rainfall and river in-flow is quantified using in situ measurements. River inflow is the usable freshwater supply source. Therefore, it is plausible to put the three terms in equivalent river inflow terms as shown in table (4). The average components of the freshwater budget of the basin (Evaporation, river inflow, and rainfall) can be partitioned among the three terms approximately in the order of (60 : 5 : 1) respectively.

Table (4) Annual mean of Evaporation, runoff and rainfall in the Gulf basin.

	Annual Mean (cm/yr)	River Inflow Equivalent (M^3/s)
Evaporation	140 - 500	10913 - 37893
River Runoff	10 - 46	758 - 3488
Rain	3 - 8	227 - 606

The strong sea-air interaction of evaporative fresh-water in the basin makes little contribution to the local rainfall, as the complex dynamic hydrological cycle has no recognition of geographic boundaries. It is clear that rainfall makes a small contribution to the Gulf freshwater budget. Its distribution is not uniform, and the flat Arabian shoreline has no significant rainfall runoff component, in relative comparison to the mountainous Iranian side.

The major river inflow system that drains into the basin is shown in table (5). These rivers are all on the Iranian side, except Shatt-Al-Arab which is shared along the boundary between Iraq & Iran. The small stream of Mehran (5 m^3/s) and Mirab (9 m^3/s) are also present close to the strait.

Table (5) Rivers inflow into Gulf coastline [15].

River's Name	Discharge (M^3/s) (Flow Station)
Shatt - Al - Arab	708 (Basra)
Karoon	748 (Ahwaz)
Jarahi	43 (Shadgan)
Hendijan	203 (Deh moila)
Hilleh	444
Mand	1387

Shatt - Al - Arab is the major fresh water inflow that drains into the Gulf basin at the head. It is a combination of three rivers: the Iraqi rivers Tigris and Euphrates together provide an annual average of 708 m^3/s and the Iranian river Karoon adds 748 M^3/s. This gives the total average inflow of Shatt-Al-Arab as 1456 m^3/s [16]. This freshening source is evident in the salinity isohaline toward Kuwaiti waters, as it is deflected to the right due to the Coriolis effect. The largest runoffs of Shatt-Al-Arab and Karoon, are the only navigable and drinkable rivers along the Iranian coast. Dams upstream have reduced their volume discharge into the Gulf, and the quality may deteriorate due to increased pollutant sources. All other small rivers have a high salt content due to soil conditions. The most significant marshes are those of the Shatt-Al-Arab. This marsh system acts as a pollutant sink and filter the pollutants contained in the runoff. The disruption and draining of this marsh may increase total pollutants into the Gulf.

Several attempts are available to quantify fresh water scarcity. If we denote Scarcity Index (S.I) as :

$$(S.I. = C/R \times 100)$$

Where C is the annual consumption and R is the annual natural renewable supply for a country, then 100% is the limit. Countries which consume annually more freshwater than is naturally replenished are facing water deficiency. A vivid example of this reality is the GCC states. Table (6) shows S.I. indices for GCC states, Iraq and Iran for the late 1980's. It is expected that S.I. is on the rise as water demands are rising and will continue to increase following population growth, urbanization, industrialization and agricultural policy. Thus, tapping seawater, the unlimited source, via desalting technology is the only viable option for hydrocarbon-rich, freshwater-poor Arab Gulf States.

Table (6) S.I. Indicies for the Gulf states [17].

Country	S.I.
Qatar	174
UAE	140
Saudi Arabia	106
Kuwait	> 100
Bahrain	> 100
Iraq	43
Iran	39

Man-made Hydrological Cycle - Sea water is the source of fresh-water in the natural hydrological cycle. River-runoff and rainfall are the only components human beings can interact with for the fresh-water supply system. The Arab Gulf States with the exception of Iraq have to depend on technology to overcome the natural scarcity of this natural resource. Desalination technology is a man-made copy of the hydrological cycle (Evaporation, Condensation and Collection). It is the hydrocarbon economy (oil and gas) that provides energy and funds to "manufacture" fresh-water to flow. Desalination plants are located on the Arabian coastline which is deprived of surface water and the continuous flows of distillate water from these plants may be considered as a man-made river to supply domestic and industrial demands. While the Iranian coastline has freshwater river that flow into the Gulf, man-made rivers along the Arabian coastline flow out of Gulf basin to augment scarce natural freshwater supply systems. As with any industry, supply can be added with more production units. Existing desalination plants (Location and Capacity) around the Gulf are shown in Table (7).

Table (7) MSF plants along the Gulf Coast [19], [20], [35], [36], [37] :

Location	Fresh-Water Capacity (m^3/day)	%	Equivalent River Outflow (m^3/s)
KUWAIT	(1,050,126)	20%	12.15
Al Doha Plant	627,348		
Al Shoeikh Plant	68,190		
Al Shaiba Plant	136,380		
Al Zoor Plant	218,208		
SAUDI ARABIA	(1,698,874)	33%	19.66
Al Jubail Plant	1,094,696		
Al Khobar Plant	422,347		
Al Khafji Plant	68,181		
Gazlan Plant	22,730		
El Grays Plant	45,460		
"Safani, Tanajib & Ras Tanura Plants operated by Aramco"	46,460		
BAHRAIN	(113,650)	2%	1.32
Sitra Plant	113,650		
UAE	(1,766,580)	34%	20.45
Almirfa Plant	76,800		
Abu Dhabi Plant	57,660		
Umm Alnar Plant	397,500		
Al Taweelah Plant	476,160		
Dubai Aluminum Plant	113,900		
Jebel Ali Plant	561,260		
Sharjah Plant	83,300		
QATAR	(309,128)	6%	3.58
Ras Abu Aboud Plant	36,368		
Ras Abu Fantas Plant	272,760		
IRAN	(260,609)	5%	3.01
Boushher	260,609		
TOTAL	**5,198,967**	**100%**	**60.17**

Total water desalinated from all the plants along the Gulf coast is over 5 million per day which is approximately 43% of word-wide desalination capacity of sea water in 1994 (over 12 million m^3/d [18]. This total volume discharge outflowing through the plants, which is an equivalent river runoff of about 60 is very small compared to the natural hydrological cycle components of the Gulf basin in table (4). It is comparable to small river discharges like Limpopo of South Africa (54 m^3/s) or Assiniboine river in Canada (51 m^3/s) [19].

Saudi Arabia is the largest producer of desalinated water in the world, as it is also the largest producer of oil. Its production from the Gulf accounts only for about 13% of its total desalination capacity [20]. Most of its desalination plants are located along the Red sea which has a different hydrodynamic systems, Although the Al Jubail desalination plant of Saudi Arabia is the largest in the world, UAE is the largest producer of desalinated water from the Gulf Sea as a source of Fresh-water supply (34%).

Raw water sources are chosen according to: Availability, reliability of quantity and quality and proximity to demand of consumers. Desalting the unlimited quantity of seawater produces a high quality of freshwater (Highest pure form, less than 30 PPM). The Thermal process of desalination (MSF type) has proved so far to be very successful in the Gulf region and a reliable source of freshwater supply. RO using seawater as the prime feed is currently operational in Bahrain, although there are some difficulties due to high silt content in the coastal waters which might be related to the shallow depth of the Gulf along the Arabian coastline with the soft substrate ecosystem.

Although desalination has emerged as a dependable source of potable water, it is a point source of supply that is prone to many risks, Table (8) shows the main perils emanating from energy-producing facilities [21]. It shows clearly that although insurance coverage may be extensive, pollution risks are not on the agenda.

Table (8) Hazards and basic covers in the insurance of energy systems [21].

Property Covers
Fire Explosion, Chemicals Lightning Plane Crash Faulty Products Faulty operation Explosion, physical Short Circuit Leakage Windstorm Snow, rain, hail Flood, inundation Frost, ice Earthquake, landslide, subsidence Deliberate damage, sabotage Strike, riot, civil commotion War, nuclear energy Damage during transportation

THE GULF BASIN AS A DUMPING SINK

The Gulf basin has always been the sink for anthropogenic pollutants. As is the case with any seawater, it is in use as an environmental cleanser, because of its natural ability to dilute, transport and transform pollutants. Pollution of the Gulf basin may occur in one or more of the following ways:

Aesthetic Pollution - The appearance of flotsam, solid wastes, untreated sewage and litter is unattractive. Litter is an increasing problem in the Gulf from both mainland shores and ships. It is estimated that 1.1 - 2.6 Kg/person/day of plastic waste is generated on ships, much of which is thrown overboard [22].

Thermal Pollution - Gulf marine water is used by the industries as a cold reservoir for plants' thermodynamic cycle. Hot discharges like saline discharges modify ambient water density distribution (active tracers) and increase the impact of other pollution. In winter, thermal pollution probably promotes biological activity. In summer, it has a stronger impact (critical time). Shams Eldin (1994) reported that in Gulf Water biological activity on biofilm thrives at 33 - 34^o (Water temperature in Summer) and abruptly ceases around 38 - 39^{o}C [23]. Data on thermal pollution in the Gulf coastal areas are not available, since industries do not reveal such information. For MSF plants, cooling water discharge mixed with the concentrate is a raw water composition at a more concentrated level, since pretreatment chemicals have relatively low levels (< 10 PPM). Concentration Factor (CF) depends on the fractional process water recovery according to [24]:

CF = 1/(1 - Recovery)

For MSF, recovery based on feed is theoretically about 30%, but in practice it may be lower depending on environmental factors (salinity and temperature of seawater) and efficiency of distiller. A typical seawater flow diagram for MSF distiller is shown in Fig. 6.

