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Effects of Irrigation with Treated Wastewater on the Physical and Chemical Properties of Soil in Kuwait

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ABSTRACT

With the passage of time, reclamation and reuse of wastewater gain global importance as the demand for water increases and usable sources of water dwindle due to high consumption rates and quality degradation resulting from anthropogenic pollution. The problem is even further manifested in arid and semiarid regions such as Kuwait where desalination plants provide most of the freshwater supplies. The main objective of this study was to determine the effects of the infiltrating return water as it passes through the soil and the corresponding changes on chemistry, mineralogy, and hydraulic parameters of the soil. The study was conducted in the United Agricultural Production Company (UAPCO) Farm which is located in Sulaibiya area at the west of Kuwait City. The UAPCO Farm has been irrigated with tertiary treated wastewater since 1976. For the purpose of this study, data were collected through drilling of boreholes, establishment of ceramic cups and lysimeters, collection of soil samples from different depths, field penetration and infiltration tests as well as laboratory infiltration tests through sand columns. Soil samples were collected from irrigated and non-irrigated areas down to a depth of 1 m below the ground surface at 10-cm intervals to investigate the soil's characteristics. The chemical constituents of the leachate that was prepared from extracts of the soil samples were analyzed for nitrate, ammonia, phosphate, sulphate, chemical oxygen demand (COD) and biological oxygen demand (BOD). The collected soil samples were also analyzed using x-ray diffraction (XRD) to identify their mineralogical composition, with special emphasis on the clay content. Physical and chemical analyses of the soils revealed that there has been no negative impact of the wastewater used for irrigation on the upper 50-cm layer of the soil. Therefore, treated wastewater (with an EC of 1.47 dS/m) was considered appropriate for irrigation of forage crops.

Key words: *Farm, infiltration, return water, chemical, parameters, agriculture*

1. INTRODUCTION

Treated wastewater is used for landscaping and greenery activities at sites that are far away from urban areas in Kuwait. As noted by [1], during 1995, out of a total of 251,000 m^3/d of available wastewater, 147,000 m^3/d underwent tertiary treatment and 54,000 m^3/d underwent secondary treatment only. Of this amount, 108,000 m^3/d of tertiary treated and 11,000 m^3/d of secondary treated wastewater were used for irrigation. The rest was discharged into the sea. Use of this water for landscaping and gardening is expected to substantially conserve costly freshwater and brackish groundwater in Kuwait.

Recently, the municipal wastewater is processed by reverse osmosis after tertiary treatment. This treated water is used for landscaping and producing alfalfa and animal feed in farming areas. The volume of wastewater generated will be increased in the future with the increase in consumption, and the treatment capacity will also be increased to keep pace. It has been estimated that the daily production of treated wastewater will reach 635,600 m^3/d by the year 2015 [2] and utilization of this resource is a high priority for the water managers of the country.

This study was conducted in the United Agricultural Production Company (UAPCO) Farm that was established in 1976 and is located in the Sulaibiya area (Fig. 1). The main forage crops that are produced in this farm include alfalfa and barley. The study focused on potential effects of irrigation wastewater on the soil characteristics.

2. METHODOLOGY

The execution of this study involved several tasks, including: collection of available data; drilling of monitoring wells and installation of ceramic cups and lysimeters; collection of soil and groundwater samples from the monitoring wells, investigation of water chemistry; and analysis of data.

The available data on the soil characteristics and groundwater conditions before the establishment of the UAPCO Farm, the quality of the treated wastewater used for irrigation, its application rates and schedules, the types of crops produced, the types and amounts of fertilizers used and other relevant information were extensively collected.

An intensive drilling and sampling program was carried out to install a permanent network of 8 monitoring wells, 11 ceramic cups and four lysimeters and to collect the infiltrating irrigation water and groundwater samples.

A total of ten sites were selected based on the soil characteristics and crops produced for determination of infiltration rates, penetration resistance rates and other soil properties such as porosity and bulk density, as well as the soil's chemical and mineralogical contents.

