

# **STUDY ON THE SILT DENSITY INDEX PROBLEM IN THE SWCC JEDDAH SEAWATER REVERSE OSMOSIS PLANTS<sup>1</sup>**

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## **SUMMARY**

*A two-year study was carried out along the Red Sea coast of the SWCC desalination and power plants in Jeddah to investigate factors causing a high silt density index (SDI) in SWRO plants. The study determined certain vital biological and physicochemical parameters. These parameters included: total suspended solids (TSS), SDI, visibility, plankton, chlorophyll, nutrients, dissolved oxygen (DO), biochemical oxygen demand (BOD), temperature, pH, conductivity, salinity and marine and sewage bacteria.*

*Five sampling sites were chosen; four were in coastal waters close to the shore line and one 5 km offshore. At each sampling site there were three sampling points at depths of 1m, 15m, and 25m. The analyses were carried out between October, 2002 and September, 2004.*

*Statistical comparison of treatment means, during normal operation time did not reveal outstanding differences between coastal sites near the plants or between coastal and offshore waters. Some parameters (TSS, SDI, turbidity, phytoplankton, chlorophyll and total organic carbon) increased during high SDI periods, but decreased to their normal values within 2-5 days. Sewage water reached the plant intake but was not a causal agent of high SDI nor was it*

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*hazardous to product water, and pollution indicating parameters such as DO, BOD, nutrients and bacterial growth rates, remained stable at levels associated with periods of normal SDI.*

*The frequency of high SDI encounters has witnessed significant decline in recent years. Two high SDI periods were encountered during the study, one in late October to early November 2002, and the other in October 2003. During the high SDI period of 2002, TSS increased 6.9 times over normal SDI values compared to a 2.5 fold increase during the 2003 high SDI. However, plankton density was higher in the 2003 high SDI than the previous high SDI period. The 2002 high SDI is attributed to a sharp rise in silt load, and the 2003 high SDI is attributed to a moderate rise in both silt and biological growth. The rise in silt load is attributed to a natural phenomenon of a local current from shallow coastal waters south of the plant.*

*Seawater SDI was higher during periods of pretreated seawater high SDI than it was during normal times. SDI at the three depths of the RO intake ranged between 5.07-5.95, and the range for offshore water was 4.40 – 4.60. In times of normal operation, these ranges were 4.53-4.80 for the RO intake and 4.30-4.33 for offshore. During the 2003 high SDI, the difference between the SDI of raw water and filtered RO water was only 0.2 units, even though the filtration efficacy of the two RO plants exceeded 88.9%. The odd combination of high SDI and efficient filtration can be attributed to small particles escaping filtration. These particles appeared to be < 5- $\mu$ m in size.*

*The presence of sewage in the vicinity of the intake for the plants did not show any ill effects on the environmental parameters measured. Also, the chlorinated source water and product water from both SWRO and MSF plants were free of sewage bacteria and their associated viruses.*

*Inorganic nutrient concentration, plankton and chlorophyll production in coastal waters in the vicinity of the plants are similar to values reported in the coastal waters of north Jeddah. This indicates that the coastal waters near the plants are as clean as those in north Jeddah. The north Jeddah coast is reported to*

*be clean and relatively pollution-free. Heavy metal concentration in coastal and offshore waters was similar. Accordingly, any report about heavy metals pollution originating from the discharge of the desalination plants must be interpreted with caution. Measures which can be undertaken to solve the intermittent rise in SDI either on a short or long-term basis are being recommended.*

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## 1. INTRODUCTION

The Saline Water Conversion Corporation (SWCC) Jeddah phase-I and II seawater reverse osmosis (SWRO) plants use hollow fine fiber cellulose triacetate (CTA) membranes. Commissioned in April 1989, the Phase-I plant was already experiencing a noticeable drop in permeate quality one year later. Studies [1,2] attribute this decline to membrane oxidation, which in turn results from the presence of chlorine (used for disinfection) and heavy metals in the source water. This problem was alleviated by abandoning continuous chlorination in favor of intermittent chlorine injection [1,2].

A rise in silt density index (SDI) posed yet another problem. High SDI occurs primarily in late spring and fall. Between 1997 and 2003, there were 16 instances of elevated SDI in the dual media filter (DMF) filtrate. During this same period, the SDI exceeded the 4.0 limit set by the membrane manufacturer. This forced the plants to reduce output. At times, the plants even had to shut down. Plant management took the following steps to solve the problem:

- (1) Manipulation of filtration rate
- (2) Increasing the coagulant ( $\text{FeCl}_3$ ) dosing rate
- (3) Adding cationic coagulant polymer (Cat-Floc-C)

Although relatively successful when first implemented in 1996, these measures later proved to be ineffective.

The operators at the Jeddah plants suspected that the most likely culprit was excessive biological growth stemming from nutrient enrichment along the Red Sea coast. Moreover, this suspicion was born out in an earlier report to the SWCC [3] which indicated sewage dumping in coastal waters as a possible source of this problem. Likely sources of this sewage included: sewage plants at Hail and Al-Bangala, the port of Jeddah and nearby housing compounds and recreational parks.

Seawater contains a suspension of marine organisms, including mainly plankton. The density of these organisms is higher near the continental shelf where the marine fertility is enhanced by terrestrial nutrients. The region lying between 100-200m below the surface is known as the euphotic (lighted) zone and it is here that phytoplankton, the primary marine producers, proliferate. Seawater also contains, a significant non-

biological component consisting of sediment particles and detritus. Sea-floor sediments are kept in suspension by the action of waves, tides, currents and similar forces. Wadis, culverts and storm run-off are additional sources of the suspended particles found in coastal waters. These suspended solids are measured using SDI, an index which is used widely in desalination industry. The SDI is a parameter of great importance in SWRO plants which utilize various membranes to remove salts and produce fresh water.

Membrane filtration suffers from a high degree of feed-water impurity. For this reason, the water is pre-treated physically and chemically before membrane-based desalination is carried out. Such pre-treatment is especially required in the case of seawater-fed RO plants.

SWRO problems are site-specific: it is unlikely that two SWRO desalination plants in different locations face the same set of problems. For this reason, pre-treatment varies from one site to another depending on design, planning, operation and troubleshooting. Accordingly, the knowledge gained as a result of problem-solving at one location may seldom be useful or transferable to another. Consequently, procedures must be developed and practiced locally until well established.

The two SWRO plants in Jeddah produce about 26 mgd (million gallon/day) compared with 80 mgd from the three thermal desalination plants [4]. Thus SWRO accounts for approximately 30% of the water produced in Jeddah plants. Any disruption affecting the operation of SWRO plants can lead to a significant water shortfall. Given the serious nature of the matter, SWCC management recommended carrying out a study to examine the factors causing a high SDI, and this has been done.

## **2. OBJECTIVES**

1. To investigate the factors causing a high SDI in the Jeddah SWRO plants, and to ascertain the variation of this index around the intake point.
2. To investigate whether sewage discharge reaches the Jeddah plant intake, and to assess its contribution to biological growth.
3. To recommend a course of action to remedy the situation.

4. To establish an environmental data base for Red Sea water opposite the SWCC Jeddah plants.

### **3. RESEARCH DESIGN**

#### ***3.1 Sampling Site***

Five sampling locations were chosen. Four were in coastal water very close to the shoreline and one some distance off shore. These are detailed as follows:

1. 1.5 km south of the RO plants intake, and about 500m from the shore of the Ministry of Defense compound. This is designated S-location.
2. About 300m off-shore from the plants discharge bay (D-location).
3. In the vicinity of the RO plants intake (RO-location).
4. About 1.5 km north of the plants and about 200m off-shore (N location).
5. About 5 km off-shore from the plants (Open sea/off-shore).

At each sampling location there were 3 sampling points at depths of 1m, 15m, and 25m.

#### ***3.2 Duration and Frequency of Sampling***

Samples were taken between October 2002 and September 2004. Ten day samples were taken in May and October (reputed high SDI months). Bi-weekly samples were taken during the summer (June – September). Three week samples were taken during the period November-April. This period was known to be the most benign period as far as SDI is concerned. During a high SDI encounter, samples were obtained immediately

When scheduled sampling was not possible due to adverse weather conditions or mechanical problems, it was deferred to the shortest possible time.

### **4. MATERIALS AND METHODS**

#### ***4.1 Phytoplankton Density and Chlorophyll Pigment***

Phytoplankton were collected as follows: A boat towed a standard 55 $\mu$ m mesh Nansen phytoplankton net at about 2 knots (3.7km/h) for 10 min. On the average, this procedure filtered 30m<sup>3</sup> of water. A flow meter connected to the net indicated this. The sample was preserved in 5% formalin. Phytoplankton density was estimated by counting a 2.5 ml sub-sample in a Sedgwick Rafter counting chamber under a light

microscope. The counts were expressed as the number of organisms per cubic meter of seawater.

Chlorophyll-a pigment was measured with a special probe that works with a built-in standard. To ensure the accuracy of the probe, one in every three determinations standard spectrophotometric chlorophyll analysis was carried out along with this probe. This was performed in aliquots of one liter samples in accordance with procedure set out in a seawater analysis manual [5]. The samples were filtered using 045- $\mu\text{m}$  Millipore filters. The filter paper and the phytoplankton residue were homogenized with a vortex mixer in 90% acetone. The homogenizate was incubated overnight in the refrigerator and then allowed to warm up to room temperature in the dark. Following centrifugation, the supernatant optical density was measured in a 10-ml cuvette at the specified wave lengths.

#### ***4.2 Total Suspended Solids (TSS)***

TSS were determined by filtration of aliquots of one liter samples on glass fiber filters (47mm dia and about 1.2  $\mu\text{m}$  effective pore size) using membrane filtration assembly. The filter papers was soaked overnight in distilled water, then dried at 103-105°C before being cooled in a desiccator and then weighed to a constant weight before filtration. After filtration, both the tarred filter paper and the residue were dried overnight at 70°C then heated for 2 hours at 103-105°C, cooled and finally weighed to a constant weight. The difference between the two weights was calculated to the nearest milligram. The concentration of the suspended solids was expressed in mg/l.

Atomic Absorption Spectroscopy (AAS) was used to determine the composition of elements in the particulate residue and Energy Dispersive X-ray Analysis (EDX) was used to obtain a profile of the residue.

A two liter water sample was passed through membrane filter paper (47 mm dia, 0.45  $\mu\text{m}$  pore size). An identical sample was passed through a glass fiber filter. The filter paper and the residue collected on it were both dried over night in a ventilated oven at 60°C.

In the case of AAS, the filter paper and residue were extracted by boiling them in concentrated HNO<sub>3</sub> to near dryness before dissolving them in concentrated HCl.

### **4.3 Silt Density Index (SDI)**

SDI was measured using the standard 15-minutes procedure: 500 ml of water was collected on two occasions with a 15 minute interval between them, and drained at a pressure of 30 psi. This was done for seawater, chlorinated raw feed water and filtered RO feed water.

### **4.4 Transparency**

The degree of transparency was determined using a Secchi disk. The disk used in this instance was a weighted 20cm diameter disk and was painted with alternate black and white quadrants. The average depths at which the disk disappeared and reappeared constituted the Secchi disk visibility [6].

### **4.5 Physico-Chemical Parameters**

#### **4.5.1 Dissolved Oxygen (DO) and Biochemical Oxygen Demand (BOD)**

The DO was determined in 300 ml glass bottles using Winkler's method as described by ROPME [7]. Another 300 ml sample was taken from the same sample in amber glass BOD bottles and incubated for 5 days in the dark [8]. The 5-day BOD (BOD<sub>5</sub>) was obtained from the difference in the DO concentration between the initial and after 5-day incubation.

#### **4.5.2 Temperature, pH, Conductivity and Salinity**

These parameters were measured by a combination-probe instrument, (Data Sonde®-4, Hydrolab Corporation), according to manufacturer's instructions. The instrument also indicates depth and this allowed the determination of the three sampling spots of 1, 15, and 25m at each sampling location.

### **4.6 Nutrients**

#### **4.6.1 Inorganic Nutrients**

The presence of each of the nitrogen compounds (ammonia, nitrite, and nitrate) was tested for, and expressed in µg/l-nitrogen [5]. The indophenol method was used to

estimate total ammonia. The presence of nitrite was estimated by diazotizing with sulfanilamide and coupling with N-(1-naphthyl)-ethylene diamine. The presence of nitrate was demonstrated by conversion to nitrite using copperized cadmium in a reduction column.