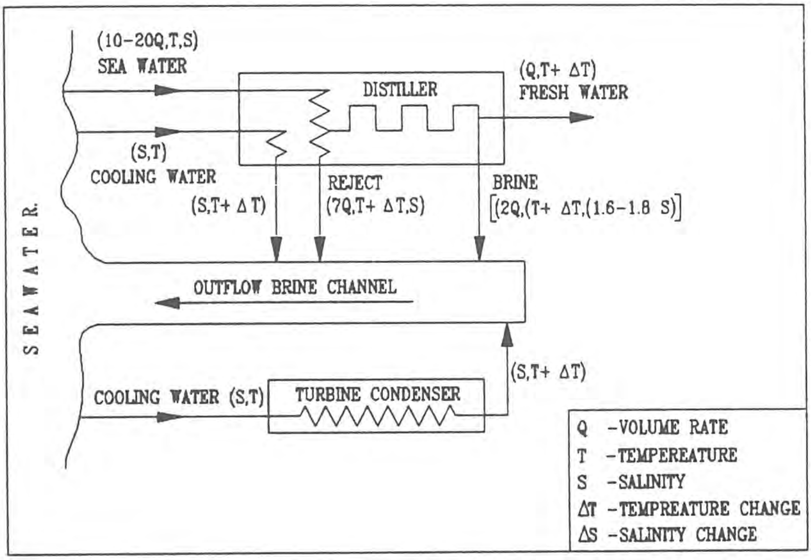

Fig. 6. Typical seawater flow diagram in MSF distiller.

The outflow for Umm Al Nar (UAN) station of Abu Dhabi is about (10M m^3/d) partitioned among brine, reject and thermal discharges as a volume percentage in the range of (11%, 37% and 57%) respectively [25]. Concentrate possess negative buoyancy in opposition to thermal discharge that has positive buoyancy in accordance with equation of State. Therefore, their combination in the brine outflow channel maximizes dilution in the initial mixing zone and achieves discharge densities close to the ambient. This is a merit of MSF Technology.

Salinity at the UAN intakes was reported as 46.26 parts per thousand, PPT. At 50m from the outfall, it was 47.18 PPT, and the volume decreased to 46.61 PPT at 700m down stream from the discharge point [26]. Natural salinity perturbation is in the order of 1 ± PPT of the ambient which appear as the benthic environment tolerance [27]. The impact of increased salinity and / or temperature on the marine environment is a function of the local ecosystem (i.e. Increasing temperature of water decreases dissolved oxygen).

Sewage and Nutrients - Most of the Gulf states are moving toward total treatment of sewage, except Iranian towns on the coast where domestic effluents are discharged into the sea and into the Karun river. ROPME (1993) reported that a total of 1.6x $10^8 m^3/yr$ of treated and untreated sewage is discharged to the Gulf [28].

Oil Pollution - Oil pollution in the marine environment came from major sources: refineries, oil spills, ballast water and water formation from oil fields.

Presently GCC countries have 18 refineries the plants with a total capacity of more than million b/d [29]. Refineries are source of oil hydrocarbons, phenols and sulfides. It has been estimated that the annual input of oil hydrocarbons to the sea from refinery processes is 2,377 Tons per year [30]. This estimate excludes data for Iran, Iraq, Qatar and UAE. The estimate at present and including all Gulf States is expected to be higher.

The Gulf marine area has been exposed to major oil spills due to Gulf wars. The present sunken vessels in the northern end containing oil represent additional potential threats for the area.

Crude oil and products account by weight for nearly 50% of international seaborne trade in the last 15 years. By vessel type, oil tankers represented 37.7% of the 1994 world total tonnage [31]. In 1994, 20% of world oil export passed the strait of Hormuz. Although new super tankers have segregated ballast water, old tankers release ballast water prior to receiving new oil cargo. This ballast contains concentrations of oil hydrocarbons.

Toxicity - toxic substances constitute a serious form of pollution for the aquatic environment (Biota, Sediments and Water). From a human health perspective. Trace metals of greatest concern are lead, mercury, arsenic and cadmium. Trace elements not particularly toxic to human beings are, nonetheless, highly toxic to aquatic life. (such as copper, silver, selenium, zinc and chromium). Sources of metal pollution are domestic effluents and industrial processing of ores and minerals.

In addition to the risks posed by each separate chemical, there is an unquantified risk arising from their synergetic interactions.

Synthetic and industrial organic pollutants are acutely toxic and very diverse (over 100,000 compounds), all with different derivatives, different solubilities and different persistence. Yet an important aspect of organic chemicals is that many are thought to be hazardous to aquatic life and human health at concentrations much lower than those that can be reliably measured by common analytical methods [32]. The most important classes of organic micropollutants from a drinking water perspective are: Pesticides (i.e. DOT), herbicides, PCBS, PAHS, Organic Solvents, Phthalates, and Disinfective by-products (DBPs).

In the industrial world there is growing concern over the link between cancer, birth defects, al chemicals miscarriages and organic chemicals in drinking water. The risk posed by individual chemicals in drinking water are relatively low, but cumulative effects of long-term exposure may be larger and cannot be well quantified. Most of these pollutants come from industrial activities such as petroleum refining, the production of iron, steel, pesticides and fertilizers and the manufacture of synthetic chemicals and products i.e. in 1992, the GCC production capacity of the petrochemical industries was over 11 Million Tons of petrochemical products (excluding fertilizers) and plastics' annual production capacity is about one million [33]. Unfortunately, no data is available to quantify the effects of the waste of such industries on the Gulf marine ecosystem.

Radioactive, Chemical and Biological Warfare Agents - clearly these cannot be dispersed in the environment without great danger to human beings, as they are designed to be exceedingly toxic in very small doses. Radioactive contamination of drinking water may be naturally occurring or from accidents. In the Gulf, the press in the early 1980's reported stories of unknown ships dumping unknown waste in the marine environment. The Gulf waters have been and still are exposed to active military activities in the last 17 years and it is not known what the environmental consequences are.

THE ENVIRONMENTAL RISK MODEL

The theory of risk is essentially a special case of the theory of random (stochastic) processes. Environmental risks are the reality of modern societies. The question then is not whether or not a risk source exists, but whether or not it is under control. Wilson (1991) developed an environmental risk model from a management prospective under the objective of "maximum feasible reduction of environmental risk". [34]. The modified model applied to the Gulf marine system as a water supply intake is shown in Fig.7. Risk sources, control mechanisms, transport mechanisms and risk target are components of a cohesive risk system.

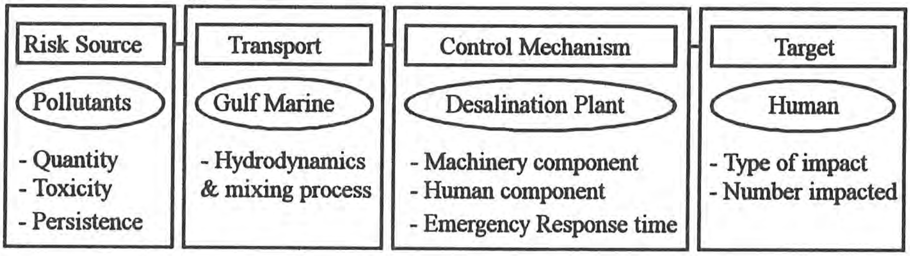

Fig. (7) Environmental risk model for desalination plant.

The risk source - sources of contaminants are risk sources with differential risk factors depending on persistence and toxicity. Persistence is related to biodegradability for hazardous substances (for non-radioactive risks). Toxicity is determined from the dose-response relationship. For carcinogenic response, there is no safe dose. For non-carcinogens, environmental toxicology recognizes some threshold levels defined by the standards.

Transport mechanism - without a transport medium the risk source cannot be brought into proximity to a water supply intake. In the case of desalination plants: hydrodynamics the circulation of the sea and mixing processes at the intakes are vital factors in understanding not only the transport, but also the dilution processes for passive tracers.

Control mechanism - The control mechanism is the means by which a risk source is controlled. A desalination plant is the primary control mechanism via the human and machine components operating the plant. The human element depends on awareness, training, equipment and discipline.

The target - The human target is of the greatest concern. The analysis in this case is governed by the negative default principle "i.e. worst case scenario". The mitigating factors are the efficiency of control mechanisms and the probability of failure of the control mechanism.

CONCLUSIONS AND RECOMMENDATIONS

Looking back at the puzzled title question of this paper, one comes to the following conclusions :

1. The Arab Gulf states, with the exception of Iraq, are totally dependent on desalination of seawater for their freshwater supply sources. The crux of the problem at present is water quality rather than water quantity. Microbiologic contamination, the traditional water supply concern, is not the issue with desalination supply. Chemical contaminations, hydrocarbons and their derivatives in the prime water supply source pose risks that should be considered.

2. Production of freshwater via desalination technology is a manufacturing process. Strict quality procedures (i.e. ISO - 9000) should be followed in the plants since toxic pollutants of a persistent nature exist in the Gulf waters.

3. Gulf basin use as a dumping sink for anthropogenic pollutants should not be allowed to continue. Declaration of the Gulf as "a marine sanctuary" with a zero-discharge policy probably is the first step in a regional strategy to protect this vital body of water.

4. Understanding hydrodynamic systems and mixing processes in the Gulf basin is vital in following pollutants' fate.

5. A coastal zone management strategy should be formulated between all Gulf states, inclusive of river-basin management for Iraq and Iran. It must entail guidance towards complex changes in the Gulf marine system and provide a framework that can help decision makers to solve current and future problems.

6. The issue at hand is unique, complex and controversial. It requires a multidisciplinary approach that needs the expertise of environmental and chemical engineers, health professionals and marine specialists, and new standards should be formulated.