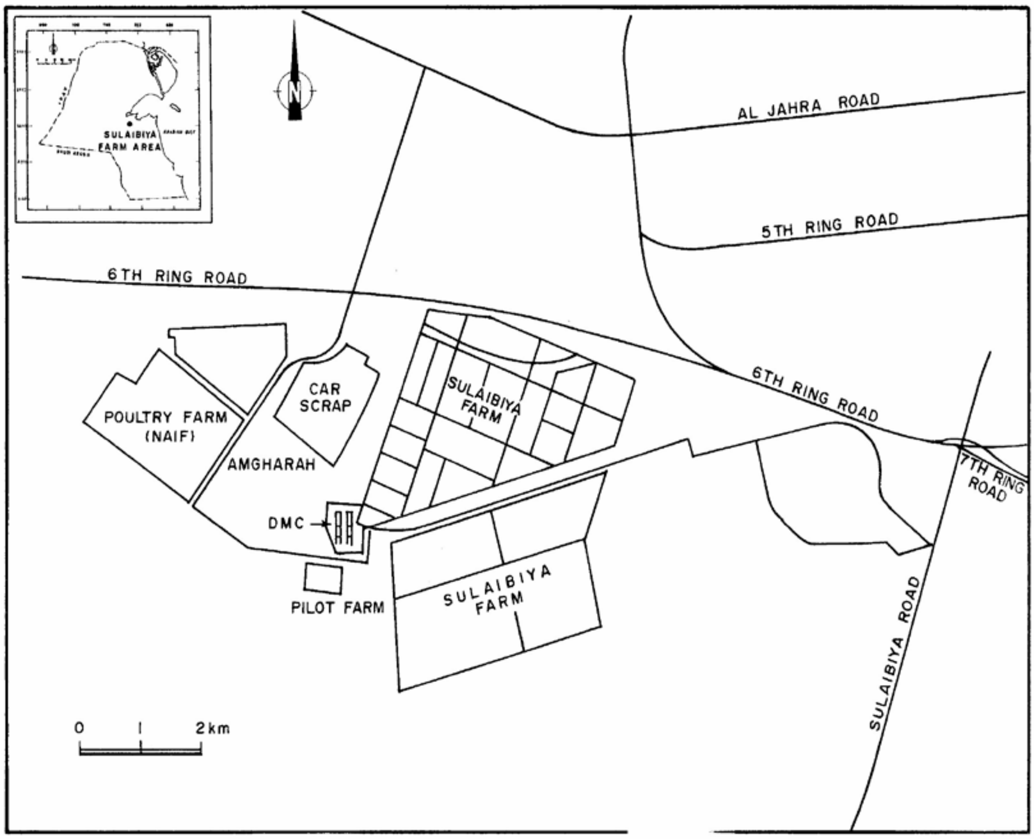

Fig. 1. Location of the United Agricultural Production Company (UAPCO) farm at the Sulaibiya area in Kuwait

Soil samples were collected from irrigated and non-irrigated sites within the UAPCO Farm down to a depth of 1 m below the ground surface at 10-cm intervals to investigate the soil characteristics of the study area. These samples underwent laboratory grain size analysis and were then leached. The leachate was analyzed to identify the nitrate, ammonia, phosphate and sulphate contents as well as chemical oxygen demand (COD) and biochemical oxygen demand (BOD). The collected soil samples were also analyzed using X-ray diffraction (XRD) to determine their mineralogical composition, with special emphasis on the clay content.

A group of ceramic cups were installed at three locations within the study area to collect infiltrating water in order to monitor the changes in water quality with depth. Ceramic cups were installed at depths of 30, 60, 90, and 120 cm below the ground surface.

Four lysimeters were constructed and installed at selected locations within the UAPCO Farm. A rain gauge was also placed near the lysimeter to record the volume of rainfall in the study area.

The infiltration rate was measured in the study area using a double-ring infiltrometer.

The penetration tests were carried out using a Bush Soil Penetrometer. Measurements were recorded every 2 cm down to a depth of 50 cm at 10 locations in and around the UAPCO Farm.

A total of 10 sites were selected to determine the infiltration rates, penetration resistance rates and other soil properties, such as porosity, bulk density, and chemical and mineralogical contents of the soil. These sites were selected based on the following criteria:

- Type of the irrigated crops (i.e., alfalfa vs. barley).
- Type of irrigation method (i.e., drip vs. sprinkle).
- Type of sprinklers used (i.e., horizontal vs. overhead).

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- Type of area investigated (i.e., irrigated vs. harvested).

Additionally, uncultivated soils outside the UAPCO Farm were tested to obtain background information and data on the soil around the study area.

Twenty soil samples were collected from different depth horizons ranging from 0 to 0.25 m and from 0.25 to 0.5 m below the ground surface (designated with the alphabetic letters a and b, respectively in the subsequent sections) at 10 different locations within and around the UAPCO Farm. The soil samples were collected using hand augers. The samples were placed in plastic bags prior to analysis. Also, 10 undisturbed soil samples were collected from the same locations in small cylinders to measure the bulk density. Additionally, soil descriptions, penetration tests and infiltration tests were carried out at the same locations from which the soil samples were collected.

3. IN-SITU DESCRIPTION OF THE SOIL IN THE STUDY AREA

A general description of the collected soil samples was presented at the site, including color, moisture content, particle size, and carbonate and gypsum contents. Almost all of the collected soil samples were composed of pebbly sand with moderate to high carbonate content. The soil color, which ranged from gray in dry soils to brown and/or dark brown in wet soils, was primarily dependent on the moisture content. None of the collected soil samples contained gypsum.

4. SOIL CHARACTERIZATION: AGRICULTURAL PERSPECTIVE

Tables 1, 2, and 3 show the physical analyses carried out on the collected soil samples include, moisture content, bulk density (wet-and dry-based), porosity, infiltration rate, soil texture (sand, clay and silt percentages), penetration rate and chemical analyses.

Data on the physical properties of the soils show that the dry bulk densities are in the range of 1.4 to 1.8, as expected for sandy soils, and the wet bulk density is higher than the dry bulk density. The mechanical analysis of the soils indicates that they are generally sandy in texture, containing 86 to 98% sand (Table 1). The data on the infiltration rates of the soil at the UAPCO farm (Table31) shows that highest infiltration rates were observed at Sites 5 and 7 (83.5 and 85.5), while the lowest was observed at Site 6 (16.5). Such variability in infiltration rates exists in sandy soils. Other physical properties of the soils do not indicate any influence of water used for irrigation.