The presence of phosphate was determined by the reaction of sea-water samples with a composite reagent containing molybdic acid, ascorbic acid and trivalent antimony, and expressed as  $\mu\text{g/l}$ -phosphorus.

#### *4.6.2 Total Carbon (TC)*

Total carbon (TC) was measured by a TC analyzer (Schimadzu-500) and the inorganic carbon (IC) was obtained by subtracting the total organic carbon (TOC) fraction. TOC was determined by measuring the  $\text{CO}_2$  released by the catalytic combustion of organic carbon in the samples. This was accomplished by using a non-dispersive infrared detector after the samples were acidified to purge off total inorganic carbon [9].

#### *4.6.3 Dissolved Organic Nitrogen and Carbohydrates*

Samples were first filtered through a 0.3 mm nylon mesh and then through a membrane filter (47mm dia and 0.45  $\mu\text{m}$  nominal pore size). Dissolved organic nitrogen was determined by oxidizing seawater samples with potassium persulfate under pressure, and organic nitrogen was converted into nitrate. The nitrate was then analyzed as described above (section 4.6.1). Carbohydrates were identified after hydrolysis of samples by HCl and subsequently examined by MBTH (3-methyl-2-benzothiazolinone hydrazone hydrochloride) assay [5].

### **4.7 Bacteriological Studies**

#### *4.7.1 Marine Bacteria*

A sterile 50 ml pipette was used to transfer water samples from the sampling bottle into plain sterile plastic sampling bags. For the sake of comparison, some samples were taken from inside the plant after chlorination. In this case, water samples were collected in sterile plastic sampling bags containing sodium thiosulfate as a de-chlorinator.

Immediately after sampling, bacteria were counted, and this count was designated as 0-h. Further counting was carried out after 24 h (24-h count) and 48 h (48-h count), following the incubation of samples in a thermostatically controlled incubator at 30°C. First, the samples were mixed thoroughly using a vortex mixer, then a pour plate count in marine agar was used to reveal the colony-forming units (CFU).

Briefly, the samples were first serially diluted in ten-fold steps in filtered (0.2 µm) and heat-sterilized seawater. Three dilutions from each sample were plated allowing a suitable number of bacteria to be counted. For each dilution, three replicates of 1 ml were seeded in separate standard size sterile Petri dishes. Thirteen milliliters of molten marine agar at 46°C were added to each dish. In each dish, the agar was mixed thoroughly with the 1 ml sample. The dishes were then allowed to cool for 30 min at room temperature before being incubated (inverted) in the constant temperature incubator. After 96h of incubation, the CFU were counted.

Zero-hour counts were taken as the basis for calculating the bacterial growth rate (generation time) during 24-h and 48-h incubation periods. This is expressed in the following formula [10]:

$$\text{Generation time (h)} = \Delta t \cdot K / (\ln N_t - \ln N_{t_0})$$

where  $\Delta t = 24$  for 24-h generation time and 48 for 48-h generation time,  $K = 0.693$ ,  $N_t$  = count at 24 or 48h and  $N_{t_0}$  is the count at 0h.

#### 4.7.2 Sewage Bacteria and Coliphages (Viruses)

Samples for sewage bacteria were collected in sterile one-liter size sampling bottles. Water samples were filtered to collect bacteria. The filtration funnel, funnel base and filter support were sterilized in boiling water for 10 minutes and then placed on the vacuum manifold. Bacteria were collected by filtering the water sample through a sterile 0.2 µm membrane filter 47mm in diameter.

This filter was then immersed in 100ml sterile buffered physiologic saline (0.85 wt/v NaCl, pH 7.2) contained in 100-ml size sterile transparent non-fluorescent polystyrene

bottle. To transfer the bacteria from the membrane filter into the saline solution, the bottle was shaken vigorously on a vortex mixer. Then, the filter was removed and discarded with a sterile forceps. A commercial preparation of coliform and *Escherichia coli* presence absence test (IDEXX Colilert® or Colisure®, IDEXX Laboratories, Inc., U.S.A) that is contained in plastic ampoules was added to the bottle containing the bacterial suspension. This product is based on defined substrate technology and utilized a nutrient indicator which fluoresces when metabolized by bacteria. It can detect bacterial concentrations as low as one CFU in 100 ml within 24h. The reagent was dissolved by shaking the bottle gently. The contents of the bottle were then poured into a Quanti-Tray®/2000 (IDEXX Laboratories, Inc.). After this, the tray was sealed with a Quanti-Tray® sealer and then incubated for 18h in a thermostatically-controlled microbial incubator at 35°C ± 0.5 °C. Following incubation, both the Quanti-Tray® vessels which were yellow with Colilert® reagent and the Quanti-Tray® vessels which were magenta-colored with Colisure® reagent were checked for fluorescence using a 6 watt 365 nm UV light in the dark. Those positive Quanti-Tray® wells which fluoresced were used for further identification of *E.coli*. A similar reagent, Enteroleet™, was used for testing the presence of enterococci (enteric Streptococci) with incubation at 42°C ± 0.5 °C.

Fluorescent Quanti-Tray® wells were incised aseptically and a sterile inoculating loop was inserted into each of these incisions. The inocula from the Colilert®/Colisure® quanti-trays were used to identify *E.coli*. To accomplish this, inocula were streaked on MacConkey agar plates in order to obtain discrete colonies. Colonies exhibiting the following characteristics were taken for definite identification: Gram's stain negative slender rods, motile, cytochrome oxidase negatives and catalase positive [11]. Such colonies were identified using the Analytical Profile Index (API 20E) system following the manufacture's instructions [12].

Enteroleet™ reaction Quanti-trays were used to identify enterococci. Inocula obtained with an inoculating loop were streaked onto Petri dishes containing bile aesculin azide agar. Following incubation at 44° - 45°C for 28h, the appearance of black colonies comprising Gram's stain positive cocci indicated the presence of enterococci [13]. Enterococci were speciated using growth characteristics in the following media:

MacConkey agar, glucose azide broth, tryptic soy agar with 5% sheep blood and 6.5% NaCl solution.

Whenever fecal coliform bacteria were isolated from seawater, product water was tested for presence of fecal coliform and coliphages (viruses). Product water derived from both MSF and SWRO was tested for the presence of fecal coliform bacteria as described above.

Viral assay was carried out following the *Standard Methods* coliphage detection procedure [9]. *E. coli* isolated from the Jeddah plants coast water was used as a host cell. Sterile distilled water and filtered (0.22  $\mu\text{m}$ ) raw sewage were used concurrently with the assay as negative and positive controls, respectively.

#### **4.8 Trace Metals**

Aliquots of one liter water samples were filtered, (0.45  $\mu\text{m}$ ), and acidified by the addition of nitric acid to a 1% concentration. Readily available (soluble) forms of arsenic, selenium, mercury, chromium, cadmium, copper, lead, iron, zinc and tin were all measured by atomic absorption technique [9]. GBC-Avanta  $\Sigma$  or Perkin Elmer-AAAnalyst-800 instruments were used to test for the presence of these trace metals. The presence of mercury was determined by cold vapor technique. Arsenic and selenium were analyzed by using the hydride generation method, and the remaining metals were analyzed after extraction using graphite technique analysis (GTA). First, the metals were separated from matrix by extracting in an organic phase (ammonium pyrrolidine diithiocarbamate/methyl isobutyl ketone APDC/MIBK). Then the metals were stripped into  $\text{HNO}_3$ . Finally, analysis was performed by means of GTA/Flame using Graphite Furnace System model 3000 (GF-3000). Trace metals were determined in the RO intake location and open sea and for comparison, these metals were also determined in a coastal lagoon. This lagoon (Arbaeen Lagoon) was known to have received sewage water [14].

#### **4.9 Data Analysis**

Data were analyzed using Sigmastat® software. Means were compared using Analysis of Variance and were reported with 95% confidence intervals. Those means which differed from each other were identified using multiple comparison tests.

## 5. RESULTS

### 5.1 *Phytoplankton and Chlorophyll*

Phytoplankton density was uniform at the order of  $10^4$  cells/m<sup>3</sup>, and increased to the order of  $10^5$  cells/m<sup>3</sup> during the latest high SDI period, which was October 2003. During this same period, there was also a noticeable proliferation of a zooplankton species of copepod. The phytoplankton production was relatively higher in fall (September-November), followed by summer (June-August), spring (March-May) and winter (December-February), but the seasonal means were only significantly different in fall and winter (Table 1).

Three phytoplankton classes were consistently represented in the samples, with an overall predominance of dinoflagellates (Class Dinophyceae). This was the case particularly during the summer months when diversity of species tends to be minimal. The dinoflagellates were mostly represented by the genus *Prorocentrum*. Diatoms (Class Bacillariophyceae or yellow-green algae) were next in abundance, with the species *Nitzschia clostrium* being predominant year-round. The third prevailing group was the blue-green algae/bacteria (Class Cyanophyceae), which was represented mainly by the genus *Trichodesmium* (*Oscillatoria*).

The average chlorophyll production in coastal waters was  $0.51 \pm 0.33$  µg/l compared to  $0.22 \pm 0.10$  µg/l in off-shore waters, there being no seasonal differences between both locations. Chlorophyll concentration increased dramatically, following the increase in phytoplankton production during the most recent occurrence of high SDI (Table 2).

### 5.2 *Total Suspended Solids (TSS)*

TSS concentration ranged from 1.54 to 2.69 mg/l. There was no significant difference in concentration among the four coastal sampling sites, nor among the three sampling depths for each sampling site (Table 3). TSS concentration was also similar at both coastal (RO intake) and off-shore sites, with a significant increase in 2004 compared to the preceding two years (Table 4).

TSS increased considerably during periods of high SDI. For depths of 1, 15, and 25 meters, TSS varied substantially more during the month of Oct., 2002 (a high SDI

month) than it did during the same month of the following year (also a high SDI month). In 2002, the range for the RO intake was 15.1 – 21.9 mg/l, compared to 6.6 – 7.0 mg/l for 2003. Corresponding TSS ranges for off-shore waters were 9.3 –14.1 mg/l and 4.4 – 5.8 mg/l for the two aforementioned high SDI periods, respectively (Table 2). During times of normal SDI, TSS ranged from 2.5 to 2.8 and from 1.6 to 1.8 mg/l for the RO intake and off-shore waters, respectively. Table 5 shows the effect of chlorination and filtration on TSS. TSS concentration during the high SDI encounter of 2003 was 6.2 mg/l in the RO intake, increased to 7.2 mg/l after chlorination and then decreased to 0.6 and 0.8 mg/l in the pretreated feed-water of the RO-1 and RO-2 plants, respectively. The pretreatment efficacy (defined here as the percentage of TSS removed after coagulation and filtration) exceeded 88%, (Figure 1 & Table 5).

Table 6 shows the composition of elements, given in percentages, for suspended solids, as revealed by atomic absorption. Figure 2 shows EDX profile of suspended solids. The picture insert shows algal filaments with entrapped debris and detritus.

### **5.3 Silt Density Index (SDI)**

Seawater SDI was higher during periods of pretreated seawater high SDI than it was during times of normal operation at all three of the depths sampled. During the period of high SDI in 2002, the SDI values in the RO intake ranged from 5.61 to 5.95, compared to a range of 5.07 to 5.58 during the period of high SDI in 2003. Offshore, those ranges were 4.50 – 4.60 and 4.40 – 4.50 for the aforementioned two high SDI periods, respectively. During normal operation period, the range was 4.53 – 4.80 for the RO intake and 4.30 – 4.33 for off-shore (Table 2). Table 5 gives SDI variation along the pretreatment line during the period of high SDI in 2003. The SDI increased upon chlorination and then decreased after filtration, but only to a very limited extent. The difference between the SDI values in raw seawater and pretreated filtered RO water was only about 0.2 (Fig.1).

### **5.4 Transparency**

Secchi disk visibility is a measure of transparency that corresponds with TSS load. As TSS concentration increases, disk visibility is reduced. For both coastal and off-shore waters, the reduction in transparency was more than 8m between high and normal SDI periods (Table 2).