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Measurement of Low-Level Emitting Nuclides of Uranium and Thorium in Groundwater by High Resolution Alpha-Spectrometry

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MEASUREMENT OF LOW LEVEL α-EMITTING NUCLIDES OF URANIUM AND THORIUM IN GROUND WATER BY HIGH RESOLUTION ALPHA-SPECTROMETRY

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ABSTRACT

Chemical analyses are usually the major means for quality evaluation of ground water. They frequently include the assessment of hardness and other dissolved salts. However, radio analysis is seldom made even though radioactive isotopes may be detected in ground water Their occurrence is due to the possibility of the leaching of the salts of their elements from rock-bearing strata. Uranium is chemically toxic to the kidneys, Generally, thorium compounds have low solubilities in ground water and the ingested thorium is poorly absorbed by the blood. Due to the high toxicity of the natural radioisotopes the regulations of the Saudi Arabian Standards Organization (SASO) and the U. S. Environmental Protection Agency (EPA) established a very low maximum contaminant levels in drinking water. Guidelines values of 20 μg/L and 5 pCi/L are established for natural uranium and the bone seeker combined radium (^{226}Ra + ^{228}Ra), respectively. Although the regulations normally do not require the measurement of thorium in drinking water, injected radioactive dose of thorium has helped to cause leukemia, bone sarcoma and other serious diseases. A sensitive radioanalytical techniques are required to meet the requirements of these regulations. Evaluation of an advanced radioanalytical technique for determining uranium and thorium using high resolution α-spectrometry is carried out. 'The lower limits of detection (LLD) for the four detectors of the operating (α-spectrometry system ranged from 0.026 to 0.082 pCi/L for 18 hours counting time. The efficiencies of the detectors in the chosen configuration ranged from 26.6 to 32.6%, with a quite satisfactory resolution of about 3 5 keV for the 3.999 MeV alpha particles. The precision for measurement of uranium in standard water samples of levels around the guide value for natural uranium of 20 μg/L (6.61 pCi^{238}U/L) was about 5%. The accuracy at this level was less than ±10%. The precision and accuracy for measurement of ^{232}Th at levels around 4 pCi/L were 6.5% and less than ±8%, respectively. This technique, together with another already tested technique for determining the α-emitting nuclides of radium, were used to investigate some representative ground water samples collected randomly from different places.

Maximum levels of 1.42 μg/L and 3.61 pCi/L were recorded for natural uranium and ^{226}Ra, respectively. Natural thorium has not detected in the investigated samples. The detected radioactivity levels were safe and below guideline values for all the investigated samples.

Key words: Ground Water / Uranium / Thorium / radioactivity / α-spectrometry.

INTRODUCTION

Ground water plays a key role in the life of communities that depend on it for their domestic or agricultural needs. Chemical analyses are usually the major means for quality evaluation of ground water. They frequently include the assessment of hardness and other dissolved salts. However, radioanalysis is seldom made and not many laboratories actually perform testing radioactivity even though natural radioactive isotopes may be detected in ground water. Their occurrence is due to the possibility of the leaching of the salts of their elements from rock-bearing strata. ^{238}U, ^{235}U, ^{234}U, ^{232}TH, ^{226} Ra, ^{229}Ra and radon are the naturally occurring radionuclides, and all or some of these radiotoxic nuclides may be present at trace levels in ground water. Their concentrations are controlled by a variety of chemical and physical processes. Therefore, ground water plays an important role in the migration and redistribution of the elements in the earth's crust, and must be investigated for those highly radiotoxic nuclides.

^{226}Ra is the most radiotoxic and wide spread long-lived isotope present in ground water. Closely following the radiotoxic behaviour is ^{228}Ra. Both isotopes present a radiological hazards due to their ability to replace calcium in bone structure[l]. The regulations of the Saudi Arabian Standards Organization (SASO) and the U. S. Environmental Protection Agency (EPA) Interim Primary Drinking Water established a maximum contaminant level for ^{226}Ra and ^{228}Ra of 5 pico Curie/liter (pCi/L) and for ^{226}Ra of 3 pCi/L [2,3].

The chemical toxicity of uranium is higher than its radiotoxicity. Uranium is chemically toxic to the kidneys. Its renal toxicity in man and animals is thoroughly described in a review by Hodge [4]. The EPA concentration limit for uranium is of 20 μg/L, based primarily on prevention of chemical toxicity to kidney.

Generally, thorium compounds have low solubilities in ground water and the ingested thorium is poorly absorbed by the blood which has a transfer factor of about 0.02% for all thorium compounds. Bone is the main target tissue and retains 60 - 75% of transferred thorium and the remainder is in the muscle [5]. Although the EPA regulations normally do not require the measurement of thorium in drinking water, injected radioactive dose of thorium has helped to cause leukemia, bone sarcoma and other serious diseases [6,7]. The toxicity has only been correlated to the radioactive dose and not to the chemical compound [8].

Very sensitive radioanalytical techniques are required to investigate ground water and to follow the releases of these highly radiotoxic nuclides into the environment in a purpose of protecting man from their hazards. Except ^{228}Ra, all these nuclides are a-emitters and may be estimated by α-spectrometry. ^{228}Th ($t_{1/2}$ = 1.9$_y$) and ^{224}Ra ($t_{1/2}$ = 3.64 d) are α-emitting daughters of ^{228}Ra and their presence in the sample is considered as a strong evidence for the presence of their parent ^{228}Ra (P-emitter with $t_{1/2}$ 5.7 y).

In a previous work [9], evaluation of a technique [10] for determining the a-emitting nuclides of radium in water by α-spectrometry is carried out. The present work is planned to test and evaluate advanced radiochemical technique [10] for determining uranium and thorium in ground water using high resolution a-spectrometry. Both techniques are generally based on the chemical separation of each element of these a-emitters from all other components of the sample and prepared for measurement.

EXPERIMENTAL

Chemical Reagents

Analytical grade chemicals were used. All solutions were filtered after preparation through well washed 0.45 gm membrane filters, and stored in polypropylene bottles. Double distilled water was used along the whole work.

Standard reference materials

^{238}U and ^{232}Th standard solutions were prepared by dilution from stock solutions of both elements. The stock solutions were prepared in the laboratory from analar uranyl and thorium nitrate salts. Tap water was used for the dilution of the standards to check the efficiency of separation of uranium and thorium from tap water salts and hence the resolution in the spectrum. A tap water sample was processed and prepared for thorium and uranium measurement to be considered as the background of the α-spectrometry system together with tap water and associated chemicals.

^{232}U and ^{133}Ba standard reference materials, purchased from the National Institute of Standards (NIST), U.S.A., under the code numbers ^{4324}A and ^{4251}C, respectively, were diluted and used as tracers for efficiency and chemical yield determinations for uranium and radium, respectively. In the analysis of thorium, owing to the complexity of the alpha-decay scheme of ^{239}Th, one of the isotopes contained in the sample was used as a tracer. Previously, it is necessary to know the activity ratios of the isotopes. So, two samples have to be measured, with and without tracer. ^{228}Th equilibrium with its parent ^{228}RA (SRM ^{4339}A, from NIST) was used in this study.

Summary of the sample preparation

The sample preparation is based on the chemical separation of each element from all other components of the sample using anion exchanger and coprecipitation under certain conditions to produce fine crystals to minimize self absorption of the aparticles in getting out of the crystal lattice. The precipitate is mounted on a membrane filter and measured using α-spectrometer. 150 mL water sample is evaporated to about 1 mL and dissolved in cone. HCl to obtain 20 mL of 10M HCl. To trap any possible uranium the solution is passed through a small separation column (5 mL bed volume, from BioRad) packed with the Cl-form of anion exchanger (BioRad AG 1-X8). The column was preconditioned by passing 20 mL of 10M HCl. Uranium is eluted by passing 20 mL of 0.1 M HCl to obtain the uranium fraction. The effluent is evaporated to near dryness and 1 mL of cone. HNO_3 is added with evaporation again to near dryness. Addition of HNO_3 and evaporation to near dryness must be repeated twice. The sample is then dissolved in 20 mL of 8M HNO_3 and passed through another similar separation column packed with the same exchanger but preconditioned with 20 mL of 8M HNO_3 to change the exchanger from Cl-form to NO_3-form. The second column of any thorium fraction. The later effluent contains any possible radium together with the other components.

Uranium and thorium fractions were prepared for counting [12] by their coprecipitation with trace amounts of Nd^{3+} as fine fluoride particles and mounted on 0.1 μm polyethylene filter and measured using α-spectrometer. The effluent containing radium in actual samples is subjected to chemical processing to separate radium and prepared for counting [13,14].

Apparatus

A Canberra model 7404 "QUAD ALPHA" α-spectrometry system was used. The system consisted of four 450 mm^2 silicon surface barrier detectors located in the same vacuum chamber (with partition). Each detector has its own individual pre-amplifier and linear amplifier as will as detector bias and gain adjustment. The amplified output of the four detectors from the QUAD ALPHA system was sent to a Canberra series 35 plus multichannel analyzer (2048 channel total memory). The MCA had an internal mixer/ router so that the output of each detector was stored in 512 channels of the memory (one quadrant). The lower limits of detection (LLD) for the four detectors of the operating a-spectrometry system were ranged from 0.026 to 0.082 pCi/L for 18 hours counting time. The efficiencies of the detectors in the chosen configuration were ranged from 26.6 to 32.6%, with a quite satisfactory resolution of about 35 keV for the 3.999 MeV alpha particles.

A motor-driven, single-stage mechanical vacuum pump (out-type) provided adequate evacuation (10^{-2} mm Hg) of the vacuum chamber of the system.

A 50-mL conical polysulphone filter funnel for 25 mm ϕ filter (Gelman Science Inc., Arm Arbor, MI, No. 4204) with a stainless steel support screen (Gelman, No. 79791) was used for mounting all precipitates for α-spectrometry.

Results and Discussion

The α-spectrometric data in Table 1 for measurement of ^{238}U in the standard solutions show that the precision in the studied activity range (0.3 to 25 pCi/L) lies between 16 and 3% for low and high activities, respectively. At the activity levels around the SASO and EPA guide values of 20 µg U/L (6.6 pCi ^{238}U/L), the precision obtained was about 5%. The accuracy (deviation from the middle of the confidence interval) ranges from -6 to +20%, and at the concentrations around 20 µg U/L the accuracy was less than ± 10%.