The soils under study had pHs ranging from 7.3 to 8.9, which indicate slight (pH<8) to medium (pH 8.1 to 8.5) alkalinity. In general, the pH of the surface layers (with depths ranging from 0 to 25 cm) is lower than that of subsurface soils (with depths ranging from 25 to 50 cm). The soils in the UAPCO farm are non saline (<4 ms/cm), with ECs ranging between 0.65 and 1.16 dS/m. This range of ECs indicates that the water used for irrigation is of fairly good quality, and is, generally suitable for most crops and forages.

Table 1: Physical Properties of the Collected Soil Samples

Sample	Moisture (%)	Bulk Density (dry basis) (g/cm^3)	Bulk Density (wet basis) (g/cm^3)	Porosity (%)	Sand (%)	Clay (%)	Silt (%)	Infiltration Rate (cm/h)
1A	2.1	1.5	1.5	42.8	86.0	8.0	6.0	
1B	2.5	-	-	42.1	88.0	7.0	5.0	24.1
2A	2.4	1.4	1.5	42.5	96.0	3.0	1.0	
2B	2.3	-	-	41.9	95.0	4.0	1.0	54.6
3A	9.3	1.6	1.6	37.8	88.0	6.0	6.0	
3B	6.3	-	-	38.2	92.0	6.0	2.0	53.0
4A	1.1	1.6	1.6	36.1	90.0	6.0	4.0	
4B	1.8	-	-	37.7	94.0	5.0	1.0	49.0
5A	1.3	1.7	1.7	34.2	95.0	3.0	2.0	
5B	1.5	-	-	33.8	96.0	3.0	1.0	85.5
6A	1.2	1.7	1.8	31.0	91.0	5.0	4.0	
6B	1.9	-	-	32.9	89.0	5.0	6.0	16.5
7A	7.9	1.4	1.6	37.2	96.0	3.0	1.0	

7B	6.6	-	-	37.0	96.0	3.0	1.0	83.5
8A	5.4	1.7	1.9	28.4	96.0	2.0	2.0	
8B	4.9	-	-	30.2	98.0	2.0	0.0	64.0
9A	1.0	1.8	1.9	29.9	97.0	3.0	0.0	
9B	1.4	-	-	28.8	96.0	3.0	1.0	50.2
10A	1.5	1.7	1.8	33.3	94.0	4.0	2.0	
10B	1.3	-	-	32.8	93.0	3.0	4.0	26.3

- Not measured
A: 0 to 25-cm Soil Layer
B: 25 to 50-cm Soil Layer

Table 2: Resistance of Soils Measured by Penetration Tests at Selected Locations

Depth (cm)	Penetration Resistance (kgf)									
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
2	35	15	6	21	11	8	15	10	6	30
4	>50	27	10	34	19	14	17	15	11	>50
6		20	14	39	30	19	19	17	20	
8		33	16	13	32	25	20	22	37	
10		22	19	16	22	32	22	27	50	
12		43	22	23	35	37	25	30	>50	
14		>50	28	30	>50	41	29	33		
16			35	49		44	35	34		
18			27	>50		42	42	38		
20			33			41	44	44		
22			42			35	42	46		
24			48			38	48	45		
26			>50			37	>50	38		
28						37		43		
30						38		49		
32						37		>50		
34						34				
36						33				
38						33				
40						32				
42						35				
44						38				
46						43				
48						34				
50						35				

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Table 3: Chemical Properties of the Collected Soil Samples