## **5.5 Physicochemical Parameters**

### **5.5.1 Dissolved Oxygen (DO) and Biochemical Oxygen Demand (BOD)**

Coastal and off-shore waters contained appreciable concentrations of DO. The concentration approached 6 mg/l, with no difference between coastal and off-shore waters. BOD was minimal and the oxygen consumed during the 5-day BOD test was less than 0.90 mg/l in either coastal or off-shore waters (Table 7).

### **5.5.2 Temperature, pH, Conductivity and Salinity**

During sampling, the temperature fluctuated within 4°C from 27.8 – 31.7°C. On any given sampling date, variation in temperature either among different depths at a given sampling site or among different sampling sites did not exceed 1°C. The pH ranged from 8.10 to 8.70. On any given sampling date, differences either among different sampling sites or among different depths of the same sampling site were minimal. Electrical conductivity ranged from 57,800 to 59,400 uS/cm. Salinity ranged from 39.30 to 39.85‰.

## **5.6 Nutrients**

### **5.6.1 Inorganic Nutrients**

Table 8 shows concentrations of inorganic nutrients. There was no statistically significant difference in any nutrient concentration among the four coastal sampling sites nor was there any among the different depths of any one given sampling site. The concentration of inorganic salts was also similar for both coastal and off-shore sites, as was the case for inorganic carbon (Table 7).

### **5.6.2 Total Carbon (TC)**

Total organic carbon (TOC) values were similar in both coastal and off-shore waters, with a range of 2.16 – 2.63 mg/l (Table 7). During the high SDI period for 2003, the range of TOC values increased to 5.0 – 6.0 mg/l in coastal waters and to 4.3 – 5.8 mg/l in off-shore waters (Table 2). Total inorganic carbon (TIC) values were also similar in coastal and off-shore waters with average values of  $24.75 \pm 0.39$  and  $24.67 \pm 0.41$  mg/l for the two sites, respectively (Table 7).

### 5.6.3 *Organic Nitrogen and Carbohydrates*

Dissolved organic-N varied with location but not with depth. Its concentration in coastal waters, ( $23.89 \pm 0.75 \mu\text{g/l}$ ), was significantly higher than that in off-shore waters ( $19.06 \pm 0.48 \mu\text{g/l}$ ). The sugar concentration was also similar in the three depths at the two locations but with a higher concentration off-shore (Table 7). The sugar concentration range was 34.2 to 70.2  $\mu\text{g/l}$ .

## 5.7 *Bacteriological Studies*

### 5.7.1 *Marine Bacteria*

Bacterial density and growth at the four coastal sampling sites are presented in Table 9. The initial bacterial concentration was higher at the two sampling sites south of the RO intake (Locations – S and D) than the concentration in the RO intake and the sampling site north of it, with a difference of somewhere between 1 and 2 orders of magnitude ( $10^4$  as compared to  $10^3$  or  $10^2$ ). All sites exhibited accelerated growth following a 24-h incubation of samples. This growth reached 2 – 3 orders of magnitude over the initial numbers. The density became uniform at the order of  $10^5$  cell/ml following 48-h incubation. The 48-h count was lowest at the RO intake. Generation time was similar after 24-h of growth, during which time the bacteria multiplied about once every three hours. The multiplication rate was slower and different upon 48-h incubation.

Table 10 provides a comparison of bacterial density and growth in coastal and off-shore waters. The density was higher in coastal waters than off-shore. Growth rates differed only by minutes. Chlorination contributed significantly to bacterial growth (Table 11).

### 5.7.2 *Sewage Bacteria and Coliphages (Viruses)*

Sewage bacteria were tested for on seven occasions during seven month of the two-year study. Samples were positive for fecal coliform bacteria on 3 sampling dates and were negative on the remaining 4. The fecal coliform bacteria identified were *Escherichia coli* and *Enterococcus fecalis*. The API identification profile was 100% for *E. coli* (Photograph 1). The *Ent. fecalis* was identified based on the following reactions: growth on MacConkey medium, production of  $\alpha$ -hemolysis on 5% sheep blood with trypticase soy agar base, survival in 6.5% salt solution and production of black colonies on bile aesculin azide agar (Photograph 1). Station-S (shore of the Ministry of Defense

compound) was positive on two out of the three occasions in which fecal coliform bacteria were isolated. On one occasion, it was positive for both *E. coli* and *Ent. fecalis*, and on the other occasion, it was only positive for *E. coli*. The N location (about 1.5km north of the plants) was positive on one sampling date for both *E. coli* and *Ent. fecalis*. Likewise, sampling station D (offshore from the plant discharge bay) was positive once for both *E. coli* and *Ent. fecalis*. The RO location (in the vicinity of the RO plant intake) was positive once for *E. coli* but negative for *Ent. fecalis*. The presence of fecal coliform bacteria was not restricted to any of the 3 depths tested and fecal coliforms could be recovered from any of these depths, but not necessarily from the surface sampling point.

Fecal coliform bacteria were not isolated from seawater after chlorination or from RO or MSF product water. Coliform viruses (coliphages) were also absent in product water. The most probable number of fecal coliform bacteria in positive samples ranged from 1 to 4.1 cells/100 ml seawater. The range for coliform bacteria was 1 – 67.7 cells/100 ml.

### **5.8 Trace Metals**

Table 12 shows the concentrations of trace metals. This table also gives a comparison of some other pollution-indicating parameters between coastal seawater, off-shore seawater and the Arbaeen lagoon. This lagoon was known to be subject to sewage dumping. The parameters given in this table do not indicate that coastal water is any different from off-shore seawater.

## **6. DISCUSSION**

A discussion of results of the different water quality parameters measured is presented below. Statistical comparison of treatment means did not reveal outstanding differences between coastal sites near the plants, between the coastal and offshore waters or between periods of high and normal SDI, (either in coastal or offshore waters). The intake site of the Jeddah SWRO plants was no more worse than other coastal locations. Moreover, apart from slight increase in phytoplankton production the intake was also found to be similar to offshore waters. Sewage water reached the plant intake, but was not a causal agent of high SDI, nor was it hazardous to product water quality. Plant operators were efficient in working through high SDI encounters.

### **6.1 *Phytoplankton and Chlorophyll***

The present data show that there is little seasonal or annual variation in the production of plankton biomass (Tables 1 & 2). The taxonomy and relative abundance of phytoplankton groups conform to those reported in the Red Sea water north of Jeddah [15]. A study of phytoplankton in Gulf coastal waters at Al-Jubail desalination and power plants showed that they were composed of the same classes of marine algae reported in the current study [16]. This study showed annual phytoplankton density in the order of  $10^4$  cell/m<sup>3</sup> compared to  $10^4 - 10^8$  cell/m<sup>3</sup> in Gulf coastal water. The difference in abundance between the Red Sea and Gulf waters is attributed to difference in water fertility as will be seen later in discussion of nutrients.

Phytoplankton density was similar for both normal SDI periods and the high SDI period of 2002. The high SDI encounter is thus attributed to a sharp rise in silt concentration as indicated in the proceeding section. During the 2003 high SDI period, phytoplankton density was relatively higher than the density of the normal SDI periods in the RO intake and open seawater, while the TSS load was appreciably less than that of the high SDI period of 2002 (Table 2). Phytoplankton in this instance contributed to the 2003 high SDI period. During this period, there was a noticeable blooming of a copepod. This is a large zooplankton animal which could easily be mutilated by intake structures. Phyto and zooplankton that are broken into pieces by the mechanical force of water drawn under high pressure and mutilated by plant structures are further decomposed by chlorine. Due to the diminutive size of plankton ( $\mu\text{m}$ -size), their physical destruction and chemical decomposition could easily reduce them to size fractions less than 10  $\mu\text{m}$ . Since the pore size of the micron cartridge filter at the Jeddah SWRO plants is 10- $\mu\text{m}$ , the plankton pieces could not be coagulated and could pass DMF and MCF and thus increase the SDI. This study shows that SDI increased upon chlorination by 0.16 and could only be reduced by 0.37 – 0.38 in feed water for the two RO plants (Table 5). This also indicates small size particles escaping filtration.

During periods of normal SDI, chlorophyll production is similar in coastal and off-shore waters ( $0.51 \pm 0.33$  and  $0.22 \pm 0.10$   $\mu\text{g/l}$ , respectively) and with no variation with depth. Lack of significant differences in chlorophyll production in coastal and offshore waters reflects the phytoplankton homogeneous distribution as shown above. It is worth

noting here that chlorophyll provides a good estimate of phytoplankton density. Approximately, 1 – 2% of the dry weight of planktonic algae is chlorophyll [17].

The sampled stratum of water up to a depth of 25m is well mixed and lighted, resulting in evenly distributed phytoplankton in the water column and similar chlorophyll production at the three sampling depths. Chlorophyll production is usually fairly constant up to a depth of 30m in seawater [18]. Following the increase of phytoplankton density during the 2003 high SDI period, chlorophyll average production increased from 0.51 µg/l to 2.1 µg/l in the RO intake, and from 0.22 to an average of 1.3 µg/l in the open sea. Chlorophyll production occurred the least in surface water (Table 2). This is usual in the tropics, where excessive surface solar radiation inhibits chlorophyll production. When the water becomes light saturated, photosynthesis is inhibited by bleaching or arresting photosynthetic pigment production [19]. The chlorophyll production in the Gulf coastal waters at Al-Jubail desalination and power plants showed an annual range of 0.82 – 1.17 µg/l [20], compared to a range of 0.18 – 0.86 µg/l during normal SDI times at the Jeddah plants' coast. This is because of high phytoplankton density in the Gulf [16], which makes Gulf waters more productive. Jubail coastal waters have not been a subject of sewage pollution as in Jeddah, and high biological productivity is not necessarily a product of pollution. The average chlorophyll production in the Red Sea coast of Obhur, north of Jeddah, is  $0.59 \pm 0.38$  µg/l [21], compared to  $0.51 \pm 0.33$  in the RO intake (Table 2). The difference between the two means is not statistically significant. The Obhur coast, and the north Jeddah coastline in general are not considered polluted. The level of chlorophyll production from the Jeddah RO intake is similar to that of north-Jeddah. This was also found to be true for phytoplankton, as mentioned already. Therefore, with respect to plankton and chlorophyll production, the Jeddah desalination plant coast is not impacted and is similar to the north Jeddah coast, which is deemed clean.

## **6.2 Total Suspended Solids (TSS)**

TSS concentrations were low and similar in the four coastal sampling locations and in the three sampling depths at each location; a range of  $1.56 \pm 0.38$  to  $2.69 \pm 0.44$  mg/l. These concentrations are extremely low compared to concentrations exceeding 20 mg/l in Gulf coastal water at Al-Jubail plants [20]. This is because the sea at the Jeddah

plants is deep and bottom sediments could not be as easily disturbed as in the shallow Gulf coast. The low TSS concentration obtained during normal SDI periods increased dramatically during high SDI encounters. The chief reason for elevated TSS levels is water column disturbance, which in turn is due to local water movements and bottom currents.

During the high SDI period of October 2002, the average TSS concentration for the three depths at the RO location was 17.6 mg/l (15.1 – 21.9) mg/l), compared to an average of 6.8 mg/l (6.6– 7.0 mg/l) for the high SDI period of October 2003 (Table 2). The high SDI in 2002 could therefore be attributed to a rise in suspended silt concentration. The silt load could be brought to the plant intake by bottom currents with the pumping force of feed water aiding in its mixing in the water column. TSS concentration at the lower depth of 25m was higher than the overlying water at 15 and 1-m depths. Since the coastal area south of the plant in the vicinity of the Ministry of Defense compound is shallow, local north-ward currents from this area could contribute significantly to TSS load at the plant intake.

The increase of coastal TSS concentration during the 2003 high SDI period was only 2.5 times the normal SDI periods, compared to an almost sevenfold (6.9) increase during the 2002 high SDI. The 2003 high SDI could be attributed to a combination of increased silt concentration and enhanced biological growth.

During normal SDI times, TSS concentration in coastal water is not different from offshore water during the two year project. However, TSS in both coastal and offshore waters showed significant increase in 2004 compared to 2002 and 2003 (Table 4). The cause of such increase in TSS concentration is not at present known.