The data given in Table I for measuring ^{232}Th in the same standard solutions show that the precision in the studied range (0.2 - 1 0 pCi/L) lies between 20 - 5% for low and high activity levels, respectively. At the activity level of 4 pCi/L the precision was about 6.5%. The accuracy was ranged from - 14 to 30% in the very low studied range and was less than +8% at the activity level around 4 pCi/L ^{232}Th. Therefore, the sensitivity of the system for analysing uranium and thorium in the water samples was satisfactory. Large sample volume (150 mL) and long counting time (18 hours) routinely used during analysis and the low values of lower limit of detection gave this satisfactory performance.

Table 1: α-Spectrometric data for ^{238}U and ^{232}Th in various standard solutions of different activities.

Sample No.	Activit of ^{231}U,pCi/L ± la		Activity of ^{232}Th, pCi/L ±1a	
	Measured	Conf. Inter.	Measured	Conf. Inter.
1	23.31±-0.79	24.63-25.17	9.53±-0.43	9.95-10.10
2	17.12±-0.64	17.56-18.02	3.82±-0.25	3.95-4.05
3	11.30±+-0.50	10.37-10.67	1.87±-0.15	1.98-2.03
4	3.91±0.24	3.48-3.64	1.04±-0.10	0.99-1.01
5	1.94±0.17	1.74-1.81	0.69±0.08	0.79-0.81
6	0.43±-0.07	0.35-0.37	0.39±0.06	0.39-0.41
7			0.26±-0.05	0.19-0.21

Some representative ground water samples were subjected to extensive investigation for natural radioactivity. The results are given in Table 2. Some levels of ^{226}Ra and ^{224}Ra are detected with concentrations up to 3.61 ±0.75 and 1.15±0.32 pCi/L, respectively. ^{238}U and ^{234}U are detected in some samples with levels up to 3.29±0.31 and 4.85±0.36 pCi/L, respectively. Those values are equivalent to about 10 µg of natural uranium (1 pCi $^{238}U \cong 3.03$ µg ^{238}U and 1 PCi $^{234}U \cong 1.6 \times 10^{-4}$ [µg ^{234}U). Neither thorium ^{232}Th nor ^{230}Th generated from ^{228}Ra, was detected in some samples with maximum level of 2.85±0.32 pC/L. Those values indicate that all concentrations are of safe levels.

Studies have shown, however, that softening have the potential for uranium reduction in drinking water [15]. It was also found that the levels of radium, as an alkaline earth metal and have similar behaviour to calcium, were highly reduced during softening processes [16].

Table 2. Content of natural α-emitting nuclides in some representative ground water samples

Sample No.	Activity, pCi/L±(y						
	^{238}U	^{234}U	^{232}Th	^{230}Th	^{228}Th	^{226}Ra	^{224}Ra
1	<LLD	<LLD	<LLD	<LLD	0.13+-0.08	1.46±-0.19	0.12±-0.08
2	<LLD	<LLD	<LLD	<LLD	<LLD	0.08:1-0.06	<LLD
3	<LLD	<LLD	<LLD	<LLD	2.85+-0.32	3.61:1-0.75	1.15±-0.32
4	<LLD	<LLD	<LLD	<LLD	<LLD	<LLD	<LLD
5	0. 14:E-0.04	0.10±-0.04	<LLD	<LLD	<LLD	<dLD	<dLD
6	3.01±-0.23	4.98±-0.30	<dLD	<LLD	<LID	0.20±-0.05	0.03±-0.02
7	3.29±-.0.31	4.85±-0.36	<LLD	<LLD	0.53+-0.27	2.37±1.26	0.47±-0.28

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Community Participation-A Mean for Improving Rural Environment—A Case Study

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COMMUNITY PARTICIPATION—A MEAN FOR IMPROVING RURAL ENVIRONMENT—A CASE STUDY

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ABSTRACT

Egypt is faced by the immigration of rural population to the urban areas, thus increasing the pressures on the existing facilities and adding to the crowd in such areas. The main reasons behind such immigration is the lack of services and job opportunities in the rural parts of Egypt, resulting in poverty problems. The most critical issue in the rural areas in the country is the lack of proper potable water supply. Potable water supplies in Egypt are generally satisfied from two sources, Nile surface water and groundwater. In the rural areas, the major portion of the potable water supply is driven from locally pumped groundwater, either from medium capacity wells or from hand dug wells. The medium capacity wells are owned and operated by the local units (government); while the hand dug wells are owned and operated by the individuals. Both types of supplies are suffering from pollution due to the poor installation and operation of the facilities. Due to the limitations imposed on the future expansion of surface water supplies in addition to the high costs of treatments, the Government plans for future domestic water supplies are highly based on the availability of groundwater. Such plans can not be achieved unless proper conservation programs are undertaken to ensure the sustainability of the groundwater resources, in terms of quality and quantity, which dictates the protection of groundwater from pollution and control of present groundwater withdrawals. These measures, although seems to fall under the responsibility of the government, they can never be achieved unless the public is aware of the problems and share in the implementation and enforcement of the protection laws. For this purpose, a public awareness campaign (PAC) has been undertaken at a local unit located within the Greater Cairo sub-urban area. Audio-visual as well as simple drawings have been used to illustrate the causes of groundwater pollution and related health impacts. The PAC has been carried out in two gatherings, one for the officials and unit leaders, and the other for the women of the community. People and officials showed high concern about the poor water quality, indicating that it was not only the poor well facilities but also the poor operation of the public water supply system. Both the people and the officials were ready to contribute in the solution of the problem.

BACKGROUND

Cairo, the Capital of Egypt and the most populated City in Africa, is located along the River Nile. Greater Cairo covers an area of about 300 km^2 (representing 0.03% of the total physical area of Egypt), within which more than 12 million persons (20% of Egypt population) are permanently living. In Greater Cairo region various types of activities [1] are taking place, including agricultural, industrial, and tourism activities (see Figure 1). Each type of activity results in specific types of pollution to the environment, including the groundwater environment. Other minor activities that might contribute to the deterioration of groundwater in Greater Cairo are of a local nature. These include: (i) gas stations, discharging their wastes on the land surface; (ii) garbage areas; and (iii) small industries. This has already resulted in various problems, namely: (i) continual increase in groundwater heads in some areas, especially within old Cairo and the antiquities areas; (ii) pollution of the shallow groundwater; and (iii) overpumping in areas where water supply wells are located.

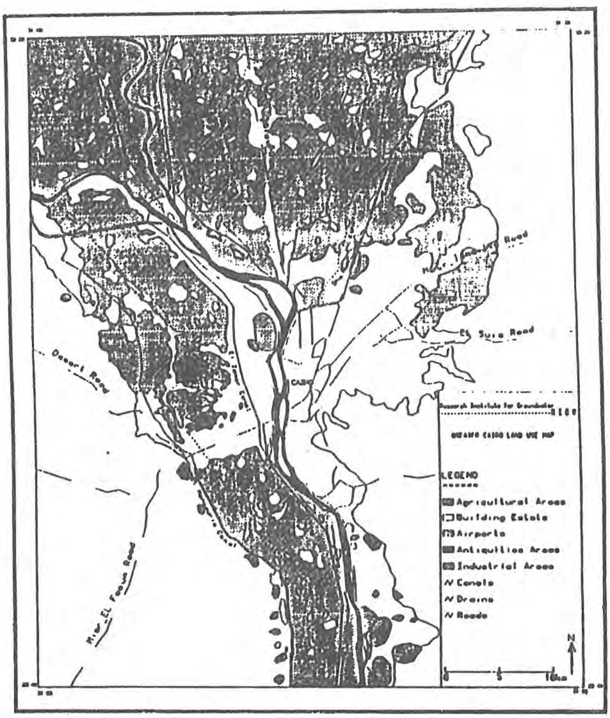

Fig. 1. Land Use in Greater Cairo

Potable water supplies in Cairo city are generally satisfied from: (i) the Nile water alone (1.5 million m^3/day); (ii) from a mixture of Nile and groundwater (1.2 million m^3/day); and (iii) from groundwater alone (0.3 million m^3/day). In the sub-urban and rural areas of the city, the major portion of the potable water supply is driven from locally pumped groundwater, either from medium capacity wells or from hand dug wells. The medium capacity wells are owned and operated by the local units (government), while the hand dug wells are owned and operated by the individuals. Both types of supplies are suffering from pollution due to the poor installation and operation of the facilities.

In the major part of the urban Cairo, the sewerage system is overloaded due the continuous increase of population. In the sub-urban and rural portions of the city, on the other hand, normally no sewerage network exist [2]. The existing facilities include septic tanks and trenches. The percent coverage of the sewerage network range from 80% to 45% (Figure 2).

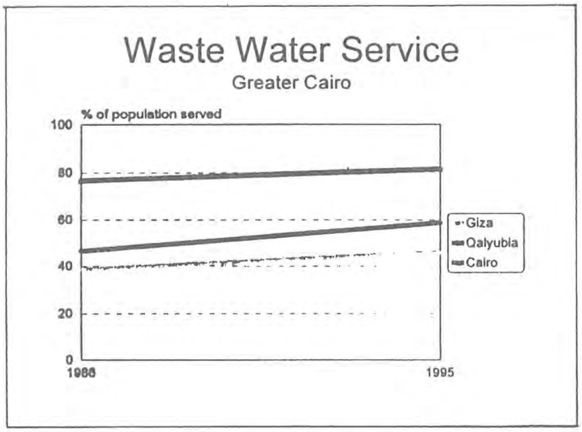

Fig. 2. Sewerage Services in Greater Cairo

THE PILOT AREA

Selection

Based on the results of the regional survey, a pilot area has been selected for detailed investigations and to conduct the public awareness program. Selection of the pilot area is based on the following criteria [2]: (1) moderate groundwater vulnerable to pollution; (2) it encompasses a variety of pollution problems from agriculture and domestic sources; (3) it encompasses more than one settlement; and (4) the willingness of the officials and the public to listen and learn. The selected area is El Mansuriya Unit.

General Conditions

El Mansuriya Unit is located west of Cairo (Figure 3). It is bounded from east and west by a drain and a canal. It comprises Mansuriya main village (the mother village), Abdel Samad village, and 15 ezbas (small private plots). The population of the unit is 65,000, and the total area under irrigation is 15,000 acres.