Sample	pH	ECe (dS/m)	Ca^{+2} (meq/l)	Mg^{+2} (meq/l)	K^{+} (meq/l)	Na^{+} (meq/l)	CO_3^{-2} (meq/l)	HCO_3^{-1} (meq/l)	Cl^{-1} (meq/l)	SO_4^{-2} (meq/l)	$CaCO_3$ equivalent (%)	Gypsum (%)	Organic Carbon (%)	SAR
1A	7.7	1.2	6.8	2.5	1.0	3.5	0.5	4.9	1.8	6.6	8.4	<.01	0.3	1.6
1B	8.0	1.2	6.5	2.0	0.8	4.5	1.0	2.6	1.5	8.6	9.0	<.01	0.1	2.2
2A	8.0	0.7	2.5	1.7	0.5	3.0	0.5	3.1	1.2	3.0	8.1	<.01	0.1	2.0
2B	8.9	1.1	2.5	0.6	0.5	7.5	1.0	2.9	1.8	5.5	9.6	<.01	0.0	6.0
3A	7.6	1.6	8.5	2.2	0.6	5.1	1.0	4.1	3.9	7.5	5.6	<.01	0.5	2.2
3B	7.9	0.8	4.0	1.0	0.3	3.8	0.5	2.4	2.3	3.9	6.2	<.01	0.1	2.4
4A	7.3	1.1	7.5	1.3	0.4	3.0	0.5	2.9	1.6	7.1	6.0	<.01	0.3	1.4
4B	8.2	1.2	5.8	1.5	0.5	4.5	0.5	1.6	1.9	8.2	6.9	<.01	0.0	2.4
5A	8.0	0.8	5.5	1.8	0.3	1.0	0.5	1.9	1.3	4.9	6.1	<.01	0.0	0.5
5B	8.5	0.8	5.5	0.8	0.3	1.5	0.5	1.9	1.3	4.5	7.1	<.01	0.0	0.9
6A	7.8	1.1	5.3	1.8	0.4	4.3	0.5	2.4	3.1	5.7	9.3	<.01	0.1	2.3
6B	8.0	1.2	7.0	1.5	0.5	3.7	1.0	1.1	3.0	7.6	8.8	<.01	0.0	1.8
7A	7.3	1.1	5.5	0.5	0.2	4.4	0.5	2.6	5.0	2.5	3.8	<.01	0.1	2.6
7B	7.9	0.9	4.5	0.0	0.1	4.1	0.0	2.1	3.4	3.2	4.4	<.01	0.0	2.7
8A	7.5	1.7	7.0	2.5	0.3	7.2	0.5	1.9	7.5	7.2	3.9	<.01	0.0	3.3
8B	7.8	1.8	7.8	1.8	0.4	7.0	0.5	1.4	7.8	7.2	4.3	<.01	0.0	3.2
9A	8.1	0.8	5.8	0.8	0.4	1.4	0.5	1.8	1.4	4.6	6.2	<.01	0.0	0.8
9B	8.4	0.8	6.3	1.0	0.5	1.5	0.0	2.1	1.2	5.9	6.7	<.01	0.0	0.8
10A	7.3	8.5	76.3	17.3	5.4	0.1	0.0	1.6	4.0	93.5	8.2	<.01	0.1	0.0
10B	7.5	6.7	59.0	11.5	4.3	0.2	0.0	1.4	4.7	68.9	9.7	<.01	0.0	0.0
Water	7.1	1.5	3.8	1.8	0.6	7.0	0.0	1.1	7.1	4.9				4.2

EC = Electrical Conductivity; SAR = Sodium Adsorption Ratio
A: 0 to 25-cm Soil Layer;
B: 25 to 50-cm Soil Layer;

The soil at Site 10 (outside the premises of the farm) was observed to have higher EC values (>6.65 ms/cm) than those of other sites due to the presence of higher concentrations of Ca, Mg, K and SO_4. However, Site 2 (also located outside the farm) had typical sandy-soil properties. These soils are non-calcareous with calcium carbonate contents less than 10% and without any traces of gypsum. The organic carbon content of soil is also very low (<0.5%), which decreases with depth. These soils are very low in carbonate and bicarbonate. Analysis of the calcium content of soils indicated that it ranged from 2.5 to 8.5 meq/l in the upper layers, and from 2.5 to 7.8 meq/l in the lower layers. The magnesium content of the soil is very low, reaching only 2.5 meq/l. Higher calcium (59.0 to 76.3 meq/l) and magnesium (1.5 to 17.3 meq/l) contents were observed in the soil samples collected from Site 10.

The sodium content of the soils in the UAPCO farm ranges from 0.1 to 7.5 meq/l at Sites 10 and 2, respectively. On the other hand, the potassium content of the soils ranges from 0.1 to 5.4 meq/l at Sites 7 and 10, respectively. The chloride content of the soil is also very low, with the highest values being 7.5 and 7.9 for soils at Site 8. The SAR of the soils is indicative of their sodicity, and it suggests that these soils are normal, having SARs <13.

Table 4 presents an estimate of the degree of soil compaction based on its resistance to penetration. The results of the penetration tests show that the layers of high resistance are found at depths ranging from 14 to 32 cm for the plots being cultivated (Sites 3, 4, 7 and 8), from 12 to 14 cm for non cultivated plots (Sites 5 and 9), from 4 to >50 cm for plots cultivated in the previous season (Sites 1 and 6), and from 4 to 14 cm for unfarmed plots outside the UAPCO farm (Sites 2 and 10). Although Site 4 is classified as a cultivated plot, it showed relatively high resistance to penetration. This can be attributed to the fact that this particular site is being irrigated by a drip system hence; localized wetting of specific spots takes place, whereas with sprinklers, the whole lot is dampened with water. Therefore, the results obtained for Site 4 fall within the same range as those for the no cultivated sites in the study area.

Table 4: Classification of Soil Compaction as a Function of Penetration Resistance

Class	Penetration Resistance (kgf)	Degree of Soil Compaction
1	0-50	Slightly Compacted
2	50-88	Moderately Compacted
3	> 99	Severely Compacted

It is worth noting that the degree of soil dryness or wetness greatly affected the penetration tests conducted. This was evident at Sites 1 and 6, representing both dry and wet sites, respectively. Site 1 showed high resistance at a depth of only 4 cm, whereas Site 6 did not show resistance to penetration down to a depth of 50 cm. It is believed that the accumulation of salts at Site 1 due to evaporation of the irrigation water played a major role in the high resistance to penetration as these salts tend to cement soil particles. Site 6 is classified as a plot that was cultivated in the previous season and was, therefore, expected to show high resistance to penetration. However, the status of this site was changed during the two-week period that preceded the penetration tests, as the farmers began to irrigate the site, and the irrigation water could have washed away any precipitated salts which, in turn, might have led to a significant reduction in the soil's resistance to penetration. In general, the high resistance of the tested soils to penetration could be attributed to compaction caused by harvest and tillage tractors. Such high resistance could also be due to the presence of high contents of cementing materials, such as calcium carbonate, which can strengthen the soil. On the other hand, compaction and cementation can have adverse effects on the soil as they can reduce the amount of water that infiltrates through the soil, root efficiency and soil fertility; and increase the potentials for plant disease.