Atomic absorption (AA) analysis of suspended solids is presented in Table 6 and EDX profile is presented in Figure 2. Na, Mg and Ca are principal constituents. These elements represent the major cations in seawater. Their salts could be adsorbed and trapped in the suspended material. The AA technique seems to be reliable and steps for preparing suspended solids for AA may further be developed so that more constituents are revealed. The organic content of suspended solids is environmentally and biologically more important than the inorganic portion. Techniques other than AA may

be more suitable and need to be considered for analyses of the organic and inorganic constituents of suspended matter.

### **6.3 Silt Density Index (SDI)**

SDI in either coastal or open seawater showed positive correlation with TSS, whereas it increases with increasing TSS concentration (Table 2). The correlation is not necessarily strong. The 2002 high SDI coastal TSS concentration is 2.7 times that during the 2003 high SDI. The difference in the coastal SDI values between the two periods was 0.42. Offshore, TSS of the 2002 period is 2.2 times that of 2003, with a difference of 0.09 in SDI (Fig. 1). The difference in SDI offshore is minimal when compared to coastal water, even though the increments in TSS are comparable. This variation in SDI values is due to difference in phytoplankton density. In coastal water, the 2003 high SDI period phytoplankton increased by 3.5 times over the 2002 count. In off-shore water, the increment was 2.3 times. Phytoplankton could be clogging the SDI-measuring membrane filter, thus giving high SDI values. Since the water content of these organisms is high, their dry weight is very negligible. Thus, while phytoplankton may clog the SDI-measuring membrane filter, thereby giving high SDI values, they nonetheless contribute little to TSS in terms of weight.

During the 2002 high SDI, the plant filters were efficient at removal of suspended solids. The filtration efficacy was 91.7% for RO-1 and 88.9% for RO-2. In spite of this efficient filtration, SDI of RO feed water remained high (above 4.80, Table 5). The plant uses 10- $\mu\text{m}$  size MCF, and at times the plant has also operated with 5- $\mu\text{m}$  MCF, but without reaching acceptable SDI levels. This means that the particle involved in SDI are  $< 5 \mu\text{m}$ . The high SDI of 2003 occurred even the TSS was considerably lower than the previous high SDI period. This indicates a higher percentage of small-size particles in the 2003 high SDI than for the previous year. Such small particles could be removed by ultrafiltration. This is an alternative for rectifying the SDI problem.

### **6.4 Transparency**

Secchi disk visibility is a measure of transparency and it corresponded with TSS load (Table 2). The difference in visibility between the same location during the two high SDI periods was less than 2m. This does not correlate strongly with the large TSS concentration of the first period, as compared to the second period and may be due to a

difference in the nature of the suspended particles. As mentioned above, the proportion of small-size particles in the second high SDI period is high. Minute suspended particles increase light attenuation. Also, in the second period, the presence of a denser phytoplankton community aids in decreasing light penetration. Secchi disk visibility during the first high SDI period was 7.5m, and for the second period it was 9.25 m (Table 2). A Secchi disk visibility of 10m may roughly be taken as a warning sign for expecting a high SDI encounter. In normal SDI periods, visibility ranges for coastal and off-shore waters overlaps, indicating similar transparencies in the two sites (Table 2).

## **6.5 Physicochemical Parameters**

### *6.5.1 Dissolved Oxygen (DO) and Biochemical Oxygen Demand (BOD)*

Concentration of DO was very stable at values approaching 6.0 mg/l. This value lies within the normal coastal water range of 4 – 8 mg/l [19]. At the temperature range of 27.8 – 31.7°C recorded during the study, the solubility of oxygen in water of 40‰ salinity under normal atmospheric pressure ranges between 5.96 – 6.35 mg/l [17]. The oxygen levels in coastal and off-shore waters (Table 7) are therefore close to 100% saturation. Although oxygen can diffuse between air and water depending on physical forces, biological processes are as important as physical processes in regulating dissolved concentrations in water bodies. Phytoplankton produce oxygen in photosynthesis, which is consumed in respiration. The stable oxygen concentration in the study area reflects moderate photosynthetic and respiratory activities. The productivity of the Red Sea coastal waters is thus moderate to low, and this is indicated by low phytoplankton density. This being the case, diffusion of oxygen from air seems to be the major source of oxygen in water. Turbulence and water mixing aided in saturation and transport of oxygen to deeper water layers. DO concentration reflects the well mixing of water column with no significant difference between concentrations at any of the sampling depths. An insignificant role of phytoplankton in oxygen saturation is also indicated by similarities of DO concentrations in coastal and offshore water, even though phytoplankton were more abundant in coastal water (Tables 2 & 7).

BOD measures the oxygen uptake in the microbiologically-mediated oxidation of organic matter. The amount consumed during a 5-day incubation period, ( $BOD_5$ ), in coastal and offshore water was very low (less than 1 mg/l). The amount of biodegradable matter must be minimal. It will be seen in the section on sewage bacteria

that on some occasions sewage discharge reached the sampling sites. Judging from the negligible BOD values, sewage discharge does not exert any significant oxygen consumption and the sewage effect is thus benign.

### *6.5.2 Temperature, pH, Conductivity and Salinity*

Minimal fluctuations in temperature, pH, conductivity and salinity in the sampling sites reflect stable sea conditions during the study. All values provided are typical of Red Sea water. Of these parameters, pH is more susceptible to fluctuation, due to photosynthesis and respiration. The Red Sea is poor in plankton growth with stable production of CO<sub>2</sub> and consumption of O<sub>2</sub>, resulting in minimal changes in pH.

## **6.6 Nutrients**

### *6.6.1 Inorganic Nutrients*

Table 8 shows concentrations of inorganic nutrients in the four coastal sampling sites. Photosynthesis of algae is controlled by factors other than light, chiefly nutrients and temperature. With plenty of solar radiation and optimal temperature in the Red Sea coastal water, nutrients become the most limiting factor for photosynthesis, the base of the food chain in an aquatic environment. Carbon, nitrogen and phosphorus are the principal nutrients in water. Carbon is abundant and rarely becomes a limiting growth factor. Next in abundance is nitrogen, followed by phosphorus. The uptake of carbon, nitrogen, and phosphorus by marine phytoplankton is generally found to be in the ratio of 106:16:1 [22]. In the oceans, nitrogen exists mainly as molecular nitrogen and as inorganic salts of nitrate, nitrite and ammonia. The usual range of concentration for these compounds in seawater is 0.01 – 50 µg-N/l for nitrate, 0.01 – 5 µg-N/l for nitrite, and 0.1 – 5µg-N/l for ammonia [23]. Algae generally show a preferential utilization for one of the three nitrogen salts and ammonia is generally utilized in preference to nitrate. Ammonia is preferred because it can be used directly for amino acid synthesis without a change in oxidation state. This makes the use of ammonia a kinetically favored process [24]. The cell synthesizes the nitrogen salts to make amino acids and then proteins. Nitrate and nitrite are taken actively by cells from the surrounding water and transported via the cellular membrane to the inside of the cell. Within the cell, the enzyme nitrate reductase, reduces nitrate to nitrite and nitrite reductase reduces nitrite to nitrogen that can be incorporated into amino acids. Likewise, ammonia is transported across the cell membrane by an active process and directly assimilated into amino

acids. The concentration of the three nitrogen salts in the four sampling coastal sites is presented in Table 7. Nitrogen salt concentration was similar horizontally in the four coastal sampling sites and vertically with depth. The concentration of nitrate and nitrite were in the lower distribution of their ranges in seawater mentioned above. The ammonia range in the present study was 1.36 – 1.67  $\mu\text{g-N/l}$ . This is close to the middle of its distribution range in seawater. Ammonia is thus consistently available and is considered the major nitrogen salt in this area. The range of nitrogen salt concentration from the north Jeddah Red Sea coast at Obhur was within the range determined here [21]. There is nothing in values reported for nitrogen salts in this study to suggest nutrient enrichment.

Phosphorus occurs in seawater in three principal phases: dissolved inorganic phosphorus, dissolved organic phosphorus and particulate phosphorus. Phytoplankton normally assimilate dissolved inorganic phosphorus (orthophosphate ion). While nitrogen is used to synthesize protein (the structural component of cells), phosphorus is used primarily in the energy cycle of the cell. Dissolved orthophosphate concentration in natural water is usually in the range 5 – 20  $\mu\text{g-P/l}$ . The concentration range in the coastal sampling locations was 0.09 – 0.1  $\mu\text{g-P/l}$  (Table 7). This concentration is very low and stable, indicating no contribution from land discharges. In a recent study [21], phosphorus concentration in the north coast of Jeddah (about 40 km from the SWCC desalination plants) reached values as high as 1.9  $\mu\text{g-P/l}$  during the summer. The high phosphorus concentration may be attributed to discharges from the very recent vast urban and recreational centers in north Jeddah. The north Jeddah coast may then be considered more affected than the desalinated plant coast and not as clean as it was claimed to be.

Table 8 gives a comparison of nutrients in coastal and offshore water. The inorganic salt concentration was similar in both locations. The ratio of N:P for coastal water was 27:1 compared to a ratio of 30:1 in offshore water. Both ratios are below the 16:1 ratio which is favorable to plankton growth. The indication from these ratios is that phosphorus is the limiting nutrient and is present at a concentration which is far too low for healthy phytoplankton growth and hence stable primary production. Considering the present low phosphorus concentrations, only an appreciable amount of land discharge of phosphorus, as from raw sewage, could trigger plankton blooming with its associated

negative effects on the desalination plants and their coast. It is estimated that phosphate levels of less than 5 $\mu$ g-P/l are unlikely to exhibit eutrophic tendencies [8].

### 6.6.2 *Total Carbon*

In addition to its inorganic major, minor and trace constituents seawater contains both particulate and dissolved organic matter [25]. The organic carbon (TOC) in water is composed of a variety of organic compounds in various oxidation states [9]. Some of these compounds can be oxidized further and utilized by various marine organisms. Others are refractive and cannot be utilized. TOC is a measure of all these carbon fractions in water and is a measure of organic load in water rather than a nutrient index. From a summary of values in the literature, Williams [26] concludes that in shallow water (< 100 m) dissolved organic carbon values range from 0.6 – 2.0 mg/l. Values reported in this study were close to this global range (Table 7).

During times of normal SDI, TOC concentrations in coastal and off-shore waters are similar. However, TOC concentrations increased about twofold in both locations during the 2003 high SDI period. The rise in TOC is attributed to the rise in plankton density (Table 2). Normally, following a phytoplankton bloom, TOC concentration may register a 3-fold increase [24].

The amount of inorganic carbon was nearly constant and similar in coastal and off-shore waters. The concentration in both locations approached 25 mg/l. At the range of the pH reported, (8.1 – 8.70), the inorganic carbon present in seawater is mostly bicarbonate in concentration of approximately 25 mgC/l [24]. The present concentration levels from the Red Sea, are therefore, typical of seawater. The level of 25 mgC/l is a large excess over the amount generally required for phytoplankton growth.

### 6.6.3 *Organic Nitrogen and Carbohydrates*

Dissolved organic nitrogen concentration was higher in coastal water than in off-shore water (Table 7). This is normal in seawater because the coastal water has greater association of living organisms and higher rate of organic decomposition than offshore water, not to exclude the possibility of sewage being a factor in higher coastal organic nitrogen concentration. The amount in the upper layers of water also showed the

greatest concentration variability. In this study, the concentration showed stable values but are about twice as high as those reported in the literature for marine water [27].

Dissolved carbohydrates showed higher concentration in off-shore water than coastal water. The presence of more organisms near the coast could reduce readily metabolizable substrate and lower its concentration. Carbohydrate levels in seawater fluctuate widely and concentrations reported in Table 7 are typical of those found in shallow seawaters [24].