Detailed hydrogeological investigations have been carried out on the pilot area to identify sources and types of pollution and groundwater pollution extent. Results of the hydrogeological studies are processed in the form of maps reflecting the geometry of the aquifer in terms of clay thickness, base of aquifer, and boundaries [2]. The aquifer is partly phreatic and partly semi-confined with a thickness ranging from 40 to 60 m. The maximum thickness of the semi-confining clay member is about 7 m along the drain. The depth to groundwater varies from 1.5 to 3 m below ground surface; while the main direction of horizontal groundwater flow is north-east to south-west. The depth to the water table varies greatly in space, with an average of 0.7 to 1.5 m.

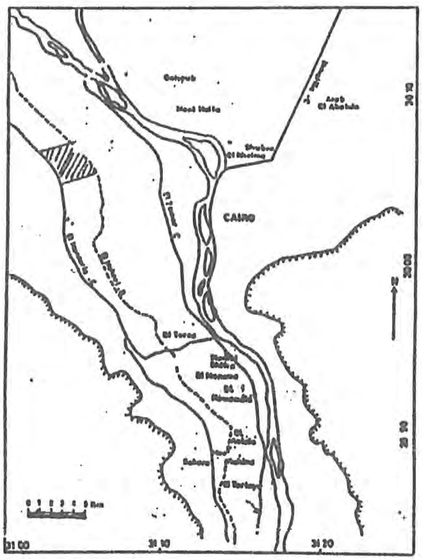

Fig. 3. Location of the Pilot Area

Groundwater use and quality

Groundwater withdrawals in El Mansuriya area are mainly for irrigation and drinking purposes. The annual extraction of groundwater for irrigation is about 30,000 m³/day, obtained from 150 medium capacity wells. Groundwater withdrawals from public wells for drinking amount about 7,000 m³/day.

To investigate the state of groundwater quality, extent and type of pollution, 28 samples have been collected and analyzed. Results indicated the following [2]:

1) The pH values range from 7.4 to 8.

2) Groundwater salinity ranges from 600 to 1300 ppm.

3) The concentration of cations and anions Mers from one location to another. The most dominant cation is either calcium or sodium; while the most dominant anion is bicarbonate. In general WHO limits for drinking water are not exceeded.

4) Ammonia is largely present in the agricultural drainage water, being negligible in groundwater. This is probably due to nitrification in the unsaturated zone of the aquifer. On the other hand, Nitrate concentrations are generally below 40 ppm.

5) Phosphate is generally high in the agricultural drains, being less in groundwater. However, its value is still higher than the allowable concentration (0.1 ppm).

6) Iron content is generally below the allowable (<0.3 ppm) for drinking water, except at very few locations. The manganese concentration, however, is above the permissible (>0.5 ppm), except at very few locations. The reason behind this is probably the respective high concentration of COD.

7) Coliform (microbiological pollution) is present in both surface water (canals) and drains, as well as shallow groundwater and taps, being less pronounced and with little spread in deep groundwater.

8) In general, both surface water conveyances and shallow groundwater are more polluted than the deep groundwater at the stations. However, due to the interrupted operation of the stations, groundwater in the pipeline is polluted.

Problem Identification and Possible Solutions

In addition to the results of the field surveys, it was found important to conduct few visits to the unit officials and a number of the inhabitants to get more information. Results of the contacts indicated the following [3]:

1) Agricultural chemicals, including ammonia/phosphate fertilizers and persistent pesticides, are heavily used due to the types of growing crops.

2) The village garbage and cleaning of the trenches are disposed in the drain crossing the main village.

3) The tap water (coming from the public well and pipes) is dark and smells, especially early morning when people start washing for the first pray.

4) The private hand-dug wells are no deeper than 8 m, and are generally located close to the trench. Their condition is very poor, no sealing and no platform surrounding the well. They are used generally for washing and drinking of both humans and animals.

5) The village has suffered from high rates of infant mortalities in the last decade.

Based on such information, a list of problems and respective solutions has been developed prior to the execution of the campaign.

Table 1. Prevailing Problems and Possible Solutions

Problems	Possible Solutions
Pollution of tap water	Maintenance of the elevated tank/ continuous pumping/Possible change of public wells location.
Poor water quality of the hand-dug wells	Proper citing/depth/sealing/ platform/use (Fig.5)
Groundwater pollution from agri-chemicals	Change to degradable types of agri-chemicals.
Groundwater pollution from other sources	No disposal of garbage and other hazards in the drain/proper sewage disposal.

Above all the mentioned solution, involvement of the public in the development and implementation of the government plans should be considered a critical issue.

THE PUBLIC AWARENESS CAMPAIGN

Objective and Strategy

The objective of the Public Awareness Campaign (PAC) is to promote awareness by the officials and inhabitants of Mansuriya of the dimensions, reasons, and effects of water pollution (deep and shallow), and of the options and the relevant procedures to the negative and hazardous effects of this problem.

The PAC strategy was based on three premises:

1) Any activity conducted within an Egyptian village, particularly one that aims at the direct participation of the people, can not be implemented without the preliminary consent and support of the leaders in that village. Approval by these groups and their willingness to participate in the PAC greatly enhances the "permeability" of the messages disseminated and their effect on the inhabitants.

2) Just as input from village headmen is important to increase the legitimacy of the PAC, direct contact with the women in the villages is also significant, since, as many earlier studies have shown, women are the main users of the water and therefore constitute one of the strongest targets for the PAC.

3) Although literacy levels in the two pilot villages were expected to be higher than the average for Egyptian villages, print material was deemed less likely to produce a measurable effect on the people than visual aids, especially in view of the penchant for Egyptian village inhabitants for watching T.V.

Implementation

For purposes of efficiency, adequate coverage and permeability of the messages disseminated, the following steps were taken in the preparation for the PAC:

1) Meetings have been held with the unit official to inform them about the PAC objectives, solicit their support for communication with the people, and seek their assistance in the organization and implementation of the gatherings.

2) Informal talks and small gatherings have been held with some of the inhabitants to obtain their views and opinions about the problem of public groundwater and hand pump pollution and to inform them of the PAC. The people contacted were asked to *spread the word* on the upcoming public gatherings.

4) During the above visits, brief inspections were made about the situation of the public as wells as the private drinking wells, and information were obtained on the use and maintenance of these wells by the inhabitants as well as the latter's opinion on the quality and taste of the water.

5) Photographic slides and cartoon drawings were developed as presentation aids for the public gatherings (see Figures 4 and 5).

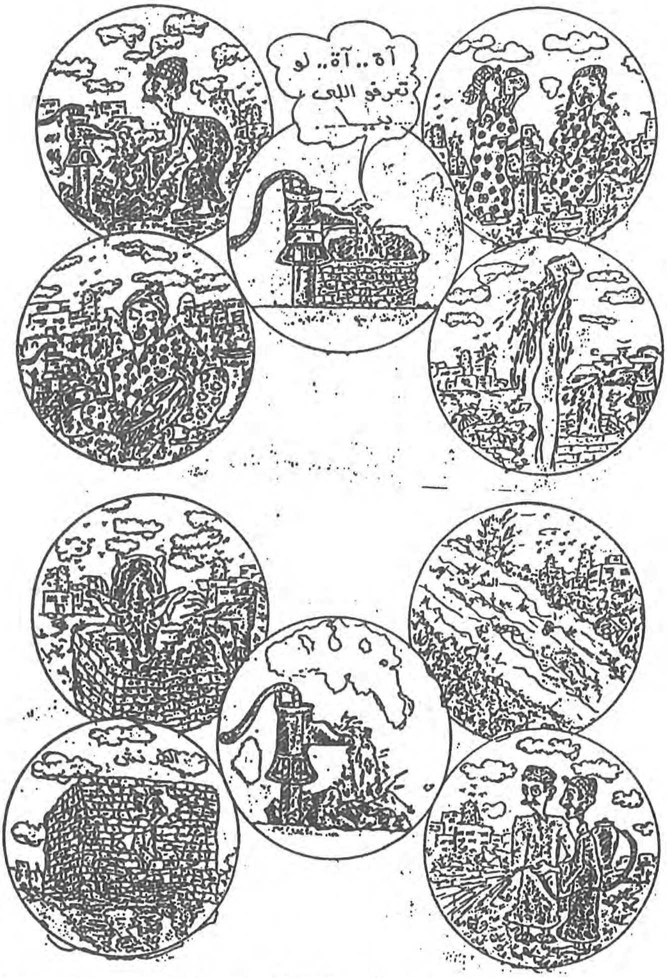

Figure. 4. Presentation of General Behaviors

The gatherings have been held in two days, as follows:

1) The first public gathering was held on September 6 at the conference hall (renewed by the village council for the gathering) of the Mansuriya Local Unit headquarter. Some 40 participants attended. These have been selected by the local unit officials as the most influential men in the area. The PAC started with speeches delivered by the officials. A slide presentation followed, which informed participants on the effects of poor well construction on groundwater pollution, the harmful effects of extensive fertilizer and pesticide application in agriculture, and other faulty practices that have been noticed during the visits to the villages. Cartoon drawings have also been demonstrated along with the slide presentation. A demonstration on the mechanism of water infiltration through the soil down to the groundwater has been made with the help of a sponge. The presentations have been followed by more than two hours discussion and questions related to possibility of corrections to groundwater pollution.