5. SOIL CHARACTERIZATION: LITHOLOGICAL PERSPECTIVE

The particle size distribution of the collected soil samples was determined using sieve analysis. The results obtained were also used to determine the permeability of the soils in the UAPCO farm. Based on the percentages of the gravel, sand and silt and clay fractions, the soil samples were classified following British Standard (BS) 5930 (1981). The coefficient of permeability of the soil samples was determined following the method adopted by [3]. Soil Classification. The collected soil samples were sieved to determine their particle size distribution in terms of the percentage of gravel, sand and mud. The soil in the study area can be characterized as being dominantly composed of sand (with an average percentage of 92.49%) with varying percentages of gravel and mud. The percentage of gravel varied from 0.1 to 7.8 with an average of 2.35. The percentage of fines varied from 1.50 to 8.81 with an average of 5.51. This indicates that the study area is covered with silty, slightly gravelly sand.

Hydraulic Conductivity. Agricultural properties are greatly determined by the texture of a soil. The particle size distribution affects the soil's properties, including the ease of tillage, capillary conductivity, compaction, moisture content, permeability, etc.

The ease with which water penetrates or passes through a bulk mass of a soil or a layer of a soil is known as permeability. The coefficient of permeability is a measure of the capability of the material to pass water through it. It can be defined as the rate of flow of water through a unit of cross-sectional area under a unit of hydrostatic gradient.

The coefficients of permeability varied from 9.80 x 10^{-3} to 1.00 x 10^{-2} cm/s with an average of 8.36 x 10^{-3} cm/s. The estimated coefficient of permeability of the collected soil samples fall within the range of typical coefficients of permeability for silty sand. The values of the coefficients of permeability indicate that the permeability of the soil in the study area is relatively high.

Infiltration Rates at the Study Site. The infiltration rates at the 10 locations within the study area were measured. They ranged from 49 to 84 cm/h for plots being cultivated, from 50 to 86 cm/h for non cultivated plots, from 16 to 24 cm/h for plots cultivated during the previous season (Sites 1 and 6), and from 26 to 55 cm/h for unfarmed sites. The plots cultivated during the previous season showed the lowest infiltration rates. This could be attributed to the precipitation of salts following the evaporation of irrigation water. It is believed that such precipitated salts would form cementing materials that would cement the soil particles and partially clog the intercalation channels between the soil pores through which irrigation water passes or the low infiltration rates at these sites could also be attributed to compaction caused by the tillage and harvest tractors, which, in turn, would reduce the soil's voids ratio and, subsequently the infiltration rate.

Other sites within the study area showed higher infiltration rates, due to minimal effects of cementing and compaction at these sites.

Field measurements have shown the presence of a measurable content of calcium carbonate within the soil particles (ranging between 9.7 and 3.8% with a mean value of 6.9%). The soil samples that were collected from the UAPCO farm consisted mainly (93.3 % on average) of sand of different grain sizes (2 to 0.063 mm), and low contents (6.7% on average) of fine materials (silt and clay). According to the soil classification of Folk [4], the UAPCO farm's soil falls into the sand category. The porosity of the soil samples ranged between 42.8 and 28.8%, with a mean value of 35.4%. The laboratory results revealed deficiencies of nutrients in the soil, including carbon, and the absence of gypsum minerals. In general, the absence of the gatch (calcium-carbonate-cemented sand grains) layers associated with the low clay contents in the upper two meters of the soil profile and the presence of highly porous sandy soils will collectively facilitate an increase in infiltration rate values, allowing treated wastewater to pass through the aquifer materials and reach the groundwater system.

6. RESULTS

Physical and chemical analyses of the soils revealed that there has been no negative impact of the wastewater used for irrigation on the upper 50-cm layer of the soil. This is expected as the chemistry of the irrigation water is considered reasonably appropriate (with an EC of 1.47 dS/m) for irrigation of forage crops.

Soil Parameters: Specific Surface Area and Cation Exchange Capacity. The Autosorb-1 apparatus was used to determine the specific surface area of the collected soil samples [5].

The clay mineral content is identified by measuring the cation exchange capacity of the soil. The cation exchange capacity is the sum of exchangeable cations that a soil can adsorbs, expressed in milliequivalents per 100 grams of soil.

The specific surface areas of the soil range from 1.15 to 7.6 m^2/g with a mean value of 4.02 m^2/g. The cation exchange capacities of the soil range from 1.7 to 4.7 meq/100 g with a mean value of 2.7 meq/100 g. Based on the mean values, kaolinite clay was the most dominant clay mineral in the tested soil samples.