## **6.7 Bacteriological Studies**

### **6.7.1 Marine Bacteria**

It could be seen from Table 9 that for the pooled 0-h and 24-h, bacterial counts in the two sampling sites south of the plant intake were higher than counts in the intake and in the sampling site north of it. The difference in both cases was one order of magnitude ( $10^4$  vs.  $10^3$  for 0-h and  $10^6$  vs.  $10^5$  for the 24-h count). The sea at the two sites south of the plants is shallow and bacteria are more concentrated in the water column. The 24-h bacterial growth rate was similar at all sampling sites. This reflects availability of sufficient nutrients that equally supported growth of differing initial bacterial concentration. Upon 48-h incubation, the bacterial count at all sites stabilized at the same order of magnitude ( $10^5$ ). This means that sites with initially higher counts showed slower growth and this is reflected in the 48-h generation times. The growth rates became inversely proportional to the initial bacterial concentration (Table 9). As indicated in the discussion of nutrients, there was no difference in nutrient concentration between the four sites. Samples with higher initial bacterial concentration exhausted nutrients faster and showed slower growth rates than samples with initially lower bacterial concentration which showed faster growth rates. Although, generation time is useful in assessing the nutrient load and biofouling potential of source water, initial bacterial density has to be considered, particularly in water sources of similar nutrient load. Also, it is advisable to incubate water samples for at least 48 hours so as to give bacteria ample growth time. This will reveal the status of nutrient load and the biofouling potential of water samples.

A comparison of bacterial concentration and growth in coastal and offshore water is given in Table 10. Analysis of average values of the three depths from each sampling

site showed higher initial bacterial density on the coast than offshore (order  $10^3$  vs.  $10^2$ ). However, the 24-h and 48-h counts were in the order of  $10^5$ , reflecting slower growth rates in coastal water. This is also shown by the higher generation times (slower growth rates) in coastal water. From the aforementioned discussion, coastal and offshore waters seem to be similar in every respect. The difference in growth rates must then be due to the higher starting bacterial density in coastal water. This has led to faster exhaustion of nutrients, as in the case of the four coastal sites.

Table 11 shows the effect of chlorination on bacterial growth rates. For comparison, results from previous studies at Al-Birk and Al-Jubail are also provided in the table [28,29]. In the three sites, growth in chlorinated samples is significantly enhanced over their non-chlorinated counterparts. The growth magnitude in Jeddah and Al-Birk is similar in chlorinated as well as in raw seawater without chlorine for both the 24 and 48-h generation times. This is due to similar nutrient composition as shown by this and another study [30]. For this reason, similar steps could be taken to control biofouling problems and to introduce process modifications in Jeddah and Al-Birk. Both plants have successfully introduced chlorine tolerant membranes and have adopted an intermittent mode of chlorination in place of the continuous chlorination operation [2, 31]. Al-Jubail water showed a different picture. Growth in Jubail raw seawater was slow compared to Jeddah and Al-Birk. However, upon chlorination, growth accelerated immensely. In Jubail, the growth of chlorinated samples after 48h was similar to that after 24h. This reflects a huge capacity for an exponential growth. In contrast, growth in chlorinated samples of Al-Birk and Jeddah following 48-h of growth was significantly lower than that after 24-h. The Gulf coast water at Jubail is more productive and contains more plankton than the Red Sea [15 and present study]. Decomposition of plankton by chlorine provides the needed nutrients for accelerated growth. Biofouling of RO membranes in Jubail could therefore be a serious problem in chlorinated feed water.

### 6.7.2 Sewage Bacteria

The bacteria *Escherichia coli* and *Enterobacter fecalis* are chief indicators of sewage contamination. The isolation of these species from the coast of the desalination plants indicates that some form of sewage is reaching the plant. In themselves, these bacteria are not dangerous, but their presence indicates that fecal matter has entered the water

supply, that the fecal bacteria have not been killed or removed by purification processes and that the supply is therefore, liable to contamination with intestinal pathogens like the agents of typhoid fever, cholera, campylobacteriosis, amoebiasis and helminthiasis [13]. Fortunately, these threats are alleviated by the fact that neither fecal bacteria nor their viruses have been detected in feed water after chlorination. They were also absent and are not likely to ever be present in product water because of the heat in MSF desalination plants and membrane particle size cut-off in membrane desalination plants. The water produced by the desalination plants in Jeddah is, therefore, of sound and safe quality.

Concentrations of nitrogen, phosphorus and organic carbon were in their regular concentrations in normal seawater. No concentration peaks were detected, even when samples were positive for fecal bacteria. The density of fecal bacteria was low (1.0-4.1 ml). The presence of even a low density of fecal coliform bacteria may indicate considerable dumping of sewage into coastal water. This is because only aliquots of two-liter seawater sample were analyzed. The samples were randomly taken from the tremendous body of the sea. The likelihood of catching such indicator organisms in a small sample volume is slim and their mere presence is therefore indicative of their wide dispersion in the area. Since there is no increase in nutrient or trace metal concentration (Table 12), primary production or DO consumption, the sewage may have received some level of treatment. It is also possible that the sewage is discharged without treatment, but the sea was able to neutralize its negative effect. The potential for dilution and dispersion of pollutants in the open sea is considerable, and there is a large self-purification capacity. Sewage discharge deep offshore with strong tidal flows are likely to be almost undetectable. Provided that discharges to the open sea are made through long outfalls with well designed diffusers on the sea bed, any environmental effects are likely to be negligible. When tidal action is limited, only full treated sewage should be discharged into the sea, as is currently practiced inland.

The procedure followed for the isolation and identification of sewage bacteria is direct, sound and reproducible (photograph a). The probability of isolating sewage indicator bacteria from various sampling sites and depths is variable due to the small sample size and the uneven dispersion of bacteria. Chemical markers of sewage pollution may be more homogeneously mixed in the water column than bacteria and could thus be useful

sewage indicators. Al-Rasheed [32] was able to detect caffeine and cholest-5-en-3 $\beta$ -oL in humic acids extracted from the Jeddah desalination plant coastal water. The cholest-5-en-3 $\beta$ -oL is a common marker of fecal contamination. This also implies that sewage waste is reaching the coast of the Jeddah plants and that chemical markers could be used to detect it.

## 6.8 Trace Metals

Table 12 shows trace metal concentration and some other pollution-indicating parameters in seawater and the Arbaeen lagoon. The Arbaeen lagoon is a coastal lagoon connected by a narrow isthmus to the Red Sea coast of Downtown Jeddah. It is known to have received sewage water [14]. The lagoon is vastly cleaned but water exchange ratio is low.

Arsenic, Selenium, Mercury, Chromium, Cadmium, and Tin were either not present at all, or present in amounts below their normal concentrations in seawater. The seawater concentrations of Lead, Copper, Iron, and Zinc exceeded their normal levels [33]. The atomic absorption spectrophotometry measures the total concentration of a particular metal. The toxicity of heavy metals is related primarily to the dissolved, ionic form of the metal, rather than the total concentration which is what the atomic absorption measures. The toxic part of a metal may only be a fraction of the concentration shown in table 12, and would probably need to be magnified several times in the food chain before it can have any harmful effect. Safe levels concentration of lead, copper and zinc for a variety of freshwater and marine animals, mostly fish, is much higher than the present concentration [17]. The safe level for lead is 100 $\mu$ g/l (its current concentration coastally, offshore and in the Arbaeen lagoon ranges from 2.0 – 4.3  $\mu$ g/l). The safe level for copper is 25 $\mu$ g/l, compared to a current range of 1.0 – 1.3  $\mu$ g/l, and the safe level for zinc is 100 $\mu$ g/l compared to a present range of 0.8 – 0.9  $\mu$ g/l (Table 12). The fourth metal (Iron), whose concentration exceeds the normal range, is not normally considered toxic. In any case, the concentration of metals is similar in both coastal and offshore waters and this does not reflect pollution of coastal water.

With respect to pollution, Lead is the metal of primary concern. The obvious source of lead is automotive fuel, where it is used as an anti-knock ingredient in the form of tetra-ethyl lead bromide [19]. Lead from this source rains from the atmosphere directly into

the sea or precipitates from air in the soil and is then washed into the sea. About 1% of the world's lead production enters the sea each year [19]. The use of fuels and paints which are free of lead has reduced the levels of lead in environment and drinking water. Other metals of particular concern in aquatic environments are Hg, Cu, Cd, Zn and Cr. Mercury was the first of these to be brought to worldwide attention. Most mercury compounds decompose in the sea to give mercury, mercuric chloride or mercuric sulfide, but some of these are converted into methyl mercury, which is extremely toxic. In humans, it affects the nervous system, causing impaired vision, hearing and speech, as well as loss of muscular coordination. These symptoms appeared with tragic results in fishing communities around Minimata Bay Japan, in 1953 and became epidemic by 1956. At least fifty people died. The mercury had entered the sea from an acetaldehyde plant, where it had been used earlier as a catalyst, and had subsequently become bio-concentrated and magnified through the food chain, which ultimately reaches fish and humans. Other sources of mercury include paper and agricultural (seed dressing) industries. Mercury average concentration in seawater averages about 0.03 µg/l, whereas levels beyond about 0.2 µg/l are considered polluting. Mercury was not at all detected in the coast of the Jeddah desalination plants.

There are a few cases in which high levels of Cd, Cu and Zn in oysters are known to have caused nausea and vomiting in humans. Copper enters seawater via mining and chemical wastes and is a common ingredient of anti-fouling paints. Uses of Cd, Cr and Zn include plating and galvanizing other metals. Cadmium is also used in the plastics industry. Considering the limited presence of such industries in Jeddah, one would venture to say that any reports about polluting levels of these metals were only obtained from an extremely limited area of an industrial effluent and would probably have no toxic effect on the environment. In any case, the present data do not indicate pollution by heavy metals in the coastal waters of SWCC desalination plants. Any report about pollution levels of heavy metals in these waters should be interpreted with extreme caution.

## **6.9 Overview**

The frequency of high SDI encounters in the Jeddah SWRO plants has witnessed significant decline in recent years. There were five such encounters in 1997, four in 1998, two in 2000, two in 2001, one in 2002, one in 2003 and none in 2004.

Encounters used to occur during summer and autumn. The last two high SDI periods occurred in autumn only, during October or late October to November. In addition, plant operators are now well experienced in manipulating pretreatment and operating parameters to minimize production loss during high SDI, and in increasing water production during normal operation periods [34]. The problem of water shortage is also vastly alleviated through coordination with Shoaiba plant.

The cause of rising SDI is a natural phenomenon of local current and water column mixing in the sea and the phenomenon appears to be cyclic in nature. The current comes from the shallow coastal waters south of the plants. It involves extreme rise in suspended solids or moderate rise in both suspended solids and algal growth. When algal growth is high, chlorination seems to aggravate the problem. Since zooplankton density is lowest at noon, chlorination may be reduced during high SDI times to once per day, with the dose given at noon. The particle escaping filtration by the DMF and MCF and giving high SDI readings are of size of  $<10\mu\text{m}$ , because the MCF is  $10\text{-}\mu\text{m}$  filter. At times, the plant has used  $5\text{-}\mu\text{m}$  filter without improvement in SDI readings. It is assumed then that the particles causing the high SDI are  $<5\text{-}\mu\text{m}$  in size. Ultrafiltration is therefore the technique which can exclude these particles. There is a strong tendency to introduce ultrafiltration as a promising solution for RO filtration problem. This tendency was very clear in the latest IDA Conference in the Bahamas in 2003, where a number of papers discussed the successful use of and advances made in ultrafiltration as a water pretreatment alternative. A project investigating the feasibility of ultrafiltration pretreatment has already been drafted by the SWCC Research and Development Center and is ready for implementation. Beachwell source water could also be, at least, used during periods of high SDI.

The question to be posed is thus: Given the experiences encountered in coping with SDI, a falling frequency of high SDI encounters, and the recent success in increasing the water recovery ratio, is it worth it to take any drastic and expensive measures to change the pretreatment or feed water source? Limited and low frequent water shortage may not warrant such changes. However, advances in RO industry may call for the introduction of new pretreatment technologies.

In short, the Jeddah, Jubail and Al-Birk, SWRO plants experience in coping with and solving pretreatment problems and maintaining or increasing water production show

that SWRO pretreatment problems are solvable and the RO technology is viable in Saudi Arabia coastal waters.