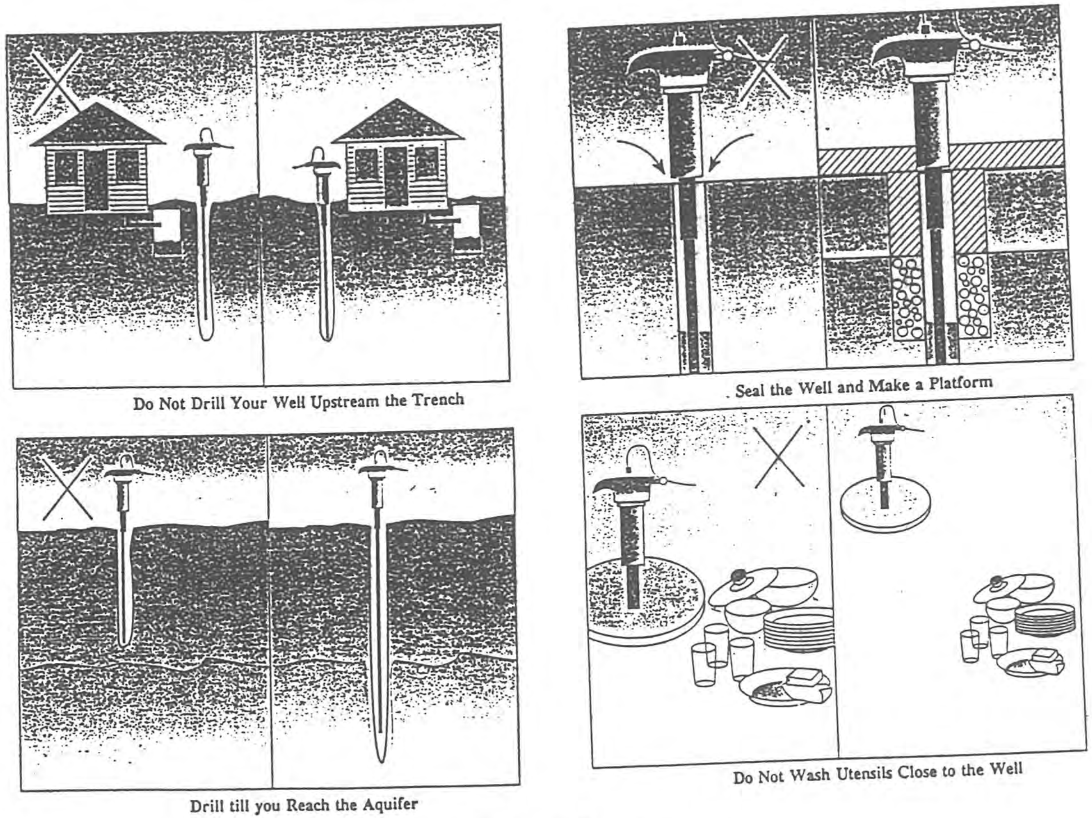

Figure 5. Technical Information

2) The second public gathering was held on September 9, and was targeted exclusively for the female inhabitants of the villages. The same presentation was given, with more emphasis on the role of women in reducing the effects of wells pollution. Negative practices in cleaning and maintaining the wells were highlighted, together with the improper handling of water from the wells.

Results

The main results obtained from the campaign can be summarized as follows:

1) In general, the inhabitants of the villages, as well as the governorate, district, and local unit officials were very receptive to the PAC and the messages disseminated. Many of them admitted that while they acknowledged the problem of water pollution in their area, they were never fully aware of its profound ramifications and long-term effects. The majority were alarmed at the negative prospects of the groundwater pollution on their children.

2) Surprisingly, women were found to be more difficult to convince than men. Indeed, many of the women who attended the second public gathering had to be collected one by one from their homes, as they were reluctant to come on their own. But, once they have been exposed to the seriousness of the problem they were greatly disturbed and became more receptive to the messages disseminated.

3) Participants were particularly influenced by a sample of water extracted from a domestic hand pump in the village, which was left for few days in a container (jar) for impurities to settle.

4) Several people, however, started to complain about lack of funds for the construction of deep wells and proper sewerage systems. But they were accepting sharing in the cost. The officials informed that fund has been allocated for the renewal of the stations with increased capacities, along with the extension of the distribution system and implementation of a sewage system. The response of the inhabitants to such an announcement was that they will be willing to share in the costs, but they want to move the stations to the outskirts of the village. This proposal has been agreed upon since it coincides with the characteristics of the supply.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Water supplies are subjected to major stresses due to the increasing demand by various uses sectors. Pollution is another aspect affecting the availability of the resource. Groundwater, if properly conserved, represents a safe source for drinking water.

The reasons behind the pollution of groundwater in Egypt are various; among which the most important are [4]: (1) high leaching capacity of the soils in many regions (high groundwater vulnerability to pollution); (2) internal pollution due to clay contamination (containing iron and other minerals); (3) poor construction and maintenance of wells that result in direct pollution of the water wells [5]; (4) poor conditions or absence of sewerage systems; (5) poor application of fertilizers and use of persistent pesticides in agriculture; and (6) absence of proper public awareness and involvement.

An important conclusion is that the public knows more than we, scientists, think. They represent an important source of information and can support or destroy resources.

Recommendations

To protect groundwater from pollution and ensure the public support, the following recommendations are found essential.

1) Groundwater monitoring is an important tool for the protection of groundwater and water wells. It should get more attention and results disseminated properly to the decision makers and the public.

2) Groundwater performance indicators are also important tools for decision making and allocation of resources. They should be based on historical data.

3) Communication is an important factor in the creation of awareness. It should be considered as essential as technical works.

4) The public should be encouraged to protect water resources. Incentives can play an important role in this respect. These may not only be financial, but other types according to each situation.

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EFFECT OF WASTE WATER ON SOIL AND PLANT

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ABSTRACT

Research has been conducted in the effects of wastewater on soil and plant and the nutrient present in those waters.

This paper will review briefly some research has been done in the Research Institute of Natural Resources and Environment at KACST on the reuse of wastewater as supplement source for irrigation purposes. Those research activities include: - (1) The effect of treated municipal wastewater on soil and crops. (2) The effect of waste-water irrigation and mineral composition of corn and sorghum. (3) The use of aquaculture effluent as supplemental source of nitrogen fertilizer to increase the yield of wheat. (4) The effect of wastewater from Wadi Hanifah on plant growth and soil properties.

It was found from these studies that the nutrients in the various sources of wastewater can improve crop yield and plant growth and the accumulation levels of mineral pollutants were not hazardous, to the soil and plant.

The Ecology of Wastewater in the Open Sections of a Sewage Treatment Continuum under Arid Conditions

Reginald Victor and Salma M. Al-Harassi

THE ECOLOGY OF WASTEWATER IN THE OPEN SECTIONS OF A SEWAGE TREATMENT CONTINUUM UNDER ARID CONDITIONS

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ABSTRACT

The ecology of wastewater in the exposed sections of a sewage treatment facility in Oman was investigated. The objectives were to determine the physical and chemical quality of the water along the treatment continuum and relate it to the respective microbial and biological qualities, also with a view of recognizing bioindicators of pollution in an arid environment. Five open sites, (1) between the inlet pump and the communitor (2) the aeration tank with rotary flow, (3) clarifier, (4) equalization tank before filtration and (5) chlorine contact tank were sampled once a month between August 1993 and January 1994. Standard methods for the examination of water and wastewater were used for the analysis of water and biological samples. Most of the physical and chemical conditions except, colour, odour, dissolved oxygen, BOD_5, total alkalinity and bicarbonate were not significantly different at the five study sites ($P > 0.05$). Monthly fluctuations in the air temperature and the levels of magnesium, silica, total dissolved solids, chloride, sulphate, fluoride, phosphate-P, and nitrate - N were significantly different ($P < 0.05$). The mean coliform concentrations as MPN decreased from 1100/100 ml at the communitor site to 400/100 ml at the equalization tank site 4. The chlorine contact site 5 had an acceptable MPN of 3/100 ml except in September, when 460/100 ml was recorded, possibly because of a breakdown in the chlorination system. The diversity of cyanobacteria (one species), algae (two species) and invertebrates (four species) at sites 1 - 4 was low. The site related differences in the abundance level of these taxa and their value as bioindicators of surface water pollution are discussed. Site 5 was devoid of algae and invertebrates. This study contributes to the understanding of the poorly known wastewater ecology in the arid zones, especially in treatment facilities depending on temperate technology.

Keywords: sewage treatment, wastewater, ecology, physical-chemical conditions, conforms, algae, invertebrates.

INTRODUCTION

Modern sewage treatment installations are designed to ensure acceptable water quality and minimize environmental hazards associated with wastewater. The sewage treatment is governed by physical, chemical and biological processes. It also involves a complex series of biochemical reactions mediated by a wide range of microorganisms (Gray 1989). The biology of wastewater in sewage treatment facilities has been well documented for the temperate region (Mudrack and Kunst 1986; Horan 1990). Developing nations in both humid and tropics predominantly rely on temperate technology for sewage treatment, but the biology of wastewater here is poorly understood. Apart from the design efficiency of facilities and the quality of wastewater influent, environmental factors play an important role in sewage treatment, especially in the open sections of the treatment continuum. This study investigated the ecology of wastewater in five open sections of a sewage treatment plant in and Oman. The main objectives were to monitor the physical and chemical qualities of the wastewater in the study sections and relate these to the corresponding biological and microbial characteristics. The study sections in the treatment continuum represented improving levels of water quality and their respective biota were expected to be useful as bioindicators of sewage pollution in surface waters.

MATERIALS AND METHODS

The study area

The sewage treatment plant studied is located in the Sultan Qaboos University Campus, Al-Khod, Sultanate of Oman. It was commissioned in 1985 to treat effluents received from all areas of the University including the hospital. Its capacity for processing is 2100 m^3 of wastewater per day. However, due to the demand for irrigation, much higher quantities up to 3110 m^3 per day have been treated. Figure I shows the various sections of the plant, the flow direction of the wastewater and the five sampling sites in the open sections of the treatment continuum.

Site 1 is located between the inlet pump and the screening bars of the comminutor which trap large solid wastes, while sites 2 and 3 are located in the aeration tanks where the secondary treatment takes place. At site 2, the activated sludge and wastewater influent are in continuous circulation facilitating mineralization and the formation of activated sludge. Site 3 is the clarifier into which the aerated effluent is pumped and here, the activated sludge settles at the bottom. Site 4 is the equalization tank which receives water from site 3 and pumps it to the filtration tank where the remaining small particles are filtered. Site 5 is the partially open chlorine contact tank where the effluent is chlorinated and conveyed to the holding tanks. Sites 4 and 5 are sections in the tertiary treatment unit.