XRD analysis of the soil samples show that they consist mainly of quartz, carbonates (calcite and dolomite), ferromagnesian silicates (pyroxenes) and few feldspar minerals (albite, microcline,

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laboradorite and anorthite) as well as low concentrations of clay minerals. Kaolinite and palygorskite are the main clay minerals of the soils in the study area. Kaolinite was found at the irrigated sites, sites cultivated the previous season and nonirrigated sites outside the farm. On the other hand, Palygorskite was found only at an irrigated site and sites cultivated during the previous season inside the UAPCO farm..

The low contents of the negatively charged clay minerals within the soils of the UAPCO farm are expected to leach the major cations (Na, Ca, Mg, and K) and the positive trace metal ions (Cu, Zn and Cd) due to the minimal effects of the cation exchange processes of the surfaces of the of clay minerals. Also, anions such as SO_4, Cl, NO_3, and HCO_3, and negative trace metal ions such as Ni and Hg will not exchange with the broken edges at the edges of the surfaces of the clay minerals. As a result of the low specific surface area and clay content, it is expected that viruses will not be adsorbed to the soil particles and will be leached towards the groundwater system. Also, the bacterial content in the treated wastewater is expected to be leached to the groundwater because of the high infiltration rates within the porous sandy aquifer.

The TOC of the collected soil samples ranged from 0.05 to 0.67% with a mean value of 0.12%, while the total carbon of the soil samples ranged from 0.30 to 1.44% with a mean value of 0.71%. The differences in the values of total carbon and TOC correspond to the total inorganic carbon (TIC) content of the soil, which may be related to the presence of carbonate and bicarbonate materials. The total inorganic carbon of the soil samples ranged from 0.08 to 1.37% with a mean value of 0.61%. Generally, the inorganic carbon contents of the soils of the UAPCO farm are higher than the organic carbon contents. Moreover, laboratory results revealed deficiencies in nutrients such as carbon (TOC <0.67%) in the soil samples. This low level of negatively charged organics in the soil is expected to result in leaching of the wastewater pollutants to the shallow groundwater (the water table within 2 to 4 m) passing through the high-porosity (35.4%) sandy aquifer.

Chemical Analysis: Extracts from the soil samples were prepared and analyzed for their contents of nitrate, ammonia, sulphide, sulphate, phosphate, chloride, and COD.

The results of the analyses are presented in Table 5. The nitrate content at Site SF-S1 was the highest, reflecting the application of fertilizers, followed by that at Site SF-S3 where farming activities had started later. The nitrate content at Site SF-S2 was the lowest, as expected for an area where no cultivation has taken place. The nitrate contents at all three sites show a general decreasing trend with depth, as is to be expected, though at Site SF-S1, a sudden jump in the curves value is seen at depths of 80 to 100 cm. Except for minor occurrences of ammonia at depths of 40 to 60 cm at Site SF-S1, ammonia was not detected in the samples, possibly reflecting its conversion to nitrate through nitrification. The chloride contents more or less reflect the same trend as the nitrate, with Sites SF-S1 and SF-S3 having higher chloride contents than the no irrigated Site SF-S2, suggesting adsorption of chloride from the irrigation water. The sulphate levels varied in the range of 60 to 160 mg/l in the extracts for all three sites without much of a discernible pattern. The COD for most of the samples was 0 mg/l. The variations of these parameters are presented in graphical forms in Figs. 2 through 4.

Table 5: Chemical Analysis of Extracts from Soil Samples of the Study Area

Sample ID	NO_3 (mg/l)	NH_3 (mg/l)	SO_4^{2-} (mg/l)	PO_4^{3-} (mg/l)	Cl^- (mg/l)	COD (mg/l)
S1 (0-20)	596.0	0.0	112		320	28
S1 (20-40)	774.4	0.0	164		96.0	0
S1 (40-60)	255.2	0.378	60.0		86.4	43.2
S1 (60-80)	137.3	0.0	104		20	0
S1 (80-100)	387.2	0.0	152		292	0
S2 (0-20)	123.2	0.0	124		38.8	0
S2 (20-40)	93.28	0.0	108		32.8	0
S2 (40-60)	73.92	0.0	112		11.6	0
S2 (60-80)	30.0	0.0	170		56.4	309.2
S2 (80-100)	35.2	0.0	116		7.2	0
S3 (0-20)	100.32	0.0	104		240	0

S3 (20-40)	158.4	0.0	164	36.4	65.2
S3 (40-60)	146.1	0.0	88.0	228	0
S3 (60-80)	82.72	0.0	132	38	0
S3 (80-100)	52.8	0.0	116	35.6	0
S3 (100-120)	51.04	0.0	104	26	0