## **7. CONCLUSIONS**

1. The main cause of the intermittent rise in silt density index (SDI) could be attributed to a natural phenomenon of local coastal current, and which appears to be cyclic in nature. This water current comes from the shallow coastal waters south of the plants. The current disturbs bottom sediments and creates water column mixing, resulting in an increased suspended solids concentration. At times, elevated plankton production enhances the sediments effect. Plankton contributes to SDI after being broken down by water force, plant structures and chlorine.
2. The suspended solids causing the SDI problem are particles which are <5- $\mu\text{m}$  in size.
3. Some form of sewage is reaching the plant. However, the many measured biotic and physico-chemical parameters (including pollution indicators) showed that these components are not significantly different in coastal and offshore waters near the plants and are comparable to coastal waters of north Jeddah, which are largely considered clean and relatively free of pollution. Any report about coastal water pollution from the desalination plants has to be interpreted with extreme caution. There is no evidence to suggest that the high SDI is pollution-dependent.
4. Sewage water impact on the intake of the desalination plants is not significant nor is sewage presence hazardous to product water. Chlorinated source water and product water from MSF and SWRO plants are free of sewage indicating bacteria and viruses.
5. There has been a significant decline in the frequency of high SDI at the Jeddah SWRO plants.
6. Secchi disc visibility is reduced by 8 – 10m from a normal average of 16 – 18m during high SDI periods.
7. An environmental data base has been established for the Red Sea coastal and offshore waters opposite the SWCC Jeddah desalination and power plants.
8. The Jeddah, Jubail and Al-Birk SWRO plants experience in coping with and solving pretreatment problems and maintaining and increasing water production

show that SWRO pretreatment problems are solvable and that the application of RO technology is practical in Saudi Arabia's coastal waters.

9. The parameters investigated along the coast near the plants did not vary significantly with respect to depth or space. Therefore, future sampling can be concentrated at only one coastal location to save time and effort.

## **8. RECOMMENDATIONS**

1. That source water chlorination be reduced to once per day during high SDI days, with the dose given at noon, the time of the day when the presence of zooplankton is minimal.
2. That DMF filtrate be refiltered for as long as it takes to keep certain SWRO units in operation during problem days.
3. That bore holes be established to test the suitability of beachwell establishment. The beachwell source water could then be used as a back-up during problem days either alone or after mixing with recirculated filtrate.
4. That a Secchi disc visibility of  $\leq 10\text{m}$  in the intake area be taken as a warning sign for expecting a high SDI encounter.
5. That pretreated feed water of higher than the currently set maximum allowable SDI be fed to the membranes in an experiment to make sure that this current SDI limit is no stricter than it ought to be.
6. That trends in RO technology calling for the introduction of ultrafiltration pretreatment be considered for all SWCC SWRO plants. In Jeddah, the option of introducing ultra or nanofiltration should be weighed against production loss on the one hand, and the need to introduce and make use of new technology on the other.

**Table 1. Phytoplankton density (cells/m<sup>3</sup>) and seasonal variation in coastal seawater of the SWCC Jeddah desalination and power plants during 2002-04 (n=10)**

Phytoplankton	Season <sup>1</sup>				
	Summer	Fall	Winter	Spring	Annual <sup>2</sup>
Cells/m <sup>3</sup> (X 10 <sup>4</sup> )	(2.72 ± 0.62) <sup>3</sup>	(3.79±0.80)	(2.46±1.20)	(2.93±0.73)	(2.98±0.38)

<sup>1</sup> Summer included June-August; Fall included September-November; Winter included December – February; and Spring included March – May.

<sup>2</sup> Average of all seasons (n=40)

<sup>3</sup> There is a statistically significant difference between Fall and Winter; any other pair-wise comparison between means showed no significant difference; Analysis of Variance (P = 0.392).

± 95% C.I.

**Table 2. Comparison of total suspended solids (TSS), silt density index (SDI), total organic carbon (TOC) Secchi disc visibility (visibility) phytoplankton density, and chlorophyll during high and normal SDI periods in coastal (RO intake) and open Red Sea water ( about 5 km off shore) at the SWCC Jeddah desalination and power plants**

Parameter	High SDI Periods												Normal SDI Periods					
	Period – 1 (October 2002)						Period – 2 (October 2003)						RO Intake			Open Sea		
	RO Intake			Open Sea			RO Intake			Open Sea			RO Intake			Open Sea		
	1m	15m	25m	1m	15	25m	1m	15m	25m	1m	15m	25m	1m	15m	25m	1m	15m	25m
TSS (mg/l)	15.1	15.8	21.9	10.5	14.1	9.3	7.0	6.8	6.6	5.8	4.4	5.0	2.8	2.5	2.7	1.6	1.8	1.8
SDI	5.95	5.80	5.61	4.60	4.50	4.53	5.58	5.07	5.46	4.50	4.40	4.46	4.53	4.60	4.80	4.30	4.33	4.31
TOC (mg/l)	<i>Not Measured</i>						6.0	5.0	5.1	5.8	4.3	4.4	2.60	2.15	2.40	2.40	2.11	2.60
Visibility (m)	-	7.5	-	-	11.5	-	-	9.25	-	-	13.0	-	-	16–20	-	-	18–25	-
Phytoplankton (cells/m <sup>3</sup> )	7.70 x 10 <sup>4</sup>			5.33 x 10 <sup>4</sup>			2.71 x 10 <sup>5</sup>			1.20 x 10 <sup>5</sup>			(9.37 ± 2.73) <sup>a</sup> x 10 <sup>4</sup>			(5.36 ± 2.29) <sup>b</sup> x 10 <sup>4</sup>		
Chlorophyll (µg/l)	<i>Not Measured</i>						1.2	2.3	2.9	0.9	1.6	1.5	(0.51 ± 0.33) <sup>c</sup>			(0.22 ± 0.10) <sup>c</sup>		

<sup>a,b,c</sup> For plankton and chlorophyll concentration in the RO intake and open seawater, means followed by different letter superscripts are significantly different while means followed by same letter superscript are not ; Analysis of Variance (P = 0.02 for plankton and 0.456 for chlorophyll).

± 95% C.I.

**Table 3. Comparison of total suspended solids (TSS) concentration in four sampling locations in the Red Sea coast at Jeddah around the SWCC desalination and power plants during 2002 and 2003 (N = 12)**

Location and Depth	Sampling Locations <sup>1</sup>											
	S-1m	S-15m	S-25m	D – 1m	D – 15m	D – 25m	RO-1m	RO-15m	RO-25m	N – 1m	N – 15m	N – 25m
TSS (mg/l)	2.64 ± 1.10	2.44 ± 0.97	2.35 ± 1.15	2.64 ± 0.92	2.54 ± 0.67	2.88 ± 1.09	1.54 ± 0.74	1.56 ± 1.06	1.56 ± 0.41	1.71 ± 0.96	1.71 ± 0.67	1.39 ± 0.62
TSS average <sup>2</sup>	-	2.48 ± 0.52	-	-	2.69 ± 0.44	-	-	1.56 ± 0.38	-	-	1.60 ± 0.37	-

S, D, RO and N were sampling locations around the plants' (the SWCC Jeddah desalination and power plants) shore line: the S sampling location was to the south of the plants, at a distance of about 1.5 km and about 500 m from the shore of the Ministry of Defense compound; the D sampling location was about 300m to the sea off the plants discharge bay south of the RO intake; the RO sampling location was in the vicinity of the intake areas of the SWRO plants, and the N location was about 1.5km north of the plants and 200 m from the shore. 1m, 15m and 25m represented sampling spots at 1m, 15m and 25m depth, respectively, at each sampling location.

<sup>2</sup>Average value of the 3 depths at each location.

There is not a statistically significant difference within or between means of the four sampling locations; Analysis of Variance and t- Test ( $P < 0.032$ ).

± 95% C.I.

**Table 4. Variation of total suspended solids (TSS) in coastal (RO intake) and open sea (about 5 km offshore) at the SWCC Jeddah desalination and power plants during 2002, 2003 and 2004 (n = 8)**

Year	Location	
	TSS (mg/l)	
	Coast water	Open Seawater
2002	1.53 ± 0.65 <sup>a</sup>	1.16 ± 0.70 <sup>a</sup>
2003	1.44 ± 0.57 <sup>a</sup>	0.96 ± 0.51 <sup>a</sup>
2004	4.89 ± 1.04 <sup>b</sup>	4.80 ± 0.95 <sup>b</sup>

<sup>a,b</sup> Means followed by the same letter superscript are similar, and those followed by different ones are significantly different; Analysis of Variance and Tukey Test ( $P \leq 0.001$ ).

± 95% C.I.

**Table 5. Variation of total suspended solids (TSS), silt density index (SDI) and total organic carbon (TOC) with pretreatment during a period of high SDI encounter (October 2003)**

Parameter	Raw Seawater* (RO Intake)	Chlorinated Feed Water	Filtered RO Feed Water	
			RO - 1	RO - 2
TSS (mg/l)	6.2	7.2	0.6 (91.7) <sup>†</sup>	0.8 (88.9) <sup>†</sup>
SDI	5.07	5.23	4.85	4.86
TOC (mg/l)	5.0	6.0	3.5	4.0

\* From about 12 m depth

<sup>†</sup> Numbers in parenthesis are percentages TSS removal efficacies

**Table 6. Atomic Absorption Elemental Analyses of Suspended Solids in Coastal (RO intake) and Open Red Sea water at the SWCC Jeddah Desalination and Power Plants (n = 2)**

Sampling Location <sup>1</sup>	Percentage Composition <sup>2</sup>				
	Na	Mg	Ca	Al	Fe
Coast	17.65 (14.3-21.0)	2.65 (2.2-3.1)	1.45 (1.0-1.9)	1.9 (0.7-3.1)	0.12 (0-0.24)
Open sea	10.45 (10.0-10.9)	2.55 (2.5-2.6)	3.15 (2.2-4.1)	4.8 (3.2-6.4)	ND

<sup>1</sup>Coast location represented the intake area of the SWRO plants, and sampling location open sea was at a distance of about 5 km from the shore line of the plants.

<sup>2</sup> Composition of the remaining percentage is not known

ND = Not Detected

**Table 7. Comparison of nutrients, total carbon, dissolved oxygen and biochemical oxygen demand in coastal (RO intake) and open Red Sea water at the SWCC Jeddah desalination and power plants (N = 7)**

Sampling Locations <sup>1</sup>	Parameter Concentration									
	Phosphate-P (µg/l)	Ammonia-N (µg/l)	Nitrite-N (µg/l)	Nitrate-N (µg/l)	Dissolved Sugar (µmole/l)	Dissolved Organic-N (µg/l)	Inorganic-C (mg/l)	TOC (mg/l)	Dissolved Oxygen (mg/l)	BOD (mg/l)
C - 1m					0.19 ± 0.04 <sup>a</sup>	24.68 ± 2.1 <sup>a</sup>	24.75 ± 0.80	2.60 ± 1.24	5.88 ± 0.99	0.48 ± 0.36
C - 15 m	0.15± 0.10	2.60± 0.90	0.13± 0.10	0.69± 0.49	0.24± 0.07 <sup>a</sup>	23.70± 2.1 <sup>a</sup>	24.50± 0.92	2.20± 0.72	5.85± 0.57	0.38± 0.07
C - 25m					0.21± 0.06 <sup>a</sup>	23.20± 1.3 <sup>a</sup>	25.00± 1.30	2.45± 1.79	5.69± 0.91	0.65± 0.49
C –Pooled					0.21± 0.04 <sup>a</sup>	23.89± 0.71 <sup>a</sup>	24.75± 0.39	2.42± 0.49	5.81± 0.31	0.51± 0.16
O - 1 m					0.37± 0.12 <sup>b</sup>	19.07± 0.85 <sup>b</sup>	24.25± 0.80	2.47± 1.69	5.90± 0.83	0.73± 0.38
O-15m	0.13± 0.10	2.99± 1.60	0.11± 0.09	0.70± 0.16	0.39± 0.12 <sup>b</sup>	19.06± 0.85 <sup>b</sup>	25.25± 0.80	2.16± 1.26	5.95± 0.52	0.77± 0.43
O - 25 m					0.38± 0.05 <sup>b</sup>	19.12± 0.72 <sup>b</sup>	24.50± 0.92	2.63± 0.86	5.65± 1.11	0.85± 0.34
O – Pooled					0.38± 0.04 <sup>b</sup>	19.06± 0.48 <sup>b</sup>	24.67± 0.41	2.43± 0.49	5.83± 0.32	0.75± 0.09

<sup>1</sup>Sampling location C represents the intake area of the SWRO plants, and sampling location O represents the open sea, at a distance of about 5 km from the shore of the plant. 1 m, 15m and 25m are depths in meters at each sampling location. For the inorganic nutrient salts, one depth is reported because of similarity of values within and between the two locations.