Sampling and analytical methods

Wastewater and biological samples were taken from all five sites at monthly intervals from August 1993 to January 1994. Air and water temperatures (°C) were measured using a mercury in-bulb thermometer at about 10 a.m. The colour of the wastewater was noted at each site and its odour was determined using the threshold odour test in threshold odour number (T.O.N).

Wastewater was collected in 500 ml polyethylene containers for chemical analyses. All samples were filtered in the laboratory using Mhatman No. 1 filter paper to remove organic debris. A subsample of 100 ml was taken from each sample to determine the pH, conductivity, phosphate-P and nitrate-N immediately. The remaining sample was analyzed as soon as possible for calcium, magnesium, sodium, potassium, silica, bicarbonate, chloride, sulphate, fluoride, theoretical TDS, total alkalinity and total hardness. Dissolved oxygen and BOD, samples were separately collected in 250 ml glass bottles. The dissolved oxygen was determined using Winkler's method with iodide-azide modification. All analytical procedures were adopted from APHA (1992).

Water samples for the estimation of coliform bacteria were separately collected in sterile bottles autoclaved at 120°C. The presence and the most probable number (MPN) of total coliform bacteria were determined using the multiple tube standard method (Shastree, 1991). Algae and invertebrates were collected using a nylon-net with a mesh size of 156 µm. Two samples were taken at each site; one was fixed in the field using small quantities of 40% formalin and the other was examined for live material. Each sample was qualitative and included organisms in the water column and in benthos, if applicable. Scrape samples were taken, wherever possible, to collect periphytic algae and associated animals. Samples were sorted in the laboratory and organisms were stored in appropriate preservatives. Identification was carried out to the lowest possible taxonomic category.

All statistical procedures were adopted from Zar (1989) and a statistical package, INSTAT was used to perform the analyses.

RESULTS

Physical and chemical conditions

Table 1 summarizes the physical and chemical conditions of wastewater at study sites from August 1993 to January 1994. Of 22 parameters determined, only six namely colour, odour, dissolved oxygen, BOD_5, bicarbonate and total alkalinity showed significant differences among sites (ANOVA or Kruskal- Wallis Test, $P < 0.05$). All other parameters were not significantly different among sites ($P > 0.05$).

Colour of the water improved significantly at site 3, the clarifier and it was not different from site 4, the equalization tank and site 5, the chlorine contact tank (Kruskal - Wallis, Hc = 1066.1; a posteriors comparison; $P < 0.05$). The foul odour at sites 1 and 2 significantly reduced at sites 3 and 4. Sites 1 and 2 were similar while at site 3, the unacceptable odour was significantly more than that at site 4 (Kruskal - Wallis, He = 119.3; a posteriors comparison, $P < 0.05$). At site 5, the chlorine smell, as expected was distinctly different.

The dissolved oxygen was absent in the influent at site 1. It was either absent or present in very low concentrations at site 2. The dissolved oxygen at sites 3, 4 and 5 were significantly higher than that at site 2, although these were not different from each other (ANOVA, F = 23.9; Tukey test, $P < 0.05$). The BOD_5 at site 1, was > 300 - 350 mg 1- and at site 2, it ranged between 102-250 mg 1-1. Sites 3 and 4 had ranges between 10 - 14 mg 1-' and 3 - 5 mg 1-' respectively. The estimations at site 5 were not reliable due to chlorine interference. The nature of BOD_5 data did not permit any statistical analysis to compare sites. The bicarbonate in wastewater progressively decreased from site 1 to site 4. The first three sites were significantly different from each other, but sites 4 and 5 had bicarbonate levels similar to that of site 3 (ANOVA, F = 6. 1; Tukey test, $P < 0.05$). The total alkalinity also decreased from site 1 to site 3. Sites 1, 2 and 3 were significantly different from each other while site 3 was similar to sites 4 and 5 (ANOVA, F = 4.0; Tukey test, $P < 0.05$).

Despite the lack of differences among sites, means of nine physical and chemical conditions showed significant differences during the six study months (ANOVA, $P < 0.05$). These were, the air-temperature, magnesium, silica, total dissolved solids, chloride, sulphate, fluoride, phosphate-P and nitrate - N.

Coliform bacteria

Table 2 shows the estimation of coliform bacteria at the five sites from August 1993 - January 1994. The quantities of coliforms were significantly different among sites (ANOVA on square root transformed MPN, $F = 8.4$; Tukey test, $P < 0.05$). Sites 1, 2 and 3 had higher coliform concentrations not different from each other, while sites 2 and 3 were also not different from site 4. The unexpected result showing significant similarity between sites 4 and 5 is due to the high MPN estimated at site 5 in September. Coliform levels were significantly similar in all study months (ANOVA as above, $F = 0.07$, $P < 0.05$).

Flora and fauna

Table 3 presents the distribution and occurrence of the flora, and fauna at study sites from August 1993 - January 1994. *Oscillatoria sp.* (Cyanobacteria), *Claclophora sp., Stigeoclonium sp.* (Chlorophyceae), Tubifex sp. (Tubificidae, Oligochaeta), *Stenocypris major* (Crustacea, Ostracoda), one chironomini taxon (Chironomidae, Diptera) and Plumatella sp. (Bryozoa) were the biota recorded. All taxa except Plumatella were ubiquitous in the first four sites. None of these taxa were recorded in Site 5.

The relative abundance of these taxa were variable in the study months (Table 3). Plumatella was extremely abundant in sites 2 and 3 only in August and October. It was absent in other months and also in other sites. The abundance of filamentous Chlorophyceae among sites was significantly different (Kruskal - Wallis test with tied ranks, $Hc = 20.65$, $P < 0.\ 05$). Sites 1 and 2 with a relatively higher abundance were similar, but significantly different from sites 3 and 4 which were not different from each other. The relative abundance of all other taxa were not significantly different among sites (Kruskal - Wallis test with tied ranks, $Hc = 7.50$ (Cyanobacteria), 5.50 *(Tubifex)*, 4.48 *(S. major)*, 5.51 (Chironomini); $P < 0.05$).

DISCUSSION

As expected in any sewage treatment facility, the water quality improved along the continuum from site 1 receiving the influent to site 5, the chlorine contact tank. In the Sultanate of Oman, there are two well defined standards for wastewater quality and these standards are defined as maximum quality limits for 42 parameters, taking into account the purpose for which the wastewater is reused (Ministry of Regional Municipalities and Environment 1993). Of 21 physical and chemical parameters determined in this study

(Table 1), 11 namely the BOD_5, total dissolved solids, conductivity, pH, chloride, fluoride, magnesium, nitrate-N, phosphate-P, sodium and sulphate could be compared against the Oman standards of wastewater quality.

The parameters of unacceptable quality were BOD, and sodium at sites 1 and 2, nitrate-N at sites 1, 2 and 3, and conductivity at site 1 on one occasion only. Acceptable levels of BOD, (< 20 mg 1-) and sodium (< 200 mg 1^{-1}) were recorded at all other sites and the maximum concentration of nitrate determined at site 4 (48 mg 1^{-1}) was less, but not distinctly different from the required limit (50 mg 1^{-1}). Except on the above mentioned occasion, conductivity at all sites was well below the required limit of 2000 - 2700 µS cm^{-1}. The maximum concentrations of all other compared parameters were well below the limits required by Oman standards. With the exception of BOD_5 all other factors above did not differ significantly among sites. It is difficult to establish relationships between their concentrations and biological activity, but they are all components of the environment in which the progressive improvement of the water quality takes place. Colour, odour, temperature, dissolved oxygen, calcium, potassium, silica, bicarbonate, total alkalinity and total hardness of the wastewater were also determined (Table 1) and some of these relevant to wastewater biology needs discussion.

Colour and odour are water quality parameters. The dark brown colour and the lack of dissolved oxygen at site I indicated that the wastewater was anaerobic or septic, because of the probable depletion of oxygen during transit in the sewers. The odour was moderately offensive at sites 1, sites 2 and 3 and almost odourless at site 4. The odours recorded in the present continuum were quantified as threshold odour numbers (T.O.N), but using this type of quantification as a control variable for assessing wastewater quality is difficult (Metcalf and Eddy 1991; APHA 1992). The presence of chlorine smell in site 5 needs no explanation.

Temperature is an important environmental factor which affects the activity of wastewater microbes and the rate of biochemical reactions. It also influences the community structure directly or indirectly in combination with other factors such as dissolved oxygen. The temperature of sewage is usually higher than the air temperature. Here, the maximum air temperature range of 37^{o} - $41^{o}C$ was always higher than the maximum wastewater temperature ranging from 34^{o} - $37^{o}C$, but the mean water temperatures at all sites were more than or at least equal to mean air temperatures. This water temperature regime would have enhanced the removal of BOD at sites 1 and 2, thus imposing an oxygen limitation on the system. The incidence of bulking observed at site 3 throughout this study must also be due to the warm weather.

Dissolved oxygen concentration between 1 - 2 mg l^{-1} is enough to support active aerobic microbial activity (Gray 1989). The wastewater at site 1 contained no dissolved oxygen and the concentration at site 2 ranged between 0.0 - 0.6 mg l^{-1}. Therefore, active aerobic microbial activity would have been effective only at sites 3 and 4. At site 5, the dissolved oxygen concentration was influenced by the timing of chlorine injection and the quantity of chlorine present in the water. Dissolved oxygen also influences nitrification and concentrations below 0.2 - 0.5 mg l^{-1} completely inhibit nitrification (Wild et al. 1971; Winkler 1981). There were no obvious correlations between dissolved oxygen and nitrate at study sites, although nitrification should have occurred at sites 3 and 4. Nitrate concentrations at site 1 showed that it was a component of the influent entering the system.