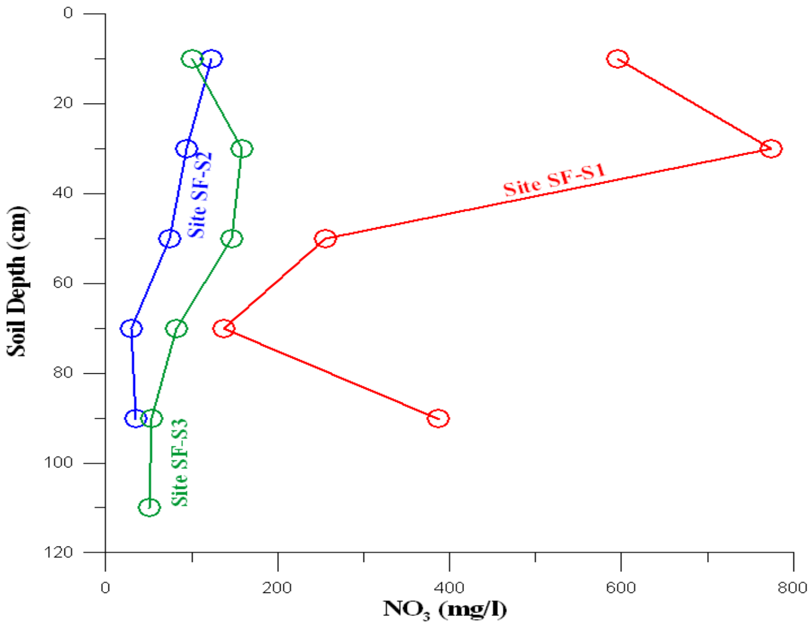

Fig. 2: Variation of nitrate content with depth in the soil extract

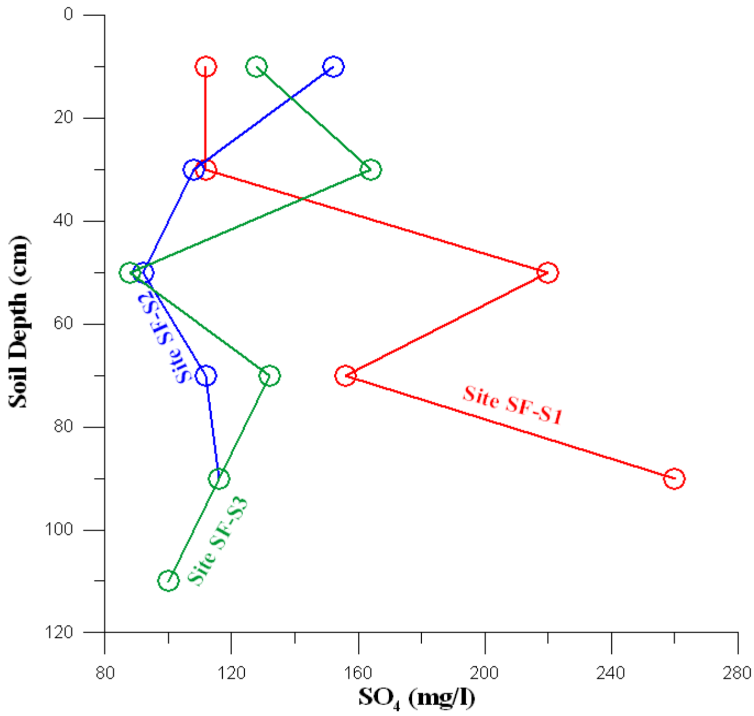

Fig. 3: Variation of sulfate content with depth in the soil extract.

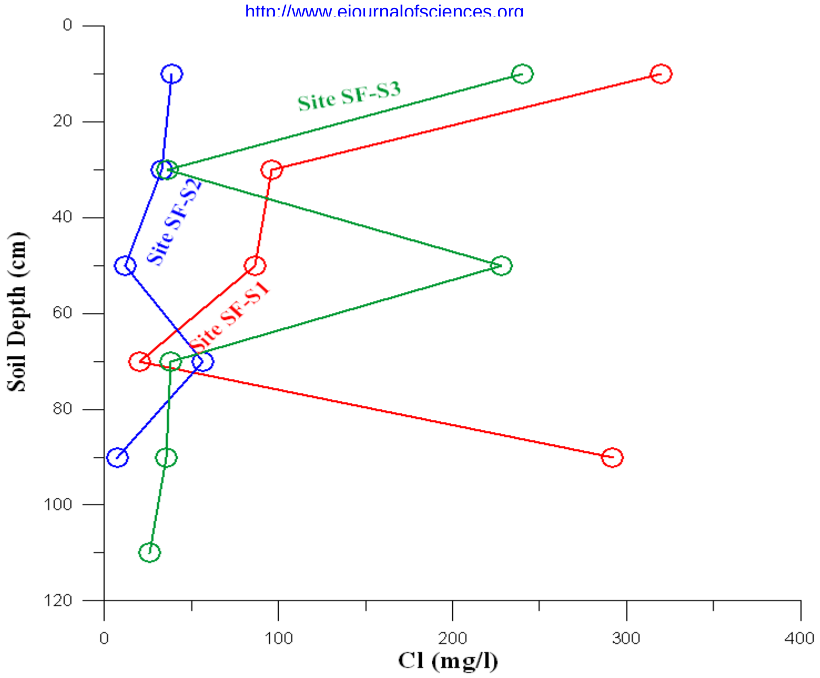

Fig 4: Variation of Chloride Content with Depth in the Soil Extract

7. CONCLUSIONS

The main conclusions of this study can be summarized in the following:

1. The distribution map of the height of the water table above the mean sea level that was developed based on the data obtained from the monitoring and other wells on the farm and in the neighborhood suggests that a water mound has been created at the center of the UAPCO farm by almost two decades of irrigation with treated wastewater. The maximum height of this mound is estimated at about 15 to 20 m. At the two monitoring sites (Wells SF-01A, and SF-03B, SF-05C, and Wells SF-02A, SF-04B, and SF-06C), the top 10 to 15 m of the water column is believed to belong to the lens created by the return water from irrigation, with a mixed transition zone followed by the original groundwater below. The characteristics of the groundwater with respect to parameters such as nitrate, ammonia, phosphate, BOD, COD and TOC in Well SF-07D, located in between the two sites and screened in the range 20 to 50 m below the surface, are representative of the original groundwater below the mound at the farm site prior to its establishment. The quality parameters of the water recovered from the mound suggests improvement with respect to BOD, phosphate and ammonia content and to some extent with respect to COD. The nitrate concentration in the mound is, however, somewhat to the high side, because of nitrification of ammonia and contribution from applied fertilizers.
2. The results of the soil column studies indicate that at the irrigated sites, most of the sulphates and organic carbon have leached out from the unsaturated zone resulting in only slight enrichment (in the case of sulphate) or some adsorption (in the case of organic carbon) of these components as the treated wastewater passes through the soil. At the non irrigated sites, however, the soil, in its pristine condition, is rich in sulphate and organic carbon, and the treated wastewater used for irrigation leaches these components out as it infiltrates the soil at these sites. The nitrification process appears to be working in both types of soil, with the decreases in ammonia concentrations and increases in nitrate concentrations in the outlet water samples, in comparison to the inlet water (treated wastewater) sample.
3. Investigation of the physical properties of the soil in the study area indicates that the dry bulk density of the soil is characteristic of sandy soils. This is also supported by the textural analysis of the soil and the variability in infiltration rates observed in the study area. The soils of the UAPCO farm tend to be slightly to moderately alkaline. In general, the pHs of the surface layers are lower than those of the surface soils. The ECe of the soils indicates that the water used for irrigation is of fairly good quality, and is, generally, suitable for most crops and forages.

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4. Physical and chemical analyses of the soils of the UAPCO farm revealed that there have been no negative impacts of the wastewater used for irrigation on the upper 50-cm layer of the soil. This is expected as the chemistry of the irrigation water is considered reasonably appropriate for irrigation of forage crops.
5. Grain size analysis of the collected soil samples indicates that the upper aquifer sequence in the UAPCO farm is composed of the undifferentiated fluviatile clastic sequence of the Kuwait Group. Megascopic investigations of the collected drill cuttings and core samples supported by grain size analysis show the prevalence of six sediment types within the drilled sequence of the Kuwait Group Aquifer in the study area. These were identified on the basis of the relative abundance of gravel, sand and mud following Folk's (1974) classification as mud, muddy sand, silty sand, sand, gravelly sand and muddy gravelly sand. Gravelly sand was the most dominant deposit within the drilled sites. The porosity of the soil samples ranged between 28.8 and 42.8%, with a mean value of 35.4%. Different stages of calcretization were identified within the gravelly sand litho-type, ranging from slight to moderate. Layers of thick mud were encountered in the upper 10 m and, more frequently, below 15 m. The thickness of the mud varied from 2 m to about 10 m. The importance of grain size distribution stems from its potential effects on the agricultural properties of the soil, including the ease of tillage, capillary conductivity, compaction, moisture content, and soil permeability.
6. As regards the chemical constituents of the soil samples collected from the study area, the field measurements have shown the presence of measurable levels of calcium carbonate within the soil particles (ranging between 3.8 and 9.7% with a mean value of 6.9%). The soil samples that were collected from the UAPCO farm consisted mainly of sand of different sizes (0.063 to 2 mm), with a mean value of 93.3%, and low contents of fines materials (silt and clay), with a mean value of 6.7%.
7. The laboratory results revealed deficiencies of nutrients in the soil, including carbon (TOC <0.50%), low specific surface areas and clay content and the absence of gypsum minerals. In general, the absence of the gatch (calcium-carbonate-cemented sand grains) layers associated with the low clay contents in the upper two meters of the soil profile and the presence of highly porous sandy soils collectively facilitate increased infiltration rates, allowing treated wastewater to pass through aquifer materials and reach the groundwater system. Thus, some of the applied wastewater constituents and associated pollutants will move from the surface towards the groundwater system under the investigated farm. The presence of fecal coliform bacteria in the sample collected from well SF-04 gives credence to the idea.

8. RECOMMENDATIONS

The recommendations of this study are as follows:
1. Long-term monitoring of the soil and groundwater of the UAPCO farm should be carried out to ensure that undesirable chemical pollutants and viruses/bacteria do not reach unacceptable limits with the passage of time. This will lengthen the life expectancy of the farm and ensure the quality of the produced crops.
2. Although it is expected that the quality of the treated wastewater will be further enhanced while it passes through the subsurface, provided travel times and travel distances (minimum of 7 meters within the soil strata beneath the ground surface) are adequate, it is important to study the behavior of these pathogens in order to arrive at a careful assessment of the usability of wastewater for irrigation. This can be done by understanding, quantifying and modeling the processes that govern the removal of bacteria and viruses by soil passage, including the manner in which adsorption and inactivation processes contribute to this removal.

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