<sup>a,b</sup>For each parameter (vertical rows), means that are followed by the same letter superscript are similar, while those followed by different ones are significantly different. Means with no letter superscript are not different; Analysis of Variance and Tukey Test (P <0.05).

± 95% C.I.

**Table 8. Comparison of inorganic nutrient concentration in four sampling locations in the Red Sea coast at Jeddah around the SWCC desalination and power plants (n = 5)**

Nutrient	Sampling Locations <sup>1</sup>											
	Nutrient Concentration (µg/l)											
	S-1m	S-15m	S-25m	D – 1m	D – 15m	D – 25m	RO-1m	RO-15m	RO-25m	N – 1m	N – 15m	N – 25m
Phosphate-P	0.09±0.04	0.10±0.04	0.10±0.04	0.13±0.10	0.09±0.04	0.1±0.08	0.10±0.07	0.08±0.30	0.12±0.06	0.09±0.01	0.09±0.02	0.12±0.05
Ammonia –N	1.33±0.25	1.39±0.27	1.41±0.17	1.57±0.48	1.33±0.25	1.17±0.26	1.55±0.26	1.40±0.29	1.57±0.51	1.68±0.53	1.87±0.74	1.46±0.33
Nitrite – N	0.04±0.02	0.04±0.02	0.05±0.03	0.05±0.03	0.03±0.01	0.03±0.01	0.07±0.01	0.03±0.01	0.03±0.01	0.02±0.01	0.02±0.01	0.03±0.01
Nitrate – N	0.25±0.35	0.25±0.18	0.31±0.26	0.35±0.28	0.25±0.18	0.23±0.30	0.69±0.69	0.29±0.14	0.31±0.17	0.45±0.44	0.38±0.28	0.28±0.21
Pooled <sup>2</sup> Phosphate		0.10±0.02			0.09±0.03			0.1±0.03			0.10±0.02	
Pooled Ammonia		1.38±0.13			1.36±0.21			1.51±0.20			1.67±0.32	
Pooled Nitrite		0.04±0.01			0.03±0.01			0.04±0.03			0.02±0.007	
Pooled Nitrate		2.69±0.13			2.75±0.21			3.46±0.29			3.68±0.14	

S, D, RO and N were sampling locations around the plants' (the SWCC Jeddah desalination and power plants) shore line: the S sampling location was to the south of the plants, at a distance of about 1.5 km and about 500 m from the shore of the Ministry of Defense compound; the D sampling location was about 500 m to the sea off the plants discharge bay south of the RO intake; the RO sampling location was in the vicinity of the intake areas of the SWRO plants, and the N location was about 1.0 km north of the plants and 200 m from the shore. 1m, 15m and 25m represented sampling spots at 1m, 15m and 25m depth, respectively, at each sampling location.

<sup>2</sup> Average value of the 3 depths at each location.

For the same nutrient there were no differences between means within a sampling location, between locations or in pooled values of the 3 depths at each location; Analysis of Variance.

± 95% C.I.

**Table 9. Comparison of bacterial density and growth rate in four sampling locations in the Red Sea coast at Jeddah around the SWCC desalination and power plants (n = 10)**

Sampling locations	Bacterial Density and Growth Rates									
	0-h count <sup>1</sup>	24-h count	48-h count	24-h generation <sup>2</sup>	48-h generation	Pooled <sup>3</sup> 0-h count	Pooled 24-h count	Pooled 48-h count	Pooled 24-h generation	Pooled 48-h generation
S – 1m	(1.05 ± 0.46)x10 <sup>4</sup>	(2.49 ± 0.98)x10 <sup>6</sup>	(7.50 ± 0.41)x10 <sup>5</sup>	2.97 ± 0.43	6.97 ± 0.42					
S - 15 m	(1.06 ± 0.56)x10 <sup>4</sup>	(2.16 ± 1.3)x10 <sup>6</sup>	(4.53 ± 0.65)x10 <sup>5</sup>	3.24 ± 0.23	6.69 ± 0.06	(1.09 ± 0.15) <sup>a</sup> x10 <sup>4</sup>	(2.45 ± 0.59) <sup>a</sup> x10 <sup>6</sup>	(6.40 ± 0.48) <sup>a</sup> x10 <sup>5</sup>	3.09 ± 0.14 <sup>a</sup>	6.33 ± 0.49 <sup>a</sup>
S - 25m	(1.16 ± 0.69)x10 <sup>4</sup>	(2.70 ± 1.46)x10 <sup>6</sup>	(7.18 ± 0.12)x10 <sup>5</sup>	3.06 ± 0.12	5.32 ± 0.38					
D - 1 m	(1.51 ± 0.97)x10 <sup>4</sup>	(2.80 ± 1.46)x10 <sup>6</sup>	(8.84 ± 3.49)x10 <sup>5</sup>	3.11 ± 0.43	5.01 ± 0.15					
D - 15 m	(1.35 ± 0.88)x10 <sup>4</sup>	(3.00 ± 1.63)x10 <sup>6</sup>	(3.57 ± 0.79)x10 <sup>5</sup>	2.96 ± 0.20	5.88 ± 0.48	(1.34 ± 0.23) <sup>a</sup> x10 <sup>4</sup>	(2.94 ± 0.73) <sup>a</sup> x10 <sup>6</sup>	(5.71 ± 0.88) <sup>a</sup> x10 <sup>5</sup>	3.02 ± 0.13 <sup>a</sup>	5.49 ± 0.26 <sup>b</sup>
D - 25 m	(1.15 ± 0.63)x10 <sup>4</sup>	(3.02 ± 1.59)x10 <sup>6</sup>	(4.73 ± 1.29)x10 <sup>5</sup>	2.98 ± 0.26	5.59 ± 0.25					
RO - 1 m	(1.21 ± 0.66)x10 <sup>3</sup>	(3.68 ± 1.36)x10 <sup>5</sup>	(3.76 ± 2.10)x10 <sup>5</sup>	2.85 ± 0.16	4.63 ± 0.04					
RO - 15 m	(1.22 ± 0.65)x10 <sup>3</sup>	(3.63 ± 1.33)x10 <sup>5</sup>	(2.66 ± 0.25)x10 <sup>5</sup>	2.92 ± 0.23	5.39 ± 0.24	(1.13 ± 0.16) <sup>b</sup> x10 <sup>3</sup>	(3.47 ± 0.59) <sup>b</sup> x10 <sup>5</sup>	(3.36 ± 0.27) <sup>b</sup> x10 <sup>5</sup>	2.89 ± 0.09 <sup>a</sup>	5.08 ± 0.22 <sup>b</sup>
RO - 25 m	(9.53 ± 3.52)x10 <sup>2</sup>	(3.11 ± 1.01)x10 <sup>5</sup>	(3.66 ± 0.17)x10 <sup>5</sup>	2.87 ± 0.14	5.21 ± 0.30					
N - 1 m	(9.38 ± 6.92)x10 <sup>2</sup>	(2.39 ± 1.48)x10 <sup>5</sup>	(4.14 ± 0.67)x10 <sup>5</sup>	2.86 ± 0.32	4.27 ± 0.09					
N - 15 m	(1.09 ± 0.78)x10 <sup>3</sup>	(3.26 ± 1.83)x10 <sup>5</sup>	(5.65 ± 0.87)x10 <sup>5</sup>	2.89 ± 0.48	4.01 ± 0.59	(1.10 ± 0.22) <sup>b</sup> x10 <sup>3</sup>	(2.89 ± 0.78) <sup>b</sup> x10 <sup>5</sup>	(5.74 ± 0.53) <sup>a</sup> x10 <sup>5</sup>	2.90 ± 0.19 <sup>a</sup>	4.21 ± 0.22 <sup>c</sup>
N - 25 m	(1.28 ± 0.95)x10 <sup>3</sup>	(3.02 ± 1.55)x10 <sup>5</sup>	(7.44 ± 2.16)x10 <sup>5</sup>	2.93 ± 0.39	4.35 ± 0.92					

S, D, RO and N were sampling locations around the plants' (the SWCC Jeddah desalination and power plants) shore line: the S sampling location was to the south of the plants, at a distance of about 1.5 km and about 500 m from the shore of the Ministry of Defense compound; the D sampling location was about 500 m to the sea off the plants discharge bay south of the RO intake; the RO sampling location was in the vicinity of the intake areas of the SWRO plants, and the N location was about 1.0 km north of the plants and 200 m from the shore. 1m, 15m and 25m represented sampling spots at 1m, 15m and 25m depth, respectively, at each sampling location.

<sup>1</sup>Count/density of bacteria (colony-forming units/ml); pour plate in marine agar.

<sup>2</sup>Generation time (h) =  $\Delta t \cdot k / (\ln N_t - \ln N_{t_0})$  where  $\Delta t = 24$  for 24-h generation time and 48 for 48-h generation time,  $k = \ln 2 = 0.693$ ,  $N_t$  bacterial count, after 24 or 48-h incubation, and  $N_{t_0}$  initial bacterial count.

<sup>3</sup>Average value of the 3 depths at each location.

<sup>a,b,c</sup>For the same parameter means that are followed by the same letter superscript are similar, while those followed by different ones are significantly different; Analysis of Variance and Tukey Test ( $P < 0.001$ ).

± 95% C.I.

**Table 10. Comparison of bacterial density and growth rate in coastal (RO intake) and open Red Sea water at the SWCC Jeddah desalination and power plants (n = 7)**

Test Parameter	Sampling Locations <sup>1</sup>					
	C - 1m	C - 15m	C - 25m	O- 1m	O- 15m	O- 25m
0-h count <sup>2</sup>	(1.99 ± 0.67)x10 <sup>3</sup>	(1.93 ± 0.81)x10 <sup>3</sup>	(1.59 ± 0.95)x10 <sup>3</sup>	(1.88 ± 1.56)x10 <sup>2</sup>	(1.91 ± 1.76)x10 <sup>2</sup>	(4.82 ± 4.01)x10 <sup>2</sup>
24-h count	(6.39 ± 1.11)x10 <sup>5</sup>	(6.52 ± 1.31)x10 <sup>5</sup>	(7.15 ± 1.25)x10 <sup>5</sup>	(2.96 ± 1.73)x10 <sup>5</sup>	(2.88 ± 1.51)x10 <sup>5</sup>	(4.67 ± 1.90)x10 <sup>5</sup>
48-h count	(9.47 ± 2.05)x10 <sup>5</sup>	(9.88 ± 3.17)x10 <sup>5</sup>	(1.04 ± 0.50)x10 <sup>6</sup>	(4.25 ± 3.61)x10 <sup>5</sup>	(4.17 ± 3.07)x10 <sup>5</sup>	(6.31 ± 2.64)x10 <sup>5</sup>
24-h growth rate <sup>3</sup>	2.92 ± 0.17	2.83 ± 0.31	2.66 ± 0.25	2.67 ± 0.42	2.19 ± 0.27	2.20 ± 0.32
48-h growth rate	5.28 ± 0.33	5.19 ± 0.44	5.08 ± 0.37	4.52 ± 1.01	4.25 ± 0.50	4.25 ± 9.67
Pooled <sup>4</sup> 0-h count		(1.84 ± 0.37) <sup>a</sup> x 10 <sup>3</sup>			(2.87 ± 2.44) <sup>b</sup> x 10 <sup>2</sup>	
Pooled 24-h count		(6.69 ± 0.56) <sup>a</sup> x 10 <sup>5</sup>			(3.50 ± 0.85) <sup>b</sup> x 10 <sup>5</sup>	
Pooled 48-h count		(9.91 ± 1.61) <sup>a</sup> x 10 <sup>5</sup>			(4.91 ± 1.46) <sup>b</sup> x 10 <sup>5</sup>	
Pooled 24-h growth rate		2.81 ± 0.12 <sup>a</sup>			2.22 ± 0.15 <sup>b</sup>	
Pooled 48-h growth rate		5.19 ± 0.17 <sup>a</sup>			4.34 ± 0.34 <sup>b</sup>	

<sup>1</sup>Sampling location C represented the intake area of the SWRO plants, and sampling location O represented the open sea at a distance of about 5 km from the shore line of the plants.

<sup>2</sup>Count/density of bacteria (colony-forming units/ml); pour plate count in marine agar.