Calcium at all sites were fairly stable with mean concentrations ranging from 39 - 44 mg l^{-1} . Calcium is a limiting factor for green algae and some group of invertebrates such as molluscs and ostracods which have shells predominantly composed of calcium carbonate. *Stenocypns major*, an ostracod recorded in fair abundance at all sites does not occur in calcium poor waters. The precise form of silica dissolved in water is not known (Maitland 1990). The range of silica in natural waters is between 1-30 mg l^{-1}. The range recorded in the wastewater at all study sites was between 0.0-19.5 mg l^{-1}. Silica is biologically active and its concentration limits the occurrence of diatoms. Despite careful search, diatoms were not recorded here. Potassium is also utilized by algae, but can be lost from the water due to biotic sedimentation (Wetzel 1975).

The concentration of bicarbonate is < 10 mg l^{-1} in rainwater and < 200 mg l^{-1} in surface streams (Montgomery 1985). The bicarbonate ranged between 116 - 357 mg l^{-1} at site 1 indicating its high concentration in the influent. The mean bicarbonate levels reduced progressively from sites 2 to 4. Calcium and magnesium combined with carbonate, and bicarbonate ions and the latter could also be used directly by algae (Jeffries and Mills 1990). Total alkalinity trend in the wastewater continuum was similar that of bicarbonate and this is to be expected. Hardness is a related measure used in evaluating water quality and it refers to the calcium and magnesium salts combined with the bicarbonate/carbonate and other ions which compensate for acidity. Since there were no significant differences in hardness at all sites, the reduction in bicarbonate and alkalinity from site 2 to site 4 is likely to be due to biological activity.

The monthly fluctuations in air temperatures are due to seasonality. The monthly fluctuations of other factors which did not differ between sites were due to their variable concentrations in the influent. The flow rate of

unpublished data). The differences in the relative abundance of these taxa between sites did not indicate improvement in water quality.

This study has initiated the study of wastewater biology in and Oman. Water treatment facilities, although man-made and improve with technological progress, inevitably utilize natural biological processes. Transfer of temperate technology to and tropics should not expect the magnitude of these natural processes to be universal. Comparative ecological studies in other water treatment facilities of Oman and other states in the Gulf with reference to sections including stabilization ponds, activated sludge and filter systems will yield valuable information.

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Table 1. Physical and chemical conditions of wastewater at SQU study sites from August 1993-January 1994; minimum, maximum and mean±s are given for 16 parameters; minimum and maximum only are given for some parameters; number of samples = 6; means denoted by same letters are not significantly different, *a posteriori* multiple comparisons, P>0.05.

Parameters	Site 1 min	Site 1 max	Site 1 mean±s	Site 2 min	Site 2 max	Site 2 mean±s	Site 3 min	Site 3 max	Site 3 mean±s	Site 4 min	Site 4 max	Site 4 mean±s	Site 5 min	Site 5 max	Site 5 mean±s
PHYSICAL															
Temperature °C Air	21.0	37.0	31.5±6.5	21.0	40.0	31.5±7.0	22.0	40.0	30.0±6.2	22.0	40.0	30.5±6.9	22.0	41.0	31.3±6.3
Water	21.0	36.0	33.2±2.5	28.0	34.0	31.5±3.7	27.0	37.0	31.5±3.7	23.0	34.0	30.3±4.2	25.0	34.0	31.0±3.5
Colour (nominal)	Dark Brown *a*			Dark Brown *a*			Colourless *b*			Colourless *b*			Colourless *b*		
Odour (T.O.N.)	700	800*a*	-	700	800 *a*	-	200	300 *b*	-	8	10 *c*	-	Chlorine smell		
CHEMICAL															
pH	6.6	7.6	-	6.5	7.8	-	7.2	8.2	-	7.2	8.7	-	7.1	9.0	-
Conductivity μS	700	2200	1239±550	750	1700	1196±329	690	1640	1177±330	850	1650	1203±296	900	1620	1197±267
Dissolved Oxygen mgl^{-1}	nil	nil	nil *a*	0.00	0.59	0.29±0.03*b*	2.39	4.19	3.0±0.70*c*	3.9	5.2	4.38±0.48*c*	0.0	5.99	3.83±2.09*c*
BOD_5 mgl^{-1}	>300	>350	-	102	250	-	10	14	-	3	5	-	Not reliable		
Calcium mgl^{-1}	28.0	75.0	44.3±6.9	28.0	45.0	39.7±6.3	28.0	47.0	39.3±6.3	30.0	44.0	38.8±5.3	34.0	48.0	40.2±5.2
Magnesium mgl^{-1}	23.0	75.0	37.0±8.6	33.0	47.0	41.3±4.8	19.2	46.0	32.3±9.6	25.0	50.1	36.2±10.4	30.0	43.0	35.2±4.5
Sodium mgl^{-1}	94.0	309.9	154.8±78.2	113.0	210.0	158.3±40.7	92.9	185.0	135.5±38.7	105.9	182.0	148.2±31.9	109.0	172.0	140.8±28.3
Potassium mgl^{-1}	11.2	17.1	14.7±2.3	9.3	22.9	17.5±4.9	8.2	17.2	13.3±3.3	9.4	17.6	13.7±2.8	12.5	17.1	14.1±1.6
Silica mgl^{-1}	0.0	19.5	10.8±7.6	0.0	18.1	11.6±6.4	0.0	17.8	11.4±6.1	0.0	17.1	11.7±8.5	0.0	14.9	8.4±6.9
Bicarbonate mgl^{-1}	116.0	357.0	247.3±93.4*a*	66.9	308.9	195.9±82.7*b*	65.9	153.9	111.8±29.5*c*	90.9	166.9	96.7±59.3*c*	67.9	155.9	109.2±28.5*c*
Chloride mgl^{-1}	96.8	453.7	228.8±123.3	154.8	291.4	240.5±49.4	149.9	261.6	216.2±46.3	147.9	292.2	213.5±59.8	140.1	279.0	220.1±52.0
Sulphate mgl^{-1}	68.0	110.0	93.5±15.8	114.0	140.0	127.7±10.7	74.8	261.9	127.2±69.5	89.9	250.1	142.8±56.5	65.7	264.6	134.8±74.3
Fluoride mgl^{-1}	0.09	0.69	0.29±0.02	0.19	0.89	0.43±0.12	0.09	0.89	0.38±0.13	0.09	0.89	0.39±0.23	0.09	0.89	0.38±0.13
Total Dissolved Solids mgl^{-1}	502	1030	706±18	540	839	623±31	458	786	622±12	519	799	668±13	547	739	636±10
Total Alkalinity mg $CaCo_3l^{-1}$	95	293	203±76*a*	55	206	142±50*b*	54	126	91±24*c*	39	143	97±35*c*	56	253	116±70*c*
Total Hardness mg $CaCo_3l^{-1}$	171	341	271±61	239	309	288±25	172	294	230±50	178	323	249±56	219	269	241±17

Table 2. Coliform bacteria in the study sites of STP at SQU. August 1993 - January 1994: MPN/100 ml and 95% CL for lower and upper limits as shown. Average MPNs identified by same letters after ANOVA and Tukey on square-root transformed data were not significantly different (P>0.05). * indicates unusual result.

Date	Site 1 MPN	Site 1 95% CL Lower	Site 1 95% CL Upper	Site 2 MPN	Site 2 95% CL Lower	Site 2 95% CL Upper	Site 3 MPN	Site 3 95% CL Lower	Site 3 95% CL Upper	Site 4 MPN	Site 4 95% CL Lower	Site 4 95% CL Upper	Site 5 MPN	Site 5 95% CL Lower	Site 5 95% CL Upper
08.08.93	1100	150	4800	1100	150	4800	1100	150	4800	1100	150	4800	3	<0.5	9
12.09.93	1100	150	4800	1100	150	4800	1100	150	4800	43	7	210	460*	71	2400
10.10.93	1100	150	4800	240	36	1300	23	4	120	93	15	360	3	<0.5	9
15.11.93	1100	150	4800	1100	150	4800	1100	150	4800	1100	150	4800	3	<0.5	9
14.12.93	1100	150	4800	1100	150	4800	1100	150	4800	43	7	210	3	<0.5	9
25.01.93	1100	150	4800	1100	150	4800	150	30	440	23	4	120	3	<0.5	9
Average	1100 *a*			956 *ab*			762 *ab*			400 *bc*			79 *c*		

Table 3 : Monthly fluctuations in the relative abundance of organisms in the study sites of STP at SQU, August 1993 - January 1994; Key - **O** > 20, O 11 - 20, o 1 - 10, - Absent

Months →	AUGUST				SEPTEMBER				OCTOBER				NOVEMBER				DECEMBER				JANUARY			
Sites →	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Cyanobacteria *Oscillatoria* sp.	**O**	O	O	o	O	O	o	o	o	o	o	o	O	O	o	o	**O**	**O**	O	o	o	o	o	o
Chlorophyceae *Cladophora sp.* *Stigeoclonium sp.*	**O**	**O**	O	o	**O**	**O**	o	O	**O**	**O**	O	o	**O**	**O**	o	o	**O**	**O**	O	o	**O**	**O**	O	o
Annelida, Oligochaeta *Tubifex* sp.	O	O	O	o	o	O	o	o	O	O	**O**	o	o	O	O	o	O	**O**	**O**	O	O	O	**O**	**O**
Arthropoda Crustacea, Ostracoda *Stenocypris major*	O	O	**O**	**O**	o	O	o	**O**	**O**	o	O	o	o	o	O	O	o	O	O	**O**	o	o	**O**	O
Insecta Diptera, Chironomidae	O	O	O	O	o	o	o	**O**	O	O	**O**	o	o	o	**O**	o	O	O	**O**	O	O	o	**O**	**O**
Bryozoa *Plumatella* sp.	-	**O**	**O**	-	-	-	-	-	-	**O**	**O**	-	-	-	-	-	-	-	-	-	-	-	-	-

Legend to Figure

Fig. 1. The schematic diagram of the sewage treatment facility; arrows show sampling sites.