<sup>3</sup>Growth rate is the generation time (h) =  $\Delta t \cdot k / (\ln N_t - \ln N_{t_0})$  where  $\Delta t = 24$  for 24-h generation time and 48 for 48-h generation time,  $k = \ln 2 = 0.693$ ,  $N_t$  bacterial count, after 24 or 48-h incubation, and  $N_{t_0}$  initial bacterial count.

<sup>4</sup>Means of the 3 depths at each location

<sup>a,b,c</sup>For the same test parameter (horizontal rows), means that are followed by the same letter superscript are similar, while those followed by different ones are significantly different; Analysis of Variance and Tukey Test (P < 0.001).

± 95% C.I.

**Table 11. Bacterial growth rates in the Jeddah SWRO plants intake water with and without chlorination in comparison with intake waters of Al-Birk and Al-Jubail SWRO plants (n = 8)**

Plant	24-h Generation Time (h) <sup>1</sup>		48-h Generation Time (h)	
	Seawater	Chlorinated feed water	Seawater	Chlorinated feed water
Jeddah	3.01 <sup>a</sup> ± 0.11	2.20 <sup>c</sup> ± 0.14	5.27 <sup>d</sup> ± 0.31	4.03 <sup>f</sup> ± 0.34
Al-Birk	3.40 <sup>a</sup> ± 0.31	2.47 <sup>c</sup> ± 0.19	5.77 <sup>d</sup> ± 0.74	4.23 <sup>f</sup> ± 0.29
Al-Jubail	7.60 <sup>b</sup> ± 1.54	3.13 <sup>a</sup> ± 0.29	12.53 <sup>e</sup> ± 3.55	3.35 <sup>a</sup> ± 0.38

<sup>1</sup>Generation time (h) =  $\Delta t \cdot k / (\ln N_t - \ln N_0)$  where  $\Delta t = 24$  for 24-h generation time and 48 for 48-h generation time,  $k = \ln 2 = 0.693$ ,  $N_t$  bacterial count, after 24 or 48-h incubation, and  $N_0$  initial bacterial count.

<sup>abcd</sup> Means that are followed by the same letter superscript are similar, while those followed by different ones are significantly different; Analysis of Variance and Tukey Test ( $P < 0.001$ ).

± 95% C.I.

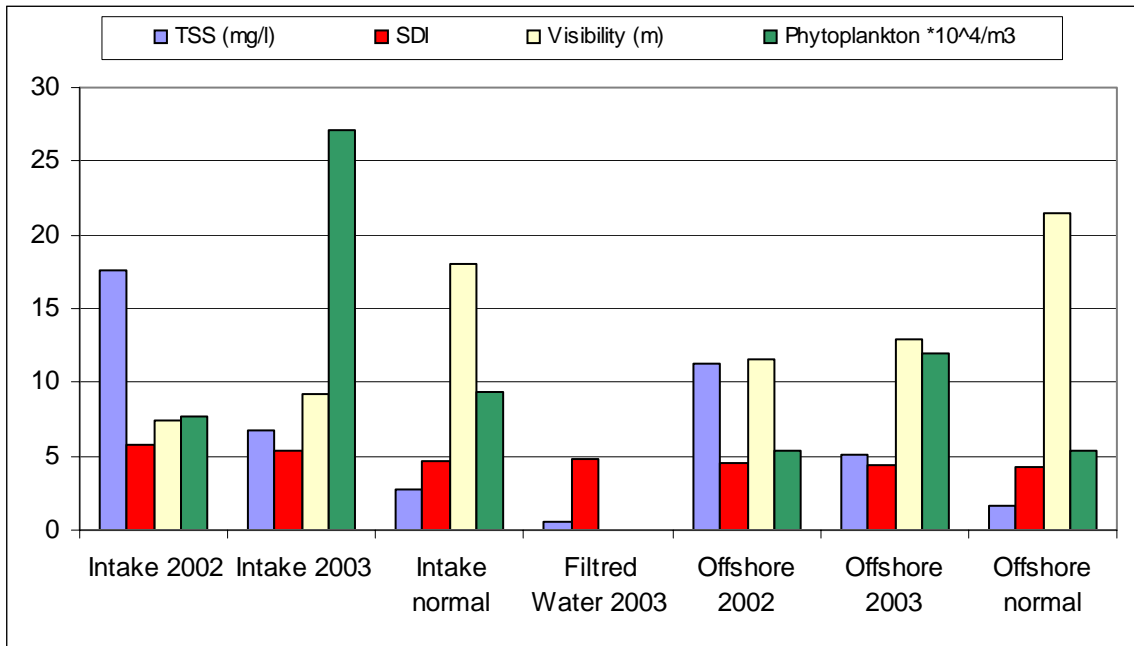
**Table 12. Concentration of pollution indicator water quality parameters in the SWCC Jeddah desalination and power plants coast (RO intake) and open seawater (about 5 km from coast) and the Arbaeen Lagoon (August, 2004)**

S.No.	Parameters	Concentration		
		Coast Water	Open Seawater	Arbaeen Lagoon
1	TOC (mg/l)	2.50	2.50	5.50
2	Phosphate (µg-P/l)	0.22	0.20	0.62
3	Ammonia (µg-N/l)	3.8	2.60	3.50
4	Nitrite (µg-N/l)	0.20	0.20	0.29
5	Nitrate (µg-N/l)	1.32	0.65	1.74
6	Total dissolved carbohydrates (µ mole/l)	0.40	0.36	0.82
7	Total dissolved organic nitrogen (µg/l)	20.00	19.00	24.50
8	Dissolved oxygen (mg/l) (10:00 O'clock morning, Temp. 28°C)	6.3	6.3	7.2
9	TSS (mg/l)	2.3	2.1	3.3
10	Heavy metals ((µg/l) <sup>1</sup>			
	1. Arsenic (1 – 2)	1.5	1.6	1.7
	2. Selenium (0.04 – 0.18)	ND	ND	ND
	3. Mercury (0.004 – 0.02)	ND	ND	ND
	4. Chromium (0.1 – 0.26)	ND	ND	ND
	5. Cadmium (0.0001 – 0.12)	ND	ND	0.1
	6. Copper (0.03 – 0.38)	1.1	1.0	1.3
	7. Lead (0.001 – 0.04)	2.0	2.0	4.3
	8. Iron (0.006 – 0.14)	4.2	3.9	5.0
	9. Zinc (0.003 – 0.02)	0.8	0.8	0.9
10. Tin (p)*	ND	ND	ND	

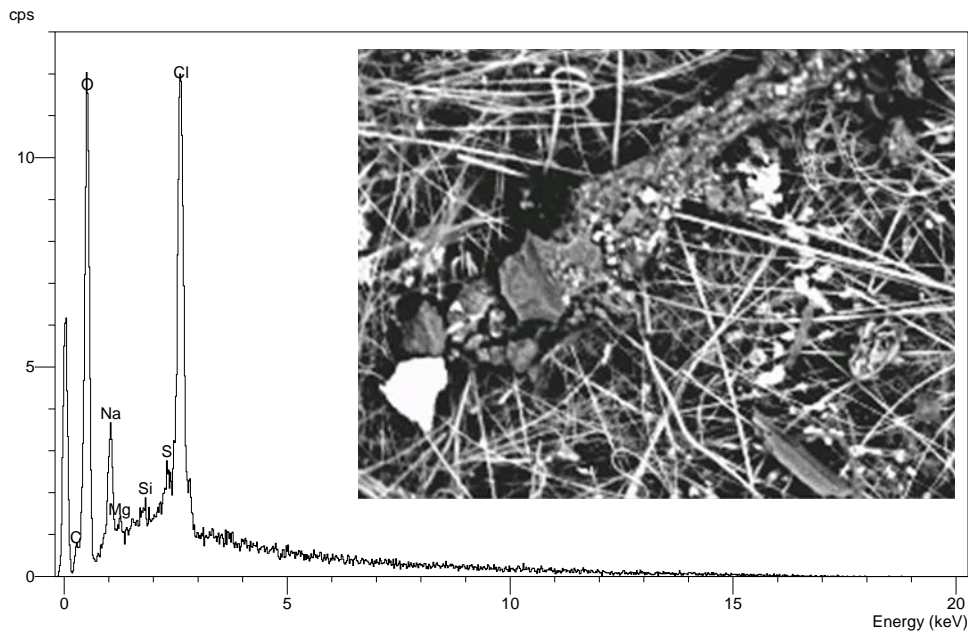
ND = Not detected

<sup>1</sup>Values in parenthesis are the reported concentration of dissolved metals in seawater (From: Bruland, Chemical Oceanography, Vol. 8 (1983): 175 - 219.

\* Present, but in negligible concentration



**Figure 1.** Comparison of total suspended solids (TSS), silt density index (SDI), Secchi disc visibility and phytoplankton density during high and normal SDI periods in coastal (RO intake) and offshore Red Sea Water ( about 5 km off shore) at the SWCC Jeddah desalination and power plants



**Figure 2.** EDX and a micrograph of suspended solids residue on membrane filter paper from coastal Red Sea water at the intake of the SWCC Jeddah desalination and power plants. The profile shows the presence of certain elements, and the micrograph insert shows algae, detritus and debris of variable size.



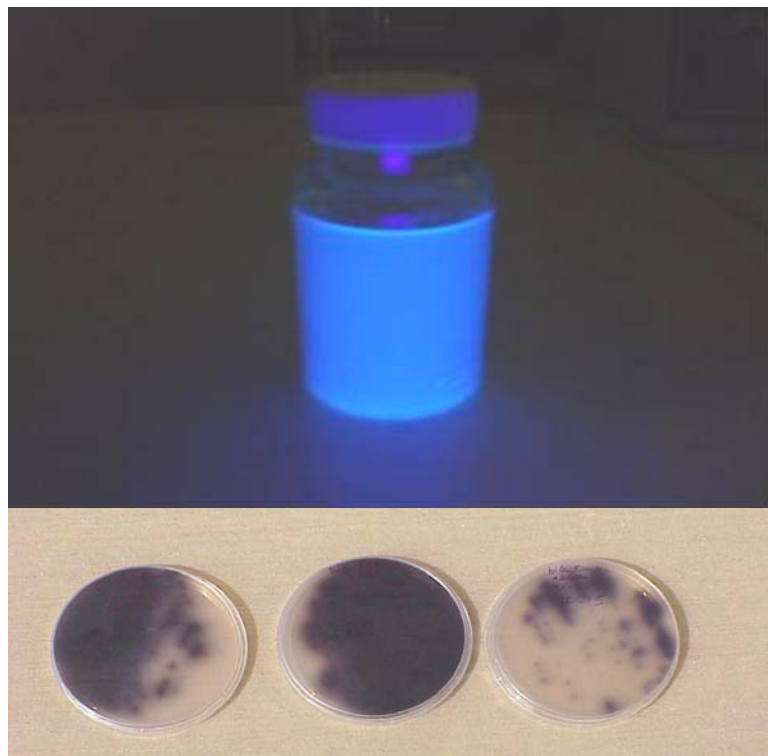
**Photograph 1a.**

Test of a water sample from the coast at the SWCC Jeddah desalination plants for fecal coliform bacteria using Quanti-Tray® with Colisure® reagent: Magneta-colored wells indicate a positive reaction for coliform bacteria and magneta-colored and fluorescing wells (marked X) indicate a positive reaction for *Escherichia coli* and the presence of sewage. Test tubes contain glucose azide broth to which water samples were added. The yellow in the right and left tubes indicates acid production and the presence of *Enterococcus* bacteria, confirming the presence of sewage. The red in the middle tube shows negative reaction for the presence of *Enterococcus*, confirming absence of sewage.



**Photograph 1b.**

Confirmatory identification of bacteria isolated from water samples in the Quanti-Tray® with Colisure® reagent in figure-1a above using analytical profile index reaction strip. The sum of reactions gives a 100% identification profile for *Escherichia coli* (90.4% for *E.coli*-1 and 9.6% for *E. coli*-2)



**Photograph 1c.**

Polystyrene bottle containing water sample from the coast at the SWCC Jeddah plants plus Enteroleet™ reagent. The sample fluoresced after incubation indicating presence of an *Enterococcus sp.*

The Petri dishes contain the differential medium bile aesculin azide agar seeded from the fluorescing bottle. Growth of black bacterial colonies on this selective medium is a confirmatory reaction for the presence of *Enterococcus fecalis* indicating the presence of sewage water.